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Ventilation and IAQ of a Gym during the Covid-19 Pandemics: Field Analysis and Proposals for Risk Mitigation

PAPER 44

RESUMO

O contexto pandêmico da Covid-19 ressaltou a importância da qualidade do ar interno (QAI) na saúde pública. O não atendimento de níveis recomendados de QAI está correlacionado ao aumento do risco de infecções por via aérea de Covid-19. Além do impacto na saúde, há também prejuízos no desempenho cognitivo causados pela baixa QAI. Em ambientes onde são realizadas atividades com alta taxa metabólica o risco intensifica-se devido a maior exalação de contaminantes pelo indivíduo fonte e surtos foram reportados em academias de ginastica. Por esta razão, este estudo se propôs a realizar a avaliação da qualidade do ar interno de uma academia de ginástica em Teresina (Brasil) a partir do monitoramento da temperatura, umidade relativa do ar, e concentração de CO_2. As taxas de ventilação foram estimadas usando-se um método indireto baseado nesse monitoramento. Verificou-se que o nível de CO_2 e a taxa de ventilação estimada encontravam-se em níveis preocupantes, abaixo de níveis recomendados para a ocupação pelas normas e comparáveis a eventos de surto de Covid-19. Por meio de um modelo de risco de infecção, avaliou-se o efeito de diferentes estratégias na melhoria da QAI para mitigar o risco de infecção por via aérea.

Palavras-chave: Ventilação. Academia. Controle de Infecção. QAI. Covid-19.

ABSTRACT

The Covid-19 pandemic context highlighted the importance of indoor air quality (IAQ) in public health. Non-compliance with IAQ standards is correlated with increased risks of airborne transmission of Covid-19. Furthermore, poor IAQ cause cognitive damages. In indoor environments where occupants engage in activities with high metabolic rates the infection risk increases due to higher exhalation of contaminants by an infected subject. The transmission of Covid-19 by asymptomatic and pre-symptomatic people hampers the source-isolation technique, and outbreaks have been reported in gyms during the pandemics. For this reason, this study proposed to evaluate the indoor air quality of a gym in Teresina (Brazil). An assessment of temperature, relative humidity, and CO_2 concentration was performed. Ventilation rates were estimated using an indirect method based on this monitoring. It was found that the CO_2 concentration and the estimated ventilation rates were at worrying levels, outside the recommended levels for occupancy by standards, and comparable to those in Covid-19 outbreaks. A transmission risk model was used to assess the cost-effectiveness of different strategies to increase IAQ for the studied gym to mitigate the airborne infection risks.

Keywords: Ventilation. Gym. Infection Control. IAQ. Covid-19.

1 INTRODUÇÃO

The COVID-19 pandemic has brought increased attention to the quality of indoor air, as people spend more time indoors and the risk of COVID-19 infection was correlated to the cohabitation of indoor spaces during this pandemic (Qian et al., 2020). Also, community outbreaks most frequently occur at larger distances through inhalation of airborne virus-laden particles (Morawska et al., 2021). Poor indoor air quality (IAQ) can result in respiratory issues, allergies, and other health problems, making IAQ a critical factor in maintaining human health and well-being. Carbon dioxide (CO2), a byproduct of human respiration, has become a focus due to its negative impact on cognitive task performance (Fan et al., 2023). CO2 concentration is closely linked to occupancy level and ventilation rate in indoor spaces, with crowded and poorly ventilated areas leading to rapid CO2 concentration increases that can cause headaches, fatigue, and long-term respiratory issues. Therefore, monitoring and controlling indoor CO2 levels through sufficient ventilation is crucial for ensuring healthy and comfortable indoor environments.

Morawska et al. (2020) state that ventilation plays a critical role in removing exhaled virus-laden air, thus lowering the overall concentration and therefore any subsequent dose inhaled by the occupants. Additionally, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) recommended the proper ventilation as an important method for preventing outbreaks (ASHRAE, 2020; REHVA, 2020).

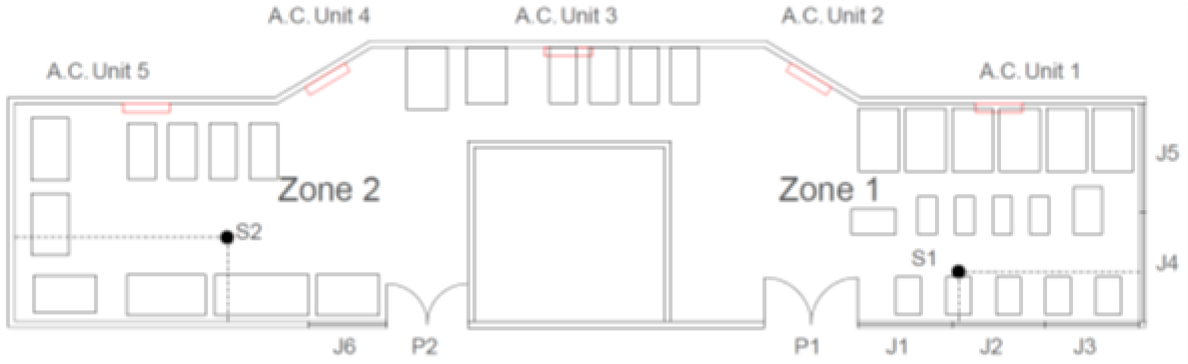
Therefore, the objective of the present study was to analyze the ventilation of a university gym in Brazil and to propose measures for reducing the long-range airborne infection risk of COVID-19 during the current pandemic.

2 METHODS

2.1 Experimental setup and design

This study was conducted in a gym with split-system air conditioners (A.C. units) in Teresina, Brazil. There is no mechanical ventilation. Natural ventilation and infiltration are the only means of indoor air renovation with outdoor air. The configuration of the space under study is depicted in Figure 1.

Figure 1 – General configuration of the gym.



The sample points are designated as S1 and S2

Source: Own authorship, 2023.

The floor area is 241.6 m^2, with a medium height of 4.8 m. Zone 1 is primarily used as aerobic, while Zone 2 is use as weight area. Type 1 windows (J1-J3) have a width of 3.0 m and a height of 2.1 m, type 2 windows (J4 and J5) have a width of 3.5 m and a height of 2.1 m, and type 3 window (J6) has a width of 2.5 m and a height of 2.1 m. The entry door has a width of 3 m and a height of 3 m, while the door located in the Zone 2 has a width of 2.6 m and a height of 3 m. The AC equipment produces a total airflow of 6280 m^3/h with a filter rating of MERV ≤ 4 (ASHRAE, 2017) and a total cooling capacity of 134,000 BTU/h.

In this study, two experimental scenarios were assessed based on the current natural ventilation capabilities of the building:

- Scenario 1: In this scenario, all type 1 and type 2 windows were closed, and all air conditioner units were running at full capacity.
- Scenario 2: In this scenario, all windows were opened, and all air conditioner units were running at full capacity.

2.2 Carbon dioxide measurement

The CO_2 concentration was measured at two points in the gym (during Scenarios 1 and 2) – at Zone 1 and Zone 2 (as shown in Figure 1) at a height of 1.5 m, based on Resolution – RE N.09, January 16, 2003, of the National Health Surveillance Agency (ANVISA) (BRASIL, 2003). A non-dispersive infrared sensor was used to determine the CO_2 concentrations. The measured concentration was recorded every 5 minutes for thirty minutes on five different days, during operational times when occupants were engaged in physical activity.

2.3 Outdoor airflow rates estimation

The outdoor airflow rates of the building were estimated using the single-zone mass balance of CO_2. Assuming that the generation rate, ventilation rate, and outdoor CO_2 concentration are constant, for a uniform CO_2 concentration, the ventilation outdoor airflow rate can be estimated as (ASHRAE, 2022):

$$Q_O=V_{CO2}\cdot 106/(C_i-C_O) \quad (1)$$

Where Q_O is the outdoor airflow rate in L/s; V_{CO2} is the CO_2 generation rate in L/s; C_i is the indoor CO_2 concentration in ppm and C_O is the outdoor CO_2 concentration in ppm.

Based on the ASHRAE Fundamentals Handbook (ASHRAE, 2021), the V_{CO2} can be calculated by the following equation:

$$V_{CO2}=(0.00276\cdot A_D\cdot M\cdot RQ)/(0.23\cdot RQ+0.77) \quad (2)$$

A_D is the DuBois body surface area in m^2; M is the metabolic rate in met. And RQ is the respiratory quotient (dimensionless).

For people engage in physical activity, the typical metabolic rate ranges from 3.0 to 4.0 met (ASHRAE, 2021). The respiratory quotient value is estimated as 0.83 for activities with $M < 1.5$ met and increasing proportionately to $RQ = 1.0$ when $M = 5.0$ met.

The DuBois surface was estimated based on available data for Brazilian population.

An error propagation was conducted considering the errors in the estimated outdoor airflow rate accounting for the uncertainties in the measured parameters.

2.4 Airborne Infection risk prediction for Covid-19

The infection risk prediction was estimated by the procedures described by Peng et al. (2022), which is based on a dose-response model for the probability of infection whit a constant quanta concentration (quantum is the dose of airborne droplet nuclei required to cause infection in 63% of susceptible persons). The infectious dose inhaled by a susceptible person (expressed in quanta) is calculated as:

$$n=V_i E_{p0} B_0 H_r \qquad (4)$$

Where V_i is the enhancement factor for variants of concern (2.5 for Omicron); E_{p0} is the quanta shedding rate of an infectious person resting in oral breathing, for the original variant (18.6 quanta/h); B_0 is the average breathing rate of a sedentary susceptible person (0.288 m^3/h).

The term H_r is defined by Peng et al. (2020) as the relative risk parameter that refers to those parameters that can be controlled to reduce the risk of shared-room airborne transmission. This parameter is defined as:

$$H_r= r_{ss} r_E r_B f_e f_i D/(V\lambda) \qquad (5)$$

In which r_{ss} is a factor to correct the concentration for events too short to reach steady state; r_E is the shedding rate enhancement factor relative to E_{p0} for an activity with a certain degree of vocalization and physical intensity (6.8, heavy exercise); r_B is the breathing rate enhancement factor relative to B_0 for an activity with a certain physical intensity and for a certain age group (5.6, mean value between 16 and 71 years old and heavy exercise); f_e and f_i are the penetration efficiencies of virus-carrying particles through the infected and susceptible person's masks or face coverings (1, no masks due to the physical intensity). D is the duration of exposure, assumed to be the same for all the susceptible persons; V is the volume of the space; and λ is the total virus removal rate through all mechanisms (ventilation with outdoor air and air purifiers, if any). Peng et al. also defined the risk parameter H that takes in account the number of susceptible persons (N_{sus}) and is calculated as:

$$H = N_{sus} \cdot H_r = N \cdot (1-I) \cdot H_r \qquad (6)$$

The term I represents the percentual of persons fully vaccinate, and N is the local population.

For a given space, the absolute probability of infection is estimated as:

$$P_a = {}^{N_{SI} \cdot \delta_N} \big/ {}_{N \cdot \left(1 - \eta_i\right) \cdot \left(1 - I \cdot \delta_I\right)} \tag{7}$$

Where N_{SI} is the number of secondary cases resultant of the exposure event (maximum 1); δ_N is a security factor to reduce the secondary cases, considering the uncertainties associated to the infection prediction method and this new disease (adopted a value to generate a scenario where the number of secondary cases would be twenty times lower than the upper limit: 0.05); δ_I is a mathematical safety factor to account for the vaccine effectiveness against the infection (symptomatic disease) by variants of concern. It was adopted the value of 0.5 for Omicron based on data by Stowe et al. (2022) and Zeng et al. (2022). It is important to note the difference from vaccine effectiveness against severe disease and death. The method aims to reduce the risk of infection.

The recommended upper limit for H is 0.5 (ideally below 0.05), and for Hr is 0.01 (ideally below 0.001) (Peng et al., 2022).

3 RESULTS

3.1 Carbon dioxide concentration and ventilation rates

The results of the CO_2 concentrations, number of people, and ventilation rates are presented in Table 1, with its respective uncertainties. The outdoor CO_2 concentration was assumed to be constant and equal to 450 ppm (measured before the indoors measurements) in both scenarios. Despite the lower occupancy in Scenario 1, the dioxide carbon levels were approximately three times greater than Scenario 2, and four times the upper limit value stipulated by regulatory agencies (BRASIL, 2003; ABNT, 2008). Although, CO_2 levels in Scenario 2 are slightly over the standard concentration established by these agencies.

The estimated air change rates correspond to a ventilation rate of 15 m^3/h per person in Scenario 1 and 71 m^3/h per person in Scenario 2. In terms of recommended ventilation per person, for both scenarios, the estimated value would produce a deficient ventilation for the maximum occupancy of 36 persons (BRASIL, 2003; ABNT, 2008).

Table 1 – CO_2 concentration levels, number of people, and ventilation rates

Parameter	Scenario 1	Scenario 2
Mean number of people	8 ± 2	15 ± 2
CO_2 concentration outdoors [ppm]	450 ± 1	450 ± 1
Mean CO_2 concentration indoors [ppm]	4153 ± 234	1362 ± 767
Ventilation rate [h^{-1}]	0.10 ± 0.06	0.91 ± 0.46

Source: Own authorship, 2023.

3.2 Maximum occupancy with different ventilation conditions and epidemiological scenarios

The maximum estimated occupancy of the gym for different orders of magnitude of ventilation rates, residence time, and prevalence of Covid-19 in the local population are presented in Table 2. These results were based on the airborne risk infection of the omicron variant through the model of Peng et al. (2022). For occupants with no mask, 90% fully vaccinated. And all the parameters remained within the limits specified in section 2.4. A color scale was used to qualitatively assess the occupancy supported in each case. A tricolor scale was adopted, where green corresponds to the maximum occupancy of the gym (36 persons), red corresponds to no occupancy possible (1 person), and a medium value (17) was considered as yellow. For a prevalence of 0.1%, it is possible to maintain the maximum occupancy of the gym for 1 hour and 20 minutes of residence time by providing ventilation in the order of magnitude of 10 ACH. However, considering ventilation in the order of 0.1 ACH (compatible with the estimated ventilation rate in Scenario 1), the maximum occupancy value for the same time of residence is about half of gym's maximum occupancy. For a prevalence of 1%, the allowed occupancy is about three times lower for all considered times of residence and ventilation rates. With deficient ventilation, the allowable occupancy is heavily reduced, even for a short time. Considering a prevalence of 10%, the space would only be able to be occupied with a two-order of magnitude increase in the ventilation rate and only for a few people. For all situations, the maximum occupancy decreases with longer residence time.

Table 2 – Maximum occupancy for different ventilation and epidemiological conditions

	Maximum Occupancy								
(prevalence) η_i =	0,1%			1,0%			10,0%		
Time of residence	1h 20min	2h	3h 20min	1h 20min	2h	3h 20min	1h 20min	2h	3h 20min
λ = 0,1 ACH	**17**	**13**	**10**	**5**	**4**	**3**	**2**	**1**	**1**
λ = 1,0 ACH	**20**	**15**	**12**	**6**	**5**	**4**	**2**	**2**	**1**
λ = 10,0 ACH	**36***	**34**	**27**	**13**	**11**	**9**	**4**	**4**	**3**

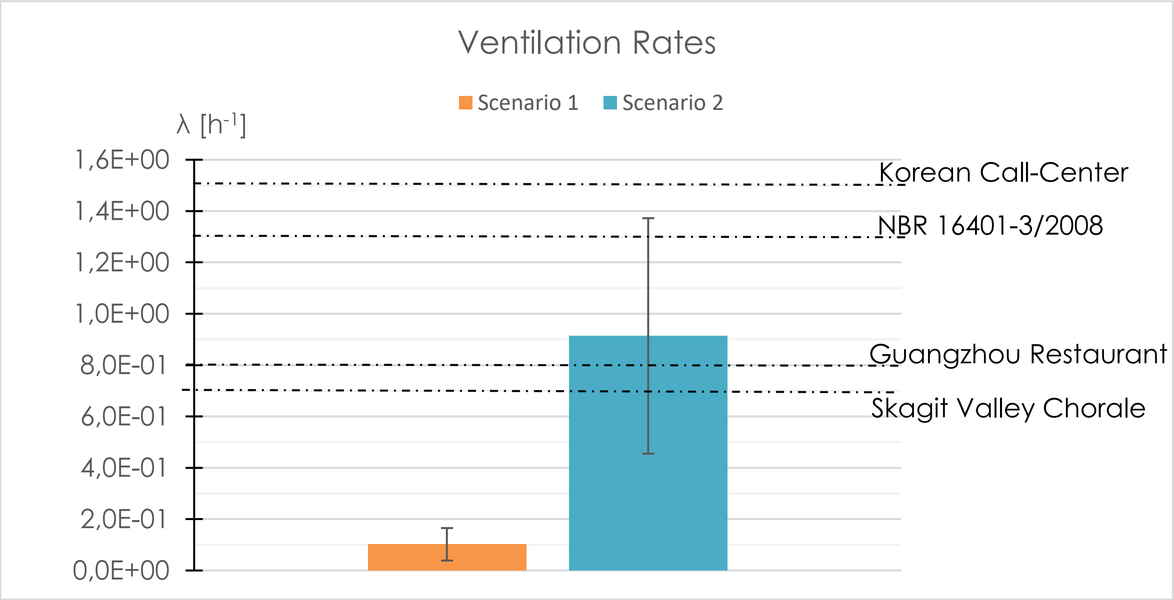
Source: Own authorship, 2023.

4 DISCUSSIONS

Despite the various uncertainties surrounding the estimated ventilation, the values reported in this study are consistent with data from the literature. Aguilar et al. (2022) reported that, for an environment with multiple windows opened on one of the facades, the ventilation rate ranges from 2.02 ACH to 5.06 ACH, which are in the same order of magnitude as the ventilation rate estimated in Scenario 2. Studies that analyzed environments with closed windows reported values varying from 0.18 ACH to 0.60 ACH (Stabile et al., 2019; Wallace et al., 2002; Bekö et al., 2016; Howard-Reed et al., 2002; Peters et al., 2022), which are compatible with the estimations conducted in scenario 1.

Notwithstanding the higher ventilation outflow rate in Scenario 2, the current ventilation in the gym is comparable to that of locations where COVID-19 outbreaks have occurred, as shown in Figure 2 (Li, 2020; Miller, 2020; Prentiss, 2020). The present situation is even more concerning because opening windows is not feasible on most days due to severe weather conditions in the region, including high temperatures and relative humidity, registered by INMET (BRASIL, 2022). Thus, Scenario 1, in which ventilation is one order of magnitude lower than in places associated with Covid-19 outbreaks, is the commonly observed condition in the gym. Even if a proper ventilation system were implemented according to local standard specifications, the situation would not be significantly different (in terms of airborne infection risk for COVID-19), as the resultant air change rate would be on the order of λ = 1 ACH (BRASIL, 2008; ANVISA, 2003). Therefore, an increase in ventilation rate aiming to create a safer environment would need to exceed the minimum value required by local standards.

Figure 1– Comparison of ventilation rates in the gym and Covid-19 outbreaks



Source: Own authorship, 2023.

Relative to infection risk, an increase in building safety is indicated by an increase in the calculated maximum occupancy supported in the gym. Therefore, there is no significant improvement in occupancy by increasing ventilation rate from 0.1 ACH and 1.0 ACH (considering other factors constant). However, by increasing the ventilation rate to the order of magnitude of 10 ACH, it is possible to approximately double the number of people allowed the gym in comparison with lower ventilation conditions. Nevertheless, even with this increased ventilation outflow, the maximum occupancy of the gym only reaches its limit for a short period of residence, supporting almost the maximum for medium periods of residence. This is due to the particularities of a gym application, where the expiratory and activity level are enhanced, increasing the emission and inhalation of infectious aerosols by pre or asymptomatic subjects. If it is desirable to increase the duration of residence to the equivalent of five days of presence, for 40 minutes per day, the occupancy is limited to 27 persons, which is seven bellow the limit.

Therefore, a risk mitigation strategy focused solely on increasing outflow rates may not be the suitable due to constraints for providing a high air change rate. A rational solution balancing ventilation, occupation, and cohabitation time could be adopted in adverse epidemiologic scenarios. The results presented in Table 2 suggest that maintaining a safe environment is possible, even in Scenario 1, with an occupancy ranging from a maximum of seventeen to ten people for residence times between 1 hour and 20 minutes and 3 hours and 20 minutes, respectively. However, it is relevant to note that this scenario does not comply with the local codes. The application of minimum ventilation is, therefore, recommended.

These results also imply that the supported number of people in the gym is highly sensitive to the prevalence of the disease. An increase of one order of magnitude in prevalence results in a three-fold reduction in the supported occupancy, as seen in cases where the prevalence increases from 0.1% to 1.0%, and from 1.0% to 10%. Therefore, disease prevalence must be carefully monitored so that occupancy can be adjusted, and airborne transmission risk can be maintained below recommended limits. Although occupancy may be almost unfeasible in the context of high prevalence, a very restricted occupancy can be considered, allowing administrative and maintenance activities to continue and services to be offered under special conditions. On the other hand, the effective ventilation rate for diluting the respiratory aerosols may be increased in one order (from standard 1 to 10 ACH) during adverse epidemiologic scenarios. The application of portable air purifiers and GUV-light (germicidal ultraviolet) could be deployed for that task.

Is noteworthy that this study has some limitations. Indoor CO_2 concentrations, the number of people, the level of metabolic activity, and the height, weight and age of the occupants varied during the measurements, resulting in uncertainties in the estimated ventilation rate. Additionally, the infection risk method presents many uncertainties regarding Coronavirus diseases and the assumption of a steady-state concentration and generation of quanta. However, the main objective of this study was not to present an accurate estimation of the ventilation or a solution that eliminates the infection risk in the gym. Rather, it aimed to promote a comparative study of the airborne infection control performance of different risk mitigation strategies.

5 CONCLUSIONS

This study has used an estimation of ventilation outdoor airflow rate for a gym, based on Indoor CO_2 measurements, to promote a comparative assessment of the safety of different scenarios, related to the COVID-19 airborne infection risk. The assessment led to the following conclusions:

- The measured ventilation produces values of air changes rate on the order of 0.1 ACH with closed windows. Opening the windows increase in 1 order the natural ventilation of the gym. However, it is relevant to note that this scenario does not comply with the local codes. The application of minimum ventilation is, therefore, recommended.
- An increase in one order from the standard 1 to 10 ACH would be necessary for airborne infection control. The application of portable air purifiers and GUV-light (germicidal ultraviolet) could be deployed for that task. However, measures balancing ventilation, occupation, and cohabitation time can be more cost-effective for settings with budget constraints and limited resources.
- The infection risk within a building is highly sensitive to the epidemiological scenario.
- The method based on indoor CO_2 measurements may be used to estimate the ventilation outdoor airflow rate when it is the only means available.
- The method proposed by this study may be used to assess the relative performance of different risk mitigation strategies to assist in a rational solution selection for future challenges in this post-pandemic era.

This study has focused on gym applications, and a specific risk assessment using the framework of this study may be used to analyze specific applications. Future work will evaluate the performance of other applications.

AGRADECIMENTOS

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