How much natural ventilation rate can suppress COVID-19 transmission in occupancy zones?

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Background: Previous research has emphasized the importance of efficient ventilation in suppressing COVID-19 transmission in indoor spaces, yet suitable ventilation rates have not been suggested. **Materials and Methods:** This study investigated the impacts of mechanical, natural, single-sided, cross-ventilation, and three mask types (homemade, surgical, N95) on COVID-19 spread across eight common indoor settings. Viral exposure was quantified using a mass balance calculation of inhaled viral particles, accounting for initial viral load, removal via ventilation, and mask filtration efficiency. **Results:** Results demonstrated that natural cross-ventilation significantly reduced viral load, decreasing from 10,000 to 0 viruses over 15 minutes in a 100 m2 space by providing ~1325 m3/h of outdoor air via two 0.6 m2 openings at 1.5 m/s wind speed. In contrast, single-sided ventilation only halved viral load at best. **Conclusion:** Natural cross-ventilation with masks effectively suppressed airborne viruses, lowering potential infections and disease transmission. The study recommends suitable ventilation rates to reduce COVID-19 infection risks in indoor spaces.

Key words: COVID-19, mask, natural ventilation, risk of infection, ventilation

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INTRODUCTION

The World Health Organization declared COVID-19 a global epidemic on March 12, 2020, due to its widespread prevalence.[1] As of February 2021, approximately 94 million people have been infected, and 2 million have lost their lives, with nearly a quarter of the cases and deaths occurring in the United States.[2] The disease can spread through respiratory droplets and airborne particulates, which can come in contact with the mucosal membrane of the eyes, nasal passages, and oral cavities, leading to infection.[3-5] The Centers for Disease Control and Prevention (CDC) recommended screening employees for symptoms such as cough and fever. However, a significant portion of the workforce may have asymptomatic infection. It is estimated that 20% of SARS-COV-2 infections were asymptomatic, with an average incubation period of 2–5 days.[6-9] The main transmission route indoors is respiratory droplets due to sneezing and coughing.[10,11] CDC recommends a distance of 6 feet or 2 m to mitigate potential exposure,[12] although these distances may not be sufficient since respiratory droplets can travel about 4–8 m.[13-15] Some respiratory droplets expelled from sneezing, speaking, or coughing are deposited on surfaces; the rest remain airborne.[16,17] Therefore, sufficient ventilation can control infection by introducing fresh, virus-free air and removing particulate matter from the environment.[18] Infection risk decreases through dilution and removal of airborne particles.[18,19] Many regulatory organizations, including the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) and CDC,[20] have emphasized that

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"proper ventilation" can help mitigate the spread of disease. However, no specific ventilation rates have been suggested so far. Recommendations generally require increased ventilation, outdoor air introduction, and decreased occupancy.[21-25] This study aimed to evaluate the impact of single or double openings on increasing ventilation and decreasing virus load in standard indoor spaces. In this study, the prevalence of the disease in occupancy zones, the effect of natural and mechanical ventilation, and the use of masks were evaluated using a mass balance equation and recommends an appropriate ventilation rate to reduce the risk of infection. Such studies will be crucial in reducing the risk of infection and expediting the revival of the economy.

METHODS

The mass balance equation has been utilized to investigate the effect of mechanical and natural ventilation and masks on the spread of the SARS-COV-2 virus in indoor air. The complete calculation steps are explained in Appendix A.

Mechanical ventilation was calculated for each type of indoor space using the ASHRAE equation described in standard 62.1–2019, which has been explained in Appendix A. Two modes of single-sided (MI) and cross-ventilation (MII) were considered to calculate the space's natural ventilation [Figure 1]. For this purpose, it is assumed that there is just one operable window with the least minimum size to meet code requirements (i.e. 0.6–1 m) which total area is equal to 0.6 m^2 (IRC, 2018). The opening in MI is on the windward wall, and MII has one opening with the same dimension as MI on the windward wall and another on the leeward wall. Two empirically validated equations were employed to model the entering natural airflow to the spaces described above, explained in detail in Appendix A.[26-28]

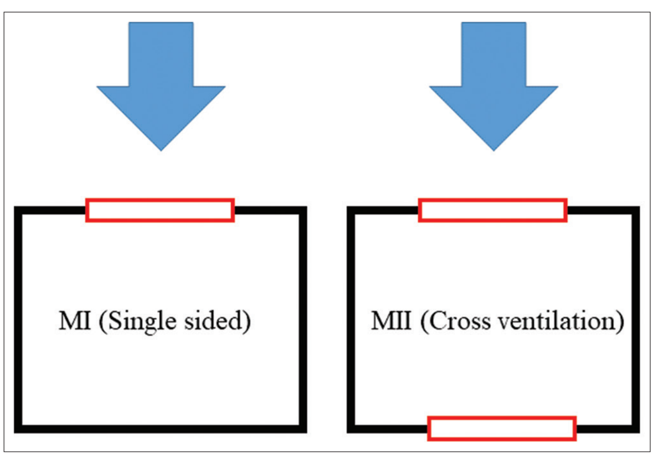

Figure 1: Single-sided and cross-ventilation (The opening in MI is in the windward wall. There is an additional opening with the same dimension as MI on the leeward wall in MII.)

It is assumed that air is entirely mixed in spaces. The number of viruses spread and suspended in the environment by the infected persons' cough after 3 s of each cough equals 415,000 infectious viruses and 140,000 after 70 s of speech without mask.[17] The total investigation time is 8 h, divided into 15-min intervals [Table 1]. Eight typical spaces of 100 m^2 were considered to investigate the effect of mechanical and natural ventilation [Table 1].

The number of people in each space is estimated according to the ASHRAE regulations, considering the maximum default occupant density every 100 m^2. Since 7% of the United States population had been infected by January 2021, it was assumed that at least 1%–7% of the people in the environment were infected.

Three types of masks were used in the study: homemade cloth masks, surgical masks, and N95 respirators, which can block 20%, 40%, and 95% of viral particles, respectively.[29] Considering that mask usage was mandatory in the specified environments, it was assumed that an infected person would use the simplest type of mask, i.e. homemade-cloth-mask with outward efficiency equal to 40% (60% of the exhaled or coughed particles pass through the mask and enter the environment.).[29] The potential exposure of noninfected individuals in the designated occupancy zones, the effect of mechanical and natural ventilation, and the use of masks were calculated [Table 1].

RESULTS AND DISCUSSION

The ASHRAE recommended outdoor ventilation rate for each breathing zone besides total viral load (TVL) is shown in Table 2. The impact of natural and mechanical ventilation on TVL was considered for both MI and MII modes. The remaining viral load in the environment after virus removal due to ventilation and inhalation every 15 min is presented in Figure 2. Masks can reduce the inhalation rate of viral particles, and their inward efficiency can block a part of the suspended virus load. As shown in Figure 2, masks that block more viral particles result in less virus exposure

Table 1: Maximum population, number of sick people, and talking minutes in each occupancy zone

Space type	Maximum population	Infected people	Talking minutes in a quarter-hour
Media center/ computer laboratory	25	1	2
Science laboratories	25	1	2
Lecture classroom	65	4	1
Office space	5	1	3
Reception areas	30	2	5
Libraries	10	1	1
Mall common areas	40	2	10
Supermarket	8	1	1

Table 2: Outdoor air ventilation rate by American Society of Heating, Refrigerating, and Air-Conditioning Engineers (OA) for each occupancy zone in 100 m^2 area (M^3/h) and total viral load every 15 min from all infected people total viral load

	Media center/ computer laboratory	Science laboratories	Lecture classroom	Office space	Reception areas	Libraries	Mall common areas	Supermarket
OA	666	774	997	153	378	306	655	217
TVL	417,000	417,000	1,332,000	501,000	1,338,000	333,000	2,178,000	333,000

TVL: Total viral load, OA: Outdoor air ventilation rate by ASHRAE

for healthy individuals. Figure 2 also shows viral loads in the environment gradually increase in all spaces until the number of viruses removed by the ventilation system equals the number entering, and the chart line levels off. Mechanical ventilation results in higher levels of airborne viruses than single-sided ventilation, which can reduce cross-ventilation across all spaces to zero. Inadequate ventilation and higher viral loads in a space increase infection risk due to greater inhalation by healthy individuals. Therefore, researchers emphasize the role of ventilation in preventing transmission in closed spaces.[23,30] However, the required ventilation and how natural ventilation contributes to suppressing the pandemic are not mentioned.

Even with a few people in an office, poor ventilation leads to inhaling many viruses. In the beginning, about 100 viruses are inhaled by healthy people unless they use an N95 mask. Virus inhalation continuously increased, and in the last quarter, about 1200 viruses were inhaled in M20 Protective Mask. However, using single-sided ventilation helps decrease this number to 800. Using single-sided ventilation with a cloth mask is more effective than using a surgical mask besides only mechanical ventilation, which bolds the natural ventilation role. Cross-ventilation is the best system as it effectively removes all viruses suspended in the air. If there is inadequate ventilation, N95 masks can prevent transmission. This finding is consistent with another study on the effects of natural ventilation in offices, which concluded that increasing the window size to wall ratio has a high potential to reduce the risk of infection.[31]

The reception area is similar to the office space, but its ventilation is three times more than the office when many people are waiting there; this makes the situation similar to an office space. However, space becomes more polluted by viruses sooner, and in the 10th quarter, people inhale about 1000 viruses unless they wear an N95 mask or use cross-ventilation. Therefore, due to people's presence in the space for a long time, one employee's infection can cause others infection. In educational spaces such as classroom lectures, science labs, and media rooms, where ventilation is relatively adequate, fewer viruses are inhaled, making it safer than other spaces. In the worst situation, students inhale 120 viruses, which decreases to <100 if single-sided ventilation is used. It is suggested that schools can be used if their ACH is above eight, which can be achieved by using natural ventilation and opening all windows of class.[32] As shown in Figure 2, if cross-ventilation cannot be used because most classes have only one side window and the other side is a hallway, single-sided ventilation with surgical masks is a relatively good option. Since it is found that both single-sided and cross-ventilation demonstrated the ability to reduce the risk of infection to <1% when a mask is worn.[33] Opening the class door behaves similarly to cross-ventilation since the air enters from one side and goes out from the other side to the hallway, which finally goes through hallway openings. We recommend that all the educational space windows remain open during and between classes. Extending break time between classes would ensure all viruses in the space are driven out by ventilation; in this case, at least one air change in the break time would be enough to replace fresh air. Although leaving windows open in the library causes noise and disturbance, keeping them open is strongly recommended. If opening windows is not possible, use N95 or KN95 masks. Increase distance between people and limit room occupancy to reduce infection risks. Furthermore, HEPA filters and air cleaners can help remove viral loads. As a result, schools and universities can open by providing a proper distance in classrooms, adequate ventilation, window opening, and proper mask utilization. However, commuting to university or school and communication during class breaks may lead to direct contact between sick and healthy people. These interactions are outside the scope of this study and require further investigation.

If one of the vendors, employees, and visitors are infected, they will spread the virus in the space, so people are at risk of being infected while they are in store sp. For example, if the seller is infected in a supermarket, the virus propagates throughout the shop over time. Therefore, it is recommended that people enter and buy what they need and leave immediately because the more time passes from shop opening increases the viral load is 100 in shops in the first quarter from opening more than 500 virus inhalation in the last quarters, unless there is natural ventilation or proper masks utilization. Results showed that the best time for shopping is at a store or mall opening when there are fewer viral loads in space. If more time is needed for shopping, using a high-performance mask and moving near open windows is recommended. The situation becomes challenging in malls where occupancy is high. Ventilation

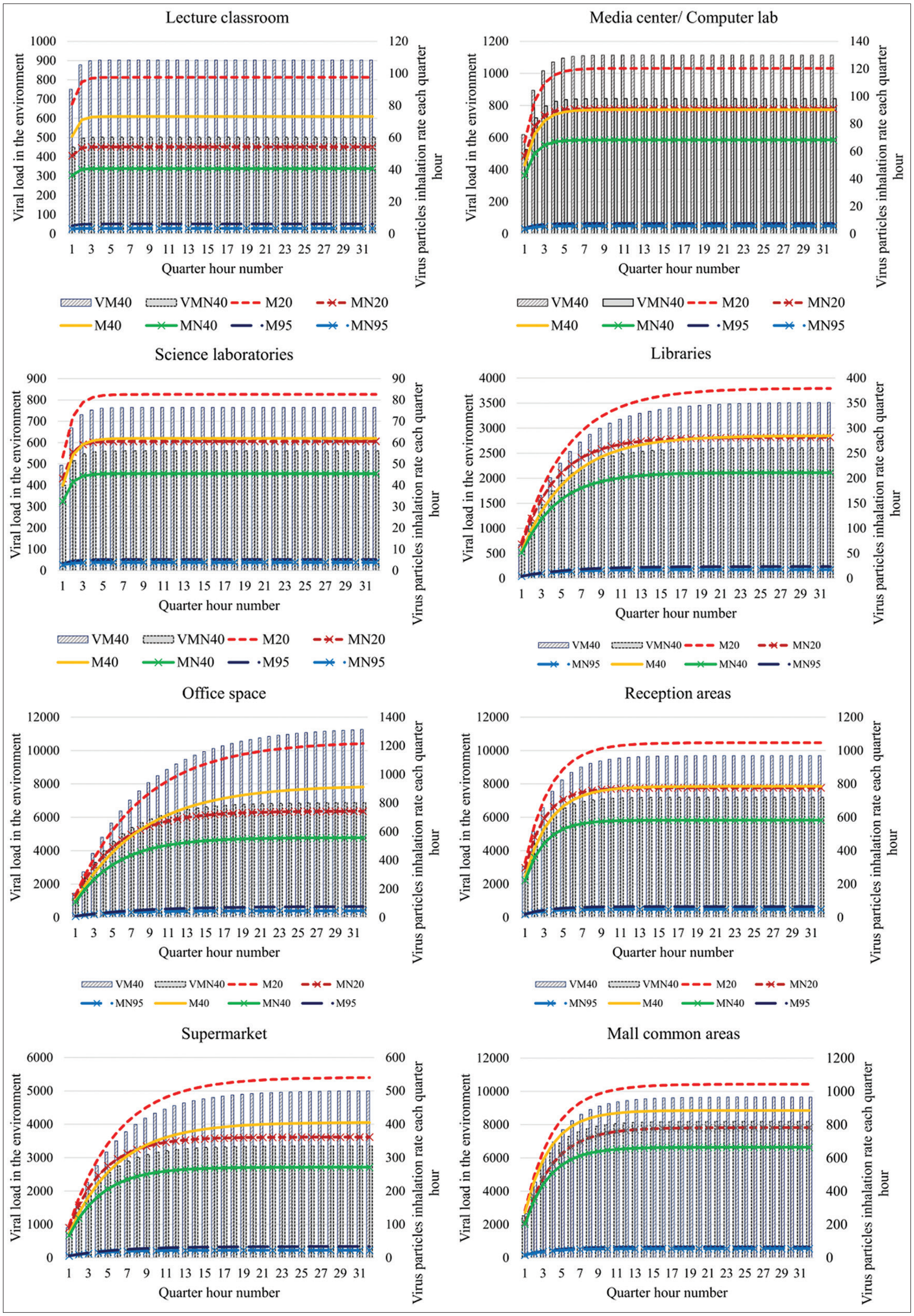

Figure 2: The remaining viral load in different ventilation strategies. In each chart, the bars show the viral loads that remained in the environment. The solid one shows in the case that there is only mechanical ventilation. The patterned one shows that the viral load remained in the single-sided ventilation. No virus remained in the space in cross-ventilation mode, so it did not draw on the chart. The lines show the inhalation rate of the viruses in each quarter hour, named by the type of mask and ventilation, as discussed before. The M stands for only mechanical ventilation, and the MN stands for when there are mechanical and single-sided ventilation together. The number after M or MN is for the inward mask efficiency of the healthy person, which is 20 for cloth masks, 40 for surgical masks, and 95 for N95 respirators. For example, MN40 is when there is mechanical and single-sided ventilation and the healthy person wears a surgical mask which blocks 40% of the virus entering the mouth, and the VM40 shows the viral load remained in the space after 15 min when the infected people wear cloth masks, and there is only mechanical ventilation

is critical; even MI ventilation and surgical masks provide limited protection. A healthy person may inhale up to 600 viruses during the mall's final open hours. The best suggestion is to use cross-ventilation to drive out all viruses in the environment or use an N95 mask to reduce virus inhalation to <60 viruses.

As is known, the more people present in an environment, the higher the chance of viral load; consequently, healthy individuals may inhale more viruses. On the other hand, the more ventilated the air in the space, the fresher air enters while polluted air leaves the environment, reducing the amount of virus inhaled. The steps calculated in this study are 15 min, showing that longer stays in environments increase virus inhalation. People should plan their work to be completed quickly to inhale fewer viruses. If the ventilation system's ability changes the total ambient air at least every 15 min, i.e., if the air change rate per hour (ACH) is more than 4, it can be said that the risk of infecting healthy people within these 15 min is close to zero, because assuming room air is mixed, the entire air changes every 15 min and whatever virus is present is expelled out. The higher ACH rate causes less risk of infection. If ACH is 60, the ambient air changes every minute, and no virus will remain in the environment. Although, achieving this amount of ACH is almost impossible without cross-ventilation with a suitable opening area. However, if ACH is established between four and six, i.e. changing total air in space every 10–15 min while assuming space is mixed, it reduces infection risk to zero. Mechanical ventilation systems have limited ability to bring fresh air into space; However, only a small opening together with slow wind velocity can direct high amounts of fresh air into space, as shown in Figure 3, and is approved and suggested by the Federation of European Heating, Ventilation and Air Conditioning Associations and other guidelines.[34]

According to the current study, if only one opening with an area of 0.6 m^2 is used on one side of a building when the wind velocity is 1.5 m/s, it can bring 81 m^3 of air into space every hour. This amount can be increased by increasing the opening area [Figure 3]. This increase has a linear relationship with the wind speed, number of openings, and opening area; increasing these parameters increases air volume entering the space.

The best way to prevent virus spread indoors is by using cross-natural ventilation where wind enters from one window and goes out through the other. Using two openings with an area of 0.6 m^2 at a wind velocity of 1.5 m/s can enter 1325 m^3/h of air into space, which is very suitable and sufficient for most spaces. No virus remains in space with cross-ventilation, as shown in Figure 2. Larger opening areas or greater wind velocity directs more air into space in cross-ventilation, which is shown in Figure 3. This indicates natural ventilation's great importance where possible to use, which significantly reduces infection risk by placing two openings on both sides of the building at low cost and uncomplicated.

As shown in Figure 2, masks can reduce virus inhalation; better mask efficiency results in fewer viruses entering a person's respiratory tract. The N95 mask is considered the best mask for reducing virus inhalation. Using masks and natural ventilation can almost prevent disease from spreading indoors; even homemade masks with 20% performance and single-sided natural ventilation are more effective than a 40% mask without natural ventilation, which amplifies natural ventilation's role. Although it is not known how many SARS-COV-2 virus inhalation may cause infection, it has been reported in various studies from one to several hundred,[35,36] and it is claimed that inhaling fewer viruses provides a milder form of disease[37,38] that makes people recover faster and prevents death.

The best advice for people who work indoors or business owners who care about their employees' health is to use natural ventilation, maintain suitable distance between

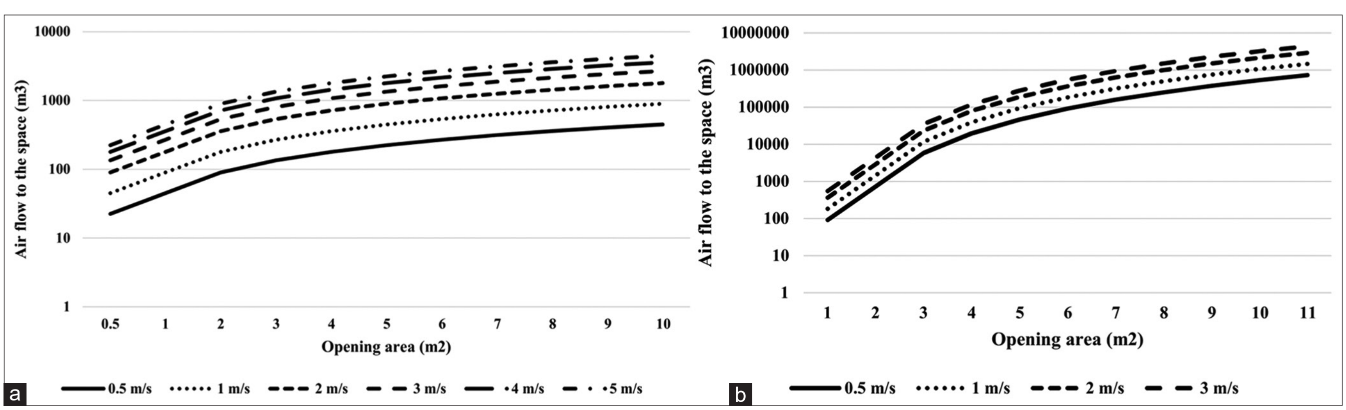

Figure 3: (a) Air entry to the space due to different wind speeds and opening areas in single-sided ventilation (logarithmic scale), (b) Air entry to the space due to different wind speeds and opening areas in cross-ventilation (in logarithmic scale)

employees, and make masks, even homemade cloth masks, mandatory. It is recommended to identify the prevailing wind direction and speed. Using Equation 3 or 4 in Appendix A, the ventilation rate of existing openings and the space's air changes per hour can be estimated based on the prevailing wind velocity and direction. An ACH above six indicates that the ambient air is completely changed every 10 min, reducing the risk of infection. A higher ACH is better because more ambient air is rate replaced with fresh air. Combining a higher ACH with mask-wearing and proper distancing can help prevent further disease spread.

CONCLUSION

This study utilized mass balance to investigate the risk of infection and determine the appropriate ventilation rate. The amount of virus remaining in the environment and inhaled by healthy individuals was calculated by considering the viral load by patients in the environment and the ventilation rate. The results demonstrated that when using only one opening on the windward wall with a wind velocity of 1.5 m/s, approximately 81 m^3/h of fresh air can enter the environment. Cross-ventilation was the most effective among mechanical, single-sided, and cross-ventilation. By utilizing just two small openings with an area of 0.6 m^2, about 1325 m^3 of fresh air can enter the environment, effectively driving out almost all of the viral loads directly related to the opening area and wind speed. An ACH above six indicates that the ambient air is changed every 10 min if well-mixed, significantly reducing the incidence rate. Using well-fitting masks and natural cross-ventilation can help prevent the spread of the disease in occupancy zones.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Acknowledgments

There are no research project numbers or ethical approval numbers applicable to this research

Authors' contributions

AN contributed to the conception of the work, conducting the study, performing formal analysis and validation, Drafting the work, revising the draft, approving the final version of the manuscript, and agreeing on all aspects of the work. FE, FMS, and SN contributed to the conception of the work, drafting and revising the draft, approving the final version of the manuscript, and agreeing on all aspects of the work. FN contributed to Drafting the work, revising the draft, approving the final version of the manuscript, and agreeing on all aspects of the work. OM contributed to the conception of the work, revising the draft critically for important intellectual content, approving the final version of the manuscript, and agreeing on all aspects of the work.

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Conflicts of interest

There are no conflicts of interest.

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APPENDIX

Appendix A

The enclosed indoor space was considered the control volume to formulate the equation. Then, the potential number of viruses entering the environment by the respiratory activity of an infected person, according to the type of mask used, was calculated. In addition, mechanical or natural ventilation computed the effect of viral removal from such closed spaces. The following formula represents the virus load mass equation balance:

$$R = L_{in} - r - L_{out} \quad (1)$$

In this equation, R represents the remaining number of viruses in the environment with the following assumptions: L_{in} represents the total number of viruses entered into the environment by infected people through breathing, coughing, or sneezing by infected individuals, r is the rate at which viruses are removed through inhalation by a healthy adult, and L_{out} represents the rate at which viruses are removed through either passive ventilation (such as opening doors or windows) or active increase in the mechanical ventilation rate include increasing airflow and filtration. The L_{in} is calculated based on infected individuals present in the space; for example, since it is assumed that there is only one infected person in the media center, the viral load from coughing would be equal to 1 × 415,000; Assuming this person speaks for 2 min in each quarter-hour, the emitted viral load would be 1 × 2 × 140,000, totaling 695,000. However, it is assumed that this person uses a cloth mask with an outward efficiency of 40%, meaning 60% of the total viral load is released into space, equal to 417,000 (695,000 × 0.6). If there are multiple infected individuals, the viral load is calculated for each. It is assumed that individuals in each hundred square of the occupancy zone are asymptomatic and unaware of their infection, so they leave home and are presented in places such as shops and libraries. This aligns with the fact that asymptomatic individuals cause most transmission.

Ventilation rates for different indoor spaces have been calculated using the ASHRAE equation outlined in standard 62.1–2019. The net rate of outdoor airflow required to enter the space, $Q_{OA,}$ s determined by the number of people in the space and the area of the place. Therefore, Q_{OA} (L/second) is the fresh outdoor air that is delivered to the space by the ventilation system and can be calculated using Equation 2:[22]

$$Q_{OA} = R_p P_z + R_a A_z \quad (2)$$

In this formula, Q_{OA} represents the fresh outdoor air delivered to the space by the ventilation system (L/s), where R_p and R_a represent the required airflow related to the number of people present in the environment (L/second.person) and the outdoor rate per unit area (L/s.m^2), respectively. P_z (person) and A_z (m^2) are the number of people in the environment and the space area, respectively. For example, in a media center, that area is 100 m^2, and a population of 25 people, R_p is five and R_a is 0.6; therefore, Q_{OA} is 5 ×25 + 100 ×0.6, which equals 185 L/s; this value is then multiplied by 3.6 to convert it to M^3/h, resulting in 666 M^3/h [Table 2].

Since the monthly mean wind speed across the United States is typically <5 m/s at the height of 10 m, the wind velocity at the height of 2 m at window level is assumed to be <3.6 m/s. To ensure consistency across all regions and to account for the lowest wind speed that occurs most of the time, a wind velocity of 1.5 m/s at window height is assumed. Two equations have been empirically derived from stimulating air flow entering the space through the opening. The results of these equations are comparable to computational fluid dynamic, large eddy simulation, and Renormalization Group theory and have been used to model airflow to the spaces described [Figure 1, MI and MII].[26-28] The net airflow entering the space (natural airflow) is calculated by these equations as follows:

$$Q_{ws} = 0.025Au \quad (3)$$

In Equations 3 and 4, Q_{ws} and Q_w are the airflows entering the space through two openings on leeward and windward walls (m^3/h), u is the wind speed at the window's height (m/s) that is measured onsite or from geographic maps that indicate the dominant wind speed in the area, and A is the opening area (m^2).

$$Q_{ws} = C_d A_e u\sqrt{\Delta Cp} \quad (4)$$

In equation 4, the C_d represents the discharge coefficient, which is considered 0.61 according to the Sharp opening assumption.[26] C_p is the pressure coefficient concerning two openings on the opposite side, equal to 0.9,[26] and A_e represents the effective area obtained by Equation (5) by assuming A_{in} and A_{out} are windward and leeward opening areas, respectively.

$$\frac{1}{A_e^2} = \frac{1}{A_{in}^2} + \frac{1}{A_{out}^2} \tag{5}$$

For example, the amount of fresh air entering the building in MI and MII equals 81 m^3/h $(0.025 \times 0.6m^2 \times 1.5\frac{m}{s} \times 3600)$. The 3600 is for converting m^3/s to m^3/h. and 1325 m^3/h $(0.61 \times \mathrm{A}_e \times 1.5\frac{m}{s} \times \sqrt{0.9} \times 3600)$, respectively. The A_e in MII is 0.42 m^2 $(\frac{1}{A_e^2} = \frac{1}{0.6^2}, \frac{1}{0.6^2})$.