Modelling the Contribution of Factors Influencing the Risk of SARS-CoV-2 Infection in Indoor Environments

Modelação da Contribuição de Fatores Influenciadores do Risco de Infeção por SARS-CoV-2 em Ambientes Interiores

ARTIGO ORIGINAL

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ABSTRACT

Introduction: This study estimates the risk of aerosol infection by SARS-CoV-2 in indoor environments where high density of occupation results in an increased probability of infection, such as schools, offices, supermarkets, restaurants and gyms.

Material and Methods: In each type of building use, several conditions were simulated, such as the use and effectiveness of masks, ventilation, use of equipment that allows air asepsis using HEPA filters, the density of occupancy and the length of stay in the spaces, using a model based on the dispersion of aerosol particles in indoor spaces and on the accumulation and inhalation of these particles over time.

Results: The results showed that the replacement of social masks by masks with FFP2 classification decreased the risk of infection by 90% in schools. In schools with natural ventilation, the complete opening of windows reduced the risk of infection by 64% in comparison with the scenario with closed windows. In spaces where mechanical ventilation is normally used, the probability of infection decreased significantly when the regulatory fresh air flow rates were doubled (reduction of 32% in offices, 42% in restaurants, 24% in supermarkets and 46% in gyms). The filtration of air with HEPA filters allowed the reduction of the probability of infection by 72% in schools, offices, and restaurants and 61% in gyms. The length of stay in the spaces was also a relevant factor in the variation of the probability of infection, especially in schools where it was found that shorter classes with a higher number of intervals reduced the risk of infection.

Discussion: The results show the importance of adequate ventilation in indoor environments, especially in places where the density of occupation and the staying times are longer, making the introduction of outside air inside the spaces essential, either through natural or mechanical means. It is expected that the infection risk estimates presented are undervalued because the model only considers transmission by particles smaller than 10 µm and does not include the short-range transmission by assuming social distancing. Vaccination was not considered in the model since it was not yet available when the study was carried out.

Conclusion: The present study contributes to the identification of measures that decrease the risk of viral transmission, and consequently provide greater security in indoor spaces.

Keywords: Aerosols; Air Pollution, Indoor; COVID-19; Risk Factors; SARS-CoV-2; Ventilation

RESUMO

Introdução: O presente trabalho estima o risco de infeção por SARS-CoV-2 em ambientes interiores onde a elevada densidade de ocupação resulta numa probabilidade acrescida de contágio, como escolas, escritórios, supermercados, restaurantes e ginásios.

Material e Métodos: Foram testadas várias condições nos espaços interiores, tais como a utilização e eficácia de máscaras, a ventilação, a utilização de equipamentos que permitem uma assepsia do ar recorrendo a filtros HEPA, a densidade de ocupação e o tempo de permanência nos espaços, tendo sido utilizado um modelo baseado na dispersão de partículas de aerossóis em espaços fechados e na acumulação e inalação destas partículas ao longo do tempo.

Resultados: Os resultados mostraram que a substituição de máscaras sociais por máscaras com classificação FFP2 diminuiu o risco de infeção em 90% nas escolas. Em escolas com ventilação natural, a abertura das janelas na sua totalidade reduziu o risco de infeção em 64% comparativamente com o cenário de janelas fechadas. Nos espaços onde a ventilação mecânica é normalmente utilizada, a probabilidade de infeção reduziu significativamente quando os caudais de ar novo regulamentares foram duplicados (redução de 32% nos escritórios, 42% nos restaurantes, 24% nos supermercados e 46% nos ginásios). A filtragem de ar com filtros HEPA permitiu a redução da probabilidade de infeção em 72% nas escolas, escritórios e restaurantes e 61% nos ginásios. O tempo de permanência nos espaços foi também um fator relevante na variação da probabilidade de infeção, principalmente nas escolas onde se verificou que aulas mais curtas e com um maior número de intervalos reduzem o risco de infeção.

Discussão: Os resultados evidenciam a importância de uma adequada ventilação em ambientes fechados, principalmente em locais onde a densidade de ocupação e os tempos de permanência são mais longos, sendo essencial a introdução de ar exterior no interior dos espaços, seja através de meios naturais ou mecânicos. É expectável que os valores de risco de infeção apresentados ao longo do trabalho estejam subvalorizados pelo facto do modelo utilizado apenas considerar a transmissão por partículas inferiores a 10 µm e por, ao assumir o distanciamento social, não incluir a transmissão de curto alcance. A vacinação não foi considerada no modelo pelo facto de ainda não estar disponível quando o trabalho foi realizado.

Conclusão: Este estudo vem contribuir para a identificação de medidas que permitem um menor risco de transmissão viral, e consequentemente, uma maior segurança no interior dos espaços fechados.

Palavras-chave: Aerossóis; COVID-19; Fatores de Risco; Qualidade do Ar Interior; SARS-CoV-2; Ventilação

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INTRODUCTION

The COVID-19 outbreak was declared as a pandemic in over 200 countries and has been associated with 230 million confirmed cases and 4,713 million deaths worldwide (data as of 24 September 2021).[1] Due to the increasing threat, it was declared as a pandemic by the World Health Organization and a public health emergency of international concern in March 2020.[1] The virus causing the disease was identified as a novel, highly infectious coronavirus known as SARS-CoV-2. Nearly two years following the onset of the pandemic in Wuhan, the world is still facing a devastating infectious disease with only preliminary scientific data to guide policies to fight against the pandemic.

Mechanisms of SARS-CoV-2 transmission

A large debate on the mode of transmission of SARS-CoV-2 arose since the onset of the pandemic, aimed at the definition of the best practices for the management of patients and the protection of healthcare workers and citizens.

Respiratory infections can be transmitted through particles with different sizes. It has been assumed that droplets larger than 5 µm in diameter are produced whenever someone coughs, sneezes, vomits, spits and speaks and can reach the mouth, nose and eyes of anyone nearby, giving rise to a short-range transmission.[2] Due to their large size, most of these droplets remain in suspension for a short time and remain on surfaces and objects less than two metres away,[3] subsequently giving rise to contact transmission. On the other hand, airborne particles with a diameter of less than 5 µm do not require coughing or sneezing to be produced and simple exhalation is enough for their emission.[2] These remain in the air for prolonged periods, from several minutes to hours and travel several metres away.[3] The scientific community has increasingly argued that airborne particles (aerosols) have an extremely relevant role in long-range virus transmission (> 2 m), especially in closed places with inadequate ventilation and where exposure is prolonged.[4-8]

However, the separation that has been established between droplets and particles, which defines the cut-off diameter at 5 µm, is a simplification; there are even authors who argue that the distinction between droplets and particles should be made at 100 µm for the evaluation of transmission phenomena.[9] In fact, the ability of a particle to remain in suspension does not depend on its size only, but also on the way it is expelled and on the characteristics of the surrounding air, such as velocity, turbulence, direction, temperature and relative humidity.[10] Therefore, droplets with a diameter greater than 5 µm, depending on the conditions, may remain in suspension for longer periods and deposit themselves at distances greater than two metres. This behaviour is particularly important for particles with diameters up to 10 µm.[10] On the other hand, particles smaller than 5 µm are also responsible for short-range transmission (< 2 m), also considering that they are present in higher concentrations near emission sources.[11] Relevant concerns associated with modelling practices used in the definition of COVID control strategies remain, related to the simplifications that have been assumed and the ignorance that still persists after two years of pandemic.

Impact on the management of public indoor spaces

Qian *et al.*[12] found that in 318 outbreaks involving 1,245 patients presenting with COVID-19 in 120 cities in China, 316 have occurred indoors, showing that the risk of SARS-COv2 infection was related to sharing these spaces. In confined spaces, viral concentration and the associated risk tends to increase over time, depending largely on the ratio between the emission rate[13] and the air change rate.[14] On the other hand, natural or mechanical ventilation is a potential vehicle for aerosol transport, a mechanism that is not relevant in the case of larger droplets.[3,15]

Heating, ventilation and air conditioning (HVAC) systems in buildings need to be adapted or operated to meet new requirements, in order to minimise the risk of infection. Therefore, different organisations worldwide have published guidelines for the management of HVAC systems, aimed at responding to COVID-19. These guidelines include recommendations on the existing ventilation systems, including their mode of operation, the type of filters and air cleaning systems to be used, temperature and humidity, in addition to the operation of heat recovery systems. Guo *et al.*[16] have compared the different guidelines and reached the conclusion that they are all in agreement on the following:

1) An adequate ventilation of spaces with new air from outside, by using natural or mechanical ventilation, is the main strategy to mitigate the risk of COVID-19 transmission. Ventilation has a crucial role in diluting the indoor air near the emitting sources and removing infectious agents, reducing the concentration and dose inhaled by the occupants. It is recommended that windows should be opened about 15 minutes before a room is occupied, especially if it has been occupied by other people and reopened at regular intervals, even in buildings with mechanical ventilation.

2) Wherever possible, air intake damper on air handling units should be set at 100% and air recirculation switched off, even when return air filters are present, as these are rarely HEPA (high-efficiency particulate arrestance) filters and therefore unable to effectively filter out viral particles. Air recirculation can thus reintroduce and distribute contaminating particles from one space to another that are interconnected by pipe networks to the same equipment.

3) Whenever appropriate, the HVAC system should be

kept operational 24/7 and, during a non-occupation period, it could run at a reduced speed, in order to decrease the viral load inside the building. However, at least two hours before and after the building is used, the system should run at nominal speed. In order to avoid faecal-oral transmission route, it is recommended that the ventilation system of the sanitary facilities should operate 24/7, any windows should remain closed to ensure the negative pressure of the space and the toilet seats should remain closed during flushing.

4) The pressure difference between areas should be maintained so that the airflow moves from the less contaminated to the more contaminated areas.

5) The air cleaning strategy should include air handling units equipped with HEPA filters as these have adequate particle removal efficiency for infectious aerosols.

A higher risk of infection through airborne transmission or through direct or indirect contact can exist in public buildings including schools, offices, shopping areas, restaurants and gyms, due to their high occupancy density and represent a special challenge for their owners and managers. In order to respond to this difficulty, different models and calculators have been developed to estimate the risk of infection in indoor spaces under different conditions and therefore structural, management or social measures have been developed to effectively reduce the risk of infection.[17-20] Most of these methodologies are based on the Wells-Riley model for the assessment of the probability of infection as a function of the quanta parameter (released viruses), exposure time, ventilation rate, space volume, among other factors.[21]

Based on an atmospheric model and an infection model, within the COVID Airborne Transmission Estimator calculation tool,[17] this study compared the effectiveness of different mitigation measures implemented in indoor public spaces, even though with an impact on infection risk that is still undetermined. The study was aimed at providing a contribution to the correct management of public buildings and reducing the risk of infection. This tool has limitations, mainly because only the transmission by particles below 10 µm was considered and short-range transmission was not included, in addition to the fact that it is based on some assumptions that are still uncertain.

MATERIAL AND METHODS

The risk of SARS-CoV-2 infection was estimated using the COVID Airborne Transmission Estimator (version 3.4.21) calculation model developed by J. L. Jimenez - University of Colorado-Boulder.[17] The model is based on the dispersion of aerosol particles containing SARS-CoV-2 in indoor spaces and the accumulation and inhalation of these particles over time.

The calculation methodology combines two sub-models: a standard atmospheric model, assuming that the emitted small particles are rapidly dispersed and mixed within a given volume[22] and a model that quantifies the risk of aerosol infection, the Wells-Riley model,[23] as formulated by Miller *et al*.[21] According to the model, the probability of infection is a

Table 1 – Characteristics of each indoor environment in which the probability of infection was assessed

	Classroom	Meeting room	Restaurant	Supermarket	Gym
Environment					
Area (m^2)	51	15	100	1500	50* 750**
Height (m)	2.8	2.8	3.0	3.5	2.8
Pressure (atm)	0.95	0.95	0.95	0.95	0.95
Temperature (°C)	18	22	22	22	22
Relative humidity (%)	60	55	55	55	55
External [CO_2] (ppm)	415	415	415	415	415
Viral decay rate (h^{-1})[28]	1.01	1.55	1.55	1.55	1.55
Particle deposition rate (h^{-1})[(29,39)]	0.24	0.24	0.24	0.24	0.24
Occupants and activities					
Inhalation rate (m^3h^{-1})[31]	0.52	1.10	1.10	1.38	3.30
CO_2 emission rate (Ls^{-1})[32]	0.0050	0.0060	0.0060	0.0085	0.0178* 0.0155**
Quanta emission rate (h^{-1})[18,26]	16.0	18.7	14.8	10.9	117.2* 48.8**
COVID-19 within the study area					
Prevalence rate of COVID in the population (%)[24,25]	2.8	2.8	2.8	2.8	2.8
Vaccination rate (%)[24,27]	5	5	5	5	5

* Cycling class; ** machine training workout

function of: 1) the viral load exhalation rate, that depends on the number of infected people and their activity; 2) the viral load concentration, which is a function of the viral load exhalation rate, the volume and ventilation rate of the space and the presence of air filtration devices; and 3) the viral load inhalation rate, that depends on factors including viral load concentration, the breathing rate associated with the activity and the use and type of masks.[17]

This methodology assumed a two-meter social distancing, did not consider the transmission by droplets or contact and assumed that aerosol particles are equally distributed in space, which means that the probability of infection is underestimated, especially in spaces where distancing is not complied with. In any case, this tool is very useful for the comparison of various scenarios and for supporting decision-making.

In total, 242 different settings were tested in five indoor environments, including classrooms, meeting rooms, restaurants, supermarkets and gyms, with the main characteristics as shown in Table 1. Different conditions were simulated within each environment, including the use and effectiveness of masks, ventilation, use of equipment that allows air asepsis through HEPA filters, occupation density and duration of stay within the spaces. The description of the conditions of each setting, as well as the associated probability of infection are shown in Appendix 1, Table S1 (Appendix 1: https://www.actamedicaportuguesa.com/revista/index.php/amp/article/view/15982/6481).

The simulations were carried out based on the population living in Lisbon and the Tagus Valley, considering the number of new cases, the percentage of asymptomatic cases, the percentage of hospitalisations and the number of deaths as of January 2021.[24,25] The quanta emission values used in each setting are shown in Table 1 and were based on the works published by Buonnano.[18,26] Vaccination was not considered in the model because it was not yet available at the time of the study.

RESULTS

This section presents the estimated probability of infection for 242 settings tested in indoor environments of public use, where the risk is increased due to high occupancy density and often inefficient ventilation, not allowing an adequate air change (Appendix 1, Table S1 at https://www.actamedicaportuguesa.com/revista/index.php/amp/article/view/15982/6481).

Classrooms

Ventilation is crucial for the removal and dilution of pollutants produced in classrooms. Natural ventilation exists in most Portuguese schools, through the opening of windows, which sometimes does not ensure an adequate ventilation of the spaces, especially during the colder months when the opening of the windows has an impact on thermal comfort. Therefore, different settings were tested in order to assess the impact of different levels of window opening on the daily individual infection risk, based on a 51 m^2 classroom with 26 occupants, during a day involving eight 50-minute classes, where all occupants wear a social mask. Fig. 1A shows that the risk of infection ranged between 2.53% for a closed window scenario where the air renewal (0.3 h^{-1}) is ensured only by infiltration processes and 0.92% for a setting with the window fully opened and allowing a 7.2 h^{-1} air change. Mechanical ventilation ensures 5.5 h^{-1} air change, thus ensuring a standard airflow (equivalent to opening windows at 75%) and presenting a risk of infection of 1.10%, i.e., 56% lower than the setting without mechanical ventilation and closed windows. Foster and Kinzel[33] have obtained similar results when applying the Wells-Riley model to a classroom, reducing the risk of infection by 50% when changing from a setting with no ventilation to one with mechanical ventilation.

Since increased ventilation may represent unbearable costs for schools or even may compromise thermal comfort, the impact of installing portable air purifiers with HEPA filters with an efficiency above 99.9% for particles of 0.3 µm was evaluated. Different settings were tested, with air change rates ranging between 1 and 10 h^{-1} and considering, on the one hand, that classrooms have natural ventilation and windows closed and, on the other hand, that classrooms have mechanical ventilation ensuring the standard airflow rate (5.5 h^{-1}). Fig. 1B shows that the use of this equipment leads to a 72% reduction in the probability of infection in the case of natural ventilation with windows closed. In these situations, the probability of infection can reach lower levels than those achieved in rooms with mechanical ventilation systems operating at the minimum flow rates defined by law. It is worth mentioning that the effectiveness of this equipment depends on air change rate. The simulations carried out show that investments should only be made for equipment that promotes an air change rate above 5 h^{-1}. In the case of mechanical ventilation, these devices also provide a reduction in the probability of infection, even though at lower magnitudes.

As regards the use of masks, three settings were tested always considering the presence of natural ventilation and closed windows (Fig. 1C). In the first setting, in which only the teacher wore a social mask (reduction efficacy of 50% in emission and 30% in inhalation)[34] a higher probability of infection has been found (6.84%) when compared to the setting in which all students wore the same type of mask (2.53%). In case that all the occupants of the room used a KN95 or FFP2 mask, it is estimated that there could be an even greater reduction, with a 0.07% probability of infection.

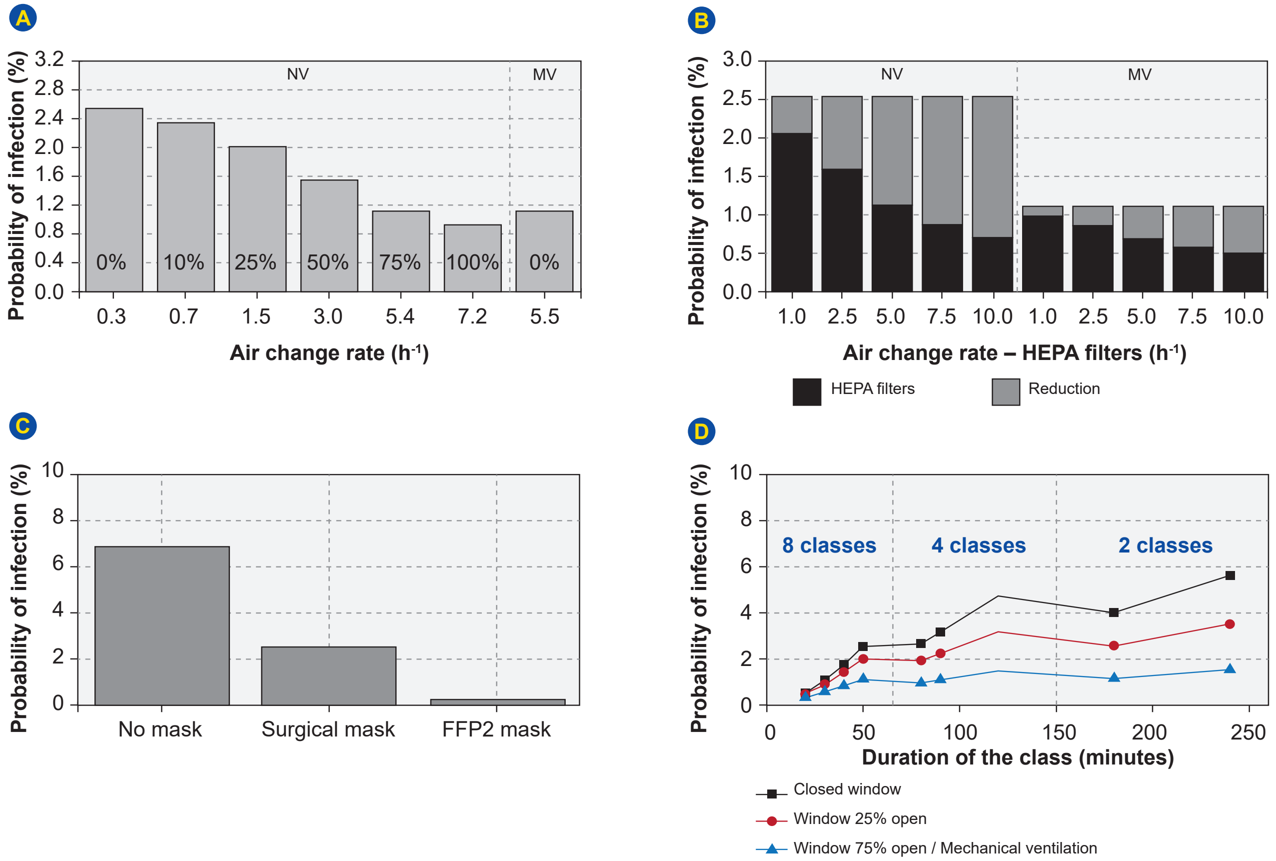

Figure 1 – Estimated risk of infection for different settings within classrooms: (A) variation in air change rate, considering natural ventilation, with different window opening rates and mechanical ventilation with regular air change rate (5.5 h^{-1}); (B) variation in air change rate, in units with HEPA filters, considering natural ventilation with closed windows and mechanical ventilation with regular air change; (C) use of mask considering natural ventilation and closed windows; (D) variation of exposure duration and number of classes and ventilation.
NV: natural ventilation; MV: mechanical ventilation

Although higher efficacy could be achieved with KN95 and FFP2 masks, only 90% efficacy was selected for both emission and inhalation to account for potential inappropriate mask placement by the community. Dai and Zhao[35] have used the Wells-Riley model to test the use of surgical masks in an indoor space with two people (one infected) and found that if both wore a mask, the ventilation rate required to ensure a probability of infection of less than 1% was reduced between 30 and 90 $m^3 h^{-1}$ for a 0.25 h exposure and between 300 and 1,000 $m^3 h^{-1}$ for a three-hour exposure.

Finally, Fig. 1D shows that the duration and number of classes also have an important influence on the probability of infection, with shorter classes leading to a lower risk of infection.

Office buildings

The risk of infection was estimated for a 15 m^2 meeting room in an office building, considering that all occupants wore a social mask. The impact of ventilation on the risk of infection for a six-people occupancy is shown in Fig. 2A and shows 1.6 times increase in risk when air change is only obtained by infiltration (natural ventilation, closed windows; 0.25 h^{-1}) instead of meeting the standard airflow rate (mechanical ventilation; 2.7 h^{-1}). It is also shown that the probability of infection is reduced from 0.34% to 0.20% by increasing up to three times the standard airflow (8.1 h^{-1}).

The use of portable air purifying equipment using HEPA filters was tested, with 10 h^{-1} renovations and a reduction in the probability of infection reaching 72% in the case of natural ventilation with the windows closed. These results have shown that the use of this equipment can be a very effective solution, especially when spaces have no mechanical ventilation and no optimal air change.

The increase in the number of occupants and the duration of meetings led to an increase in the risk of infection, as shown in Fig. 2B.

Restaurants

Restaurants, apart from involving a high occupation density, often do have an inadequate ventilation of the spaces and the occupants are unable to use the mask, therefore increasing the risk of infection.

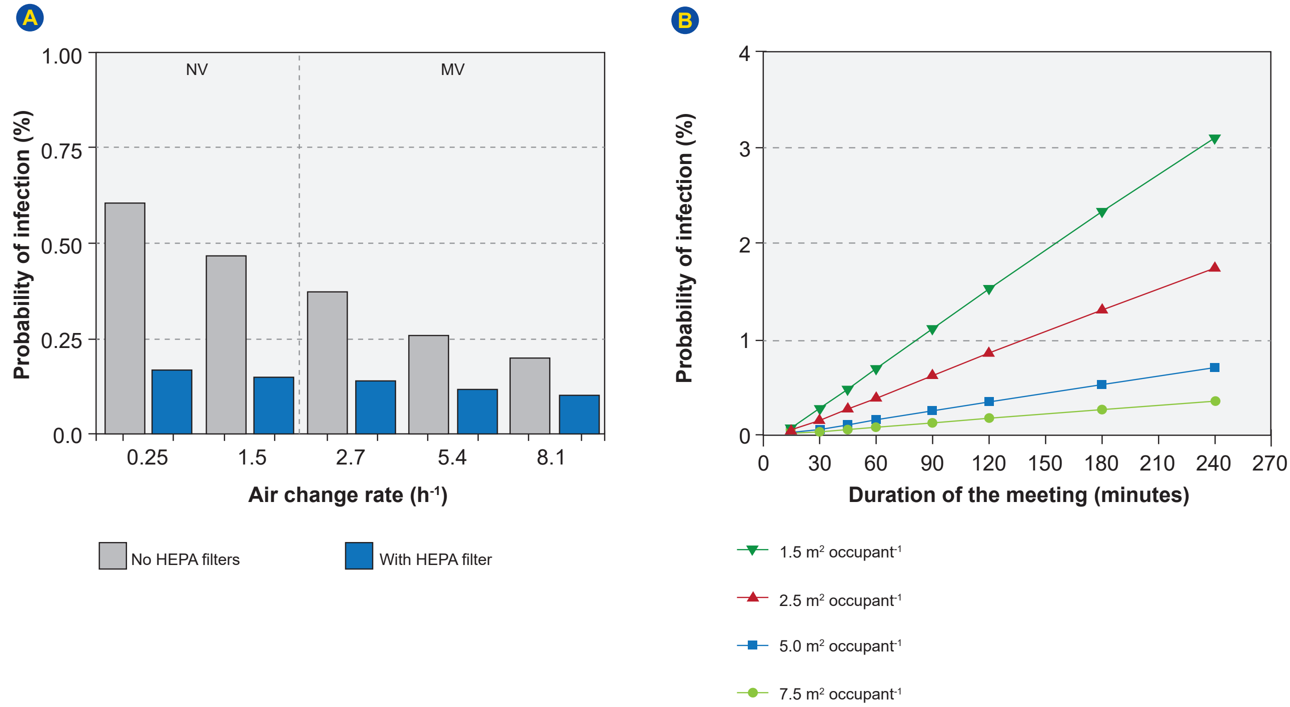

Figure 2 – Infection risk for different settings in meeting rooms: (A) Variation in air change rate, considering natural ventilation with closed windows (0.25 h^{-1}) and open windows (1.5 h^{-1}) with mechanical ventilation, considering a standard airflow rate (SAR) (2.7 h^{-1}), 2 x SAR (5.4 h^{-1}) and 3 x SAR (8.1 h^{-1}) and the presence of a HEPA filter; (B) variation in the occupancy rate and duration of the meeting.
NV: natural ventilation; MV: mechanical ventilation

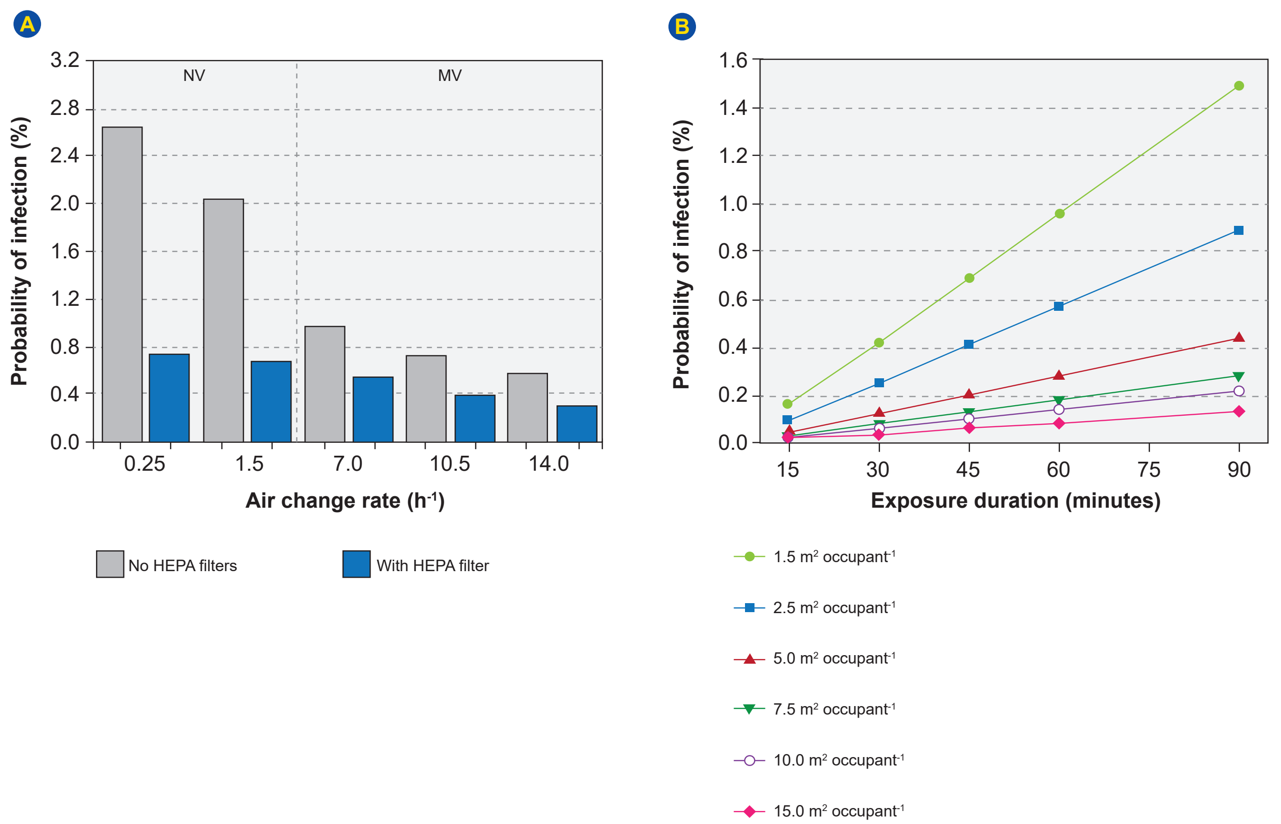

Figure 3 – Risk of infection for different settings in restaurants: (A) variation in air change rate, considering natural ventilation with closed windows (0.25 h^{-1}) and open windows (1.5 h^{-1}) and mechanical ventilation considering a standard airflow rate (SAR) (7 h^{-1}), 1.5 x SAR (10.5 h^{-1}), 2 x SAR (14 h^{-1}) and the presence of a HEPA filter; (B) variation in the occupancy rate and exposure duration.
NV: natural ventilation; MV: mechanical ventilation

Air change rate is crucial to the probability of infection, which may decrease from 2.63%, when air change is performed only by infiltration processes (0.25 h^{-1}), to 0.56% with an air change rate of 14 h^{-1}, corresponding to twice the standard airflow rate (Fig. 3A).

In the case of restaurants, since the area is larger than the other two spaces, we have analysed the use of portable air purification equipment with HEPA filters and air change rate of 10 h^{-1}, only in the presence of natural ventilation. In the case where a mechanical ventilation exists, the installation of HEPA filters in the return of the air treatment unit already installed was considered. The importance of using HEPA filters, especially when restaurants have no mechanical ventilation, is shown in Fig. 3A. In this case, a 72% reduction in the probability of infection can be obtained, ensuring a lower risk of infection than what would be achieved with mechanical ventilation operating at standard airflow rates.

An increase in the probability of infection with dwell time, especially for high occupancy densities, is shown in Fig. 3B.

Supermarkets

Supermarkets present a lower risk of infection than the three spaces described above. A probability of infection ranging between 0.13% for an air change rate of 3.6 h^{-1} (corresponding to double the standard airflow) and 0.24% for a natural ventilation setting where renovations are made only by infiltration (0.25 h^{-1}) during a 60-minute visit to the supermarket wearing a social mask, is shown in Fig. 4A. The use of HEPA filters in the return of air handling units was analysed for the mechanical ventilation settings, with a decrease in the probability of infection ranging between 25.5% and 34.6%, for air change rates of 1.8 h^{-1} and 3.6 h^{-1}, respectively.

In a mechanical ventilation setting at standard airflow rate, dwell time and occupant density have an important impact on the risk of infection, as shown in Fig. 4B. For an occupancy density of 5.0 m^2 $occup^{-1}$, a probability of infection ranging between 0.02% for a 15-minute stay and 0.28% for 90 minutes has been found. With a 60-minute stay, the probability of infection is found to increase 10 times with a reduction in density from 1.5 m^2 $occup^{-1}$ to 15 m^2 $occup^{-1}$. Vuorinen *et al.*[37] reached similar conclusions, showing that exposure during a visit to a supermarket, even with high occupancy densities, is reduced. A linear correlation between the probability of aerosol inhalation and occupancy density has been found by these authors, even though this probability increases more rapidly as a function of the duration of stay in the supermarket, thus advising that the frequency and duration of visits to the supermarket should be limited

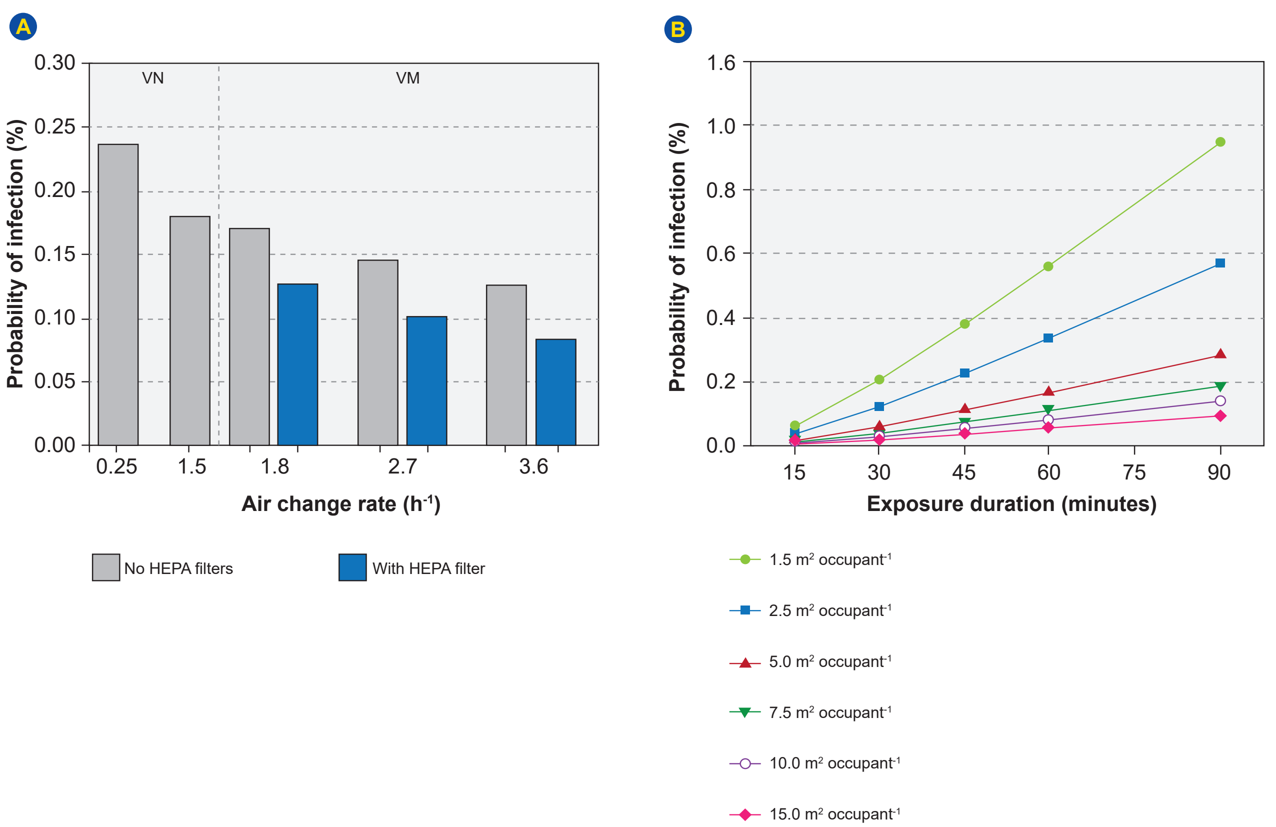

Figure 4 – Risk of infection for different settings in supermarkets: (A) variation in air change rate, considering the presence of natural ventilation with closed windows (0.25 h^{-1}) and open windows (1.5 h^{-1}) and mechanical ventilation considering a standard airflow rate (1.8 h^{-1}), 1.5 x SAR 8 (2.7 h-^{1}) and 2 x SAR (3.6 h^{-1}) and the presence of a HEPA filter; (B) variation in the occupancy rate and exposure duration.
NV: natural ventilation; MV: mechanical ventilation

and that high occupancy hours should be avoided.

Gyms

The probability of infection for a cycling class (quanta of 117.2 h^{-1}) carried out in a 50 m^2 room, compared to a machine training workout (quanta 48.8 h^{-1}) carried out at a 750 m^2 space, have shown that, in environments with air renewal only by infiltration, there is a higher risk for the cycling class (23.1%) than for the machine training workout performed within the gym's open space (2.7%) (Fig. 5A). The probability of infection remains high in the cycling class (4.72%), despite the mechanical ventilation that ensures standard airflow rates.

Therefore, air treatment units equipped with HEPA filters should be used, with 61% estimated risk reduction for natural ventilation (portable equipment with 10 h^{-1} air change rate) and 50% for mechanical ventilation (if HEPA filters are installed on the return from the air handling unit - AHU).

The probability of infection depends largely on the occupancy density and the duration of the class, as shown in Fig. 5C, referred to a 45-minute cycling class with mechanical ventilation ensuring a standard airflow rate.

DISCUSSION

The different settings analysed in this study allowed to estimate the impact of the implementation of environmental management measures for the reduction of the probability of viral transmission in public buildings.

The results showed the importance of an adequate ventilation of indoor environments, leading to the conclusion that the introduction of outside air inside the spaces, through natural or mechanical ventilation, is crucial to ensure adequate indoor air quality and higher safety. A higher probability of infection has been found in environments with higher occupancy density and longer exposures, leading to the conclusion that the use of spaces is a possibility, if there are fewer people inside and for shorter periods.

The results showed that the duration and number of classes in schools have an important influence on the probability of infection. There has been an increase in class duration in some schools to avoid contact between the students during breaks and to reduce student's duration of stay in school, even though a lower risk of infection has been found with shorter classes. In offices, face-to-face meetings should be kept to a minimum and, whenever this is not available, these should be held with as few people and for the shorter time possible. Vuorinen *et al.*[37] have also recommended working remotely and staying in offices for short periods of time. These researchers have analysed by Monte Carlo modelling the importance of the walking speed

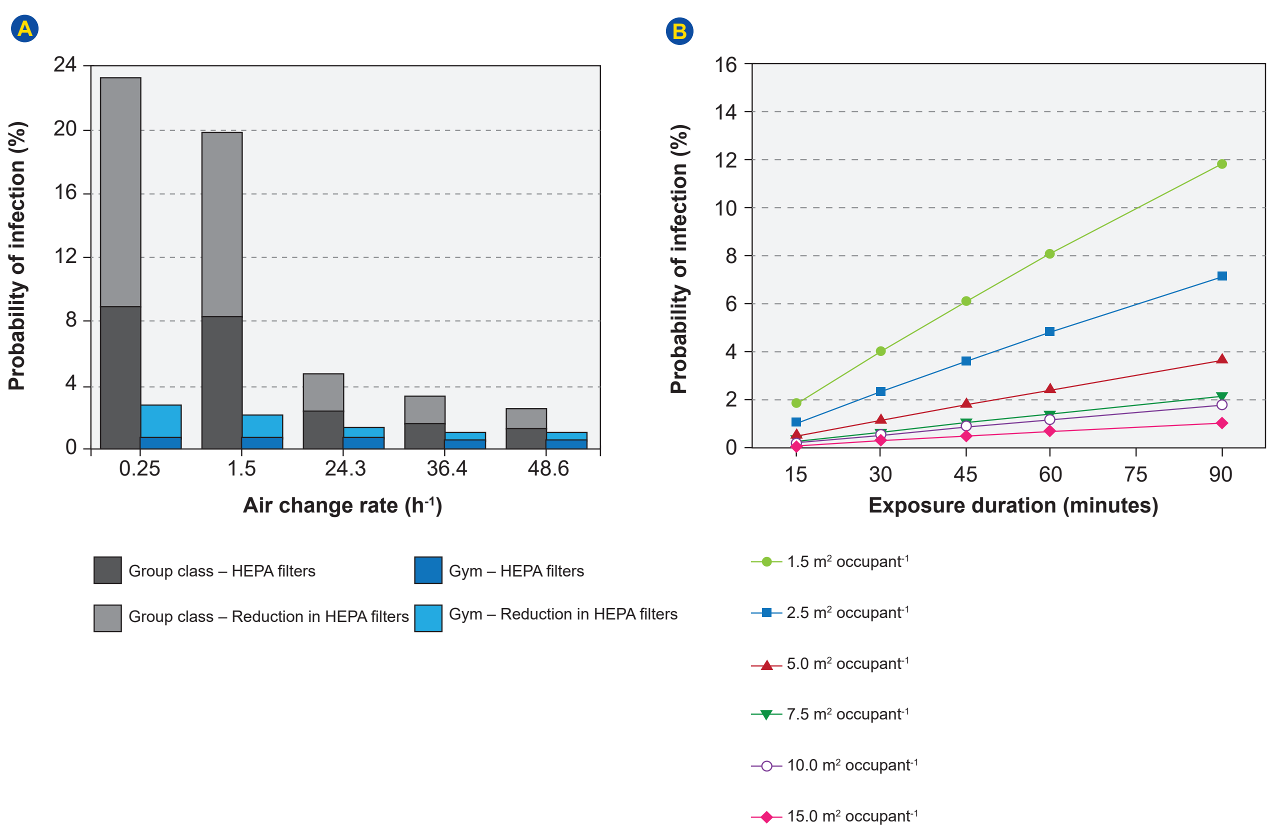

Figure 5 – Risk of infection in different settings in gyms: (A) Variation in air change rate, considering the presence of natural ventilation with closed windows (0.25 h^{-1}) and open windows (1.5 h^{-1}), mechanical ventilation considering a standard airflow rate (SAR) (24.3 h^{-1}), 1.5 SAR (36.4 h^{-1}) and 2xSAR (48.6 h^{-1}) and the use of a HEPA filter. (B) Variation in the occupancy rate and exposure duration.

at which people move within a specific place and reached the conclusion that, when people remain almost stagnant for eight to 10 hours a day, as they do in office buildings, the risk of becoming infected is higher when compared to other public spaces including schools and supermarkets. There is also an increased infection probability in restaurants, due to the occupancy density and exposure duration. The risk of a 15-minute exposure, equivalent to take-away activities, decreases significantly, with probabilities of infection lower than 0.2%. According to Vuorinen *et al.*,[37] halving the occupancy density can increase the critical exposure time by two times. As in restaurants, the risk associated with the use of gyms is increased due to the fact that users do not wear masks. Furthermore, the breathing rate and the quanta emission rate are greatly increased in these spaces, increasing the infection probability. Mittal *et al.*[20] have estimated the impact of physical activity on the risk of transmission and reached the conclusion that the risk of transmission can be 200 times higher in gyms when compared to other spaces in which occupants are almost stagnant. The results obtained for these spaces showed that the use of air treatment units equipped with HEPA filters can greatly reduce the risk of infection.

The limitations of the model must be considered and may contribute to the underestimation of the values:

1) A 2-meter physical distancing is assumed by the model, even though this cannot be ensured in some spaces.

2) The transmission by droplets and by contact were excluded from the model.

3) Only transmission by particles below 10 μm was considered by the model, even though there is evidence that particles up to 100 μm can remain in the air for periods ranging from a few minutes to hours[9] and can therefore travel significant distances.

4) The model considers that aerosols and the risk of infection are uniformly distributed in spaces, when in fact it is known that there is a dilution cone of exhaled aerosols that gives rise to concentrations inversely proportional to the square of the distance and velocity,[39] leading to a higher risk in the proximity of the infected person.

5) The model is based on assumptions that are still uncertain, such as the amount of infectious virus emitted by an infected person.

6) It is also worth mentioning that the effectiveness of the different masks used by the model are an approximation based on previous studies. However, there is a large variability in effectiveness due to the different materials used and the way the masks are used. Konda *et al.*[36] found a filtration efficacy for different fabrics ranging between 5% and 80% (for particles smaller than 300 nm in size) and between 5% and 95% (for particles larger than 300 nm in size), with increasing values whenever multiple layers of fabrics combining different materials are used. The filtration efficiency of hybrids (such as cotton-silk, cotton-chiffon, cotton-flannel) can be higher than 80% (for particles smaller than 300 nm in size) and higher than 90% (for particles larger than 300 nm in size). According to these authors, suboptimal mask fit could lead up to a 60% decrease in filtration efficiency.

Despite these limitations, this model is a semi-quantitative tool, which is very useful for comparing different people behaviours and building management options and for identifying the main risk factors.

In order to improve the results generated by this model, proximity effects, as well as different parameters with an influence on the physics of airflows, including the type of ventilation, air distribution patterns, space geometry, movement of people and other parameters with an impact on the virus viability should be included in further research.

CONCLUSION

The current pandemic situation has forced people to lockdown and return to 'normal' activity in a safer way is a strong concern for everyone, since a large part of the Portuguese economy is based on indoor spaces.

This study assessed the impact of different factors on the probability of infection, including the type of ventilation, occupancy density, exposure duration within the spaces and the use of masks, aimed at the identification of strategies to reduce the probability of infection indoors.

A reduction in the risk of infection involves adopting measures related to building ventilation systems, such as increasing ventilation with outdoor air and using more efficient air filtering systems, together with behavioural measures including the use of mask and reducing the exposure duration in spaces with high occupancy density. Subsequently, in addition to the measures that are already widespread, such as the use of mask, social distancing and personal hygiene, guidelines for building managers on ventilation, filtration and occupation routines to protect users of indoor spaces are crucial.

Given the complexity of the issue and the large number of factors involved, it is not surprising that two years later there are still fundamental issues to be clarified. These questions involve different areas including biomedicine, epidemiology, virology, public health, fluid dynamics, aerosol physics, behavioural psychology, public policy, etc. Even though this is a complex and multidisciplinary model, it was aimed at providing a simple and intuitive way to inform policy makers, professionals in different areas and the general population about the main factors associated to the spread of COVID, in addition to strategies for the reduction of the risk of infection. Limitations regarding the model were identified and tend to underestimate the probability of infection. Therefore, this method should be considered as a semi-quantitative tool allowing to compare the impact of different mitigation measures.

AUTHOR CONTRIBUTION

Both authors have equally contributed to the conception, literature revision and development of the manuscript.

HUMAN AND ANIMAL PROTECTION

The authors declare that this study complied with the regulations that were established by the Ethics and Clinical Research Committee, according to the Helsinki Declaration of the World Medical Association.

DATA CONFIDENTIALITY

The authors declare that they have followed the protocols of their work centre on the publication of data.

CONFLICTS OF INTEREST

The authors declare that there were no conflicts of interest in writing this manuscript.

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