Science of the Total Environment 744 (2020) 140908

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Short Communication

Intermittent occupancy combined with ventilation: An efficient strategy for the reduction of airborne transmission indoors

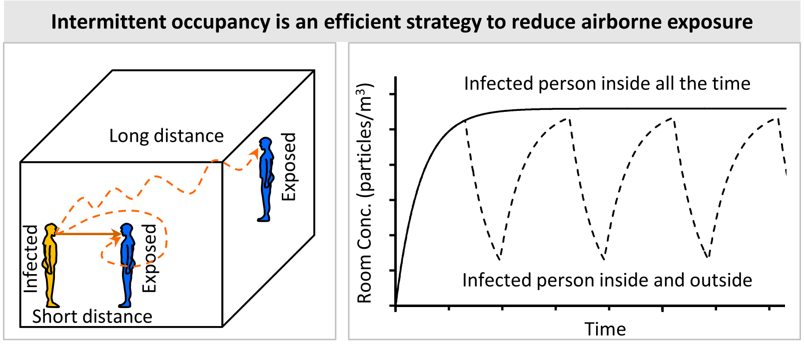
A.K. Melikov [a], Z.T. Ai [b,*], D.G. Markov [c]

[a] International Centre for Indoor Environment and Energy, Technical University of Denmark, Lyngby, Denmark
[b] Department of Building Environment and Energy, College of Civil Engineering, Hunan University, Changsha, China
[c] Department of Hydroaerodynamics and Hydraulic Machines, Technical University of Sofia, Sofia, Bulgaria

HIGHLIGHTS

- Source control of intermittent occupancy proposed for reducing airborne exposure;
- Effectiveness of proposed source control strategy applied to a classroom evaluated;
- Key influential factors of the effectiveness of proposed strategy identified;

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 June 2020
Received in revised form 8 July 2020
Accepted 10 July 2020
Available online 15 July 2020

Editor: Lidia Morawska

Keywords:
Airborne transmission
COVID-19
Control measures
Ventilation
Source control

ABSTRACT

It is important that efficient measures to reduce the airborne transmission of respiratory infectious diseases (including COVID-19) should be formulated as soon as possible to ensure a safe easing of lockdown. Ventilation has been widely recognized as an efficient engineering control measure for airborne transmission. Room ventilation with an increased supply of clean outdoor air could dilute the expiratory airborne aerosols to a lower concentration level. However, sufficient increase is beyond the capacity of most of the existing mechanical ventilation systems that were designed to be energy efficient under non-pandemic conditions. We propose an improved control strategy based on source control, which would be achieved by implementing intermittent breaks in room occupancy, specifically that all occupants should leave the room periodically and the room occupancy time should be reduced as much as possible. Under the assumption of good mixing of clean outdoor supply air with room air, the evolution of the concentration in the room of aerosols exhaled by infected person(s) is predicted. The risk of airborne cross-infection is then evaluated by calculating the time-averaged intake fraction. The effectiveness of the strategy is demonstrated for a case study of a typical classroom. This strategy, together with other control measures such as continuous supply of maximum clean air, distancing, face-to-back layout of workstations and reducing activities that increase aerosol generation (e.g., loudly talking and singing), is applicable in classrooms, offices, meeting rooms, conference rooms, etc.

---

* Corresponding author at: College of Civil Engineering, Hunan University, No.2 Lushan South Road, Yuelu District, Changsha 410082, China.
E-mail address: zhengtaoai@hnu.edu.cn (Z.T. Ai).

https://doi.org/10.1016/j.scitotenv.2020.140908
0048-9697/© 2020 Elsevier B.V. All rights reserved.

1. The need to improve existing control strategies to reduce airborne transmission

Severe containment measures including lockdown have been introduced in many countries to slow down the spread of COVID-19. The lockdown has reduced considerably economic activity and will reduce GDP by several percentage points. WHO, CDC and other organizations and responsible government bodies have determined that COVID-19 is mainly spread by large droplets emitted from the nose and mouth and by physical contact between individuals. However, the possibility of transmission due to an inhalation of virus-laden airborne expiratory aerosols should not be excluded. This consideration is especially important now that the governments in several countries have started to ease the restrictions when maintaining the most basic protection measures. The most important measures have been maintaining a distance (1–2 m) between people, frequent cleaning of hands using alcohol-based gel or soap and water, and covering the nose and mouth with a flexed elbow or disposable tissue when coughing or sneezing. Even these measures cannot effectively protect people from airborne transmission, especially long-distance and long-term exposure. The debate on whether the transmission of COVID-19 can be airborne continues. New research on the possibility of airborne transmission of COVID-19 has been published (Morawska and Cao, 2020; Read, 2020; Lu et al., 2020; Park et al., 2020; Ghinai et al., 2020).

Ventilation is recognized as an efficient method for reducing the airborne transmission of pathogens (Smieszek et al., 2019; Li et al., 2007; Knibbs et al., 2011). The recently updated guidelines for reducing the risk of airborne infection with COVID-19 therefore recommend a substantial increase of the ventilation rate, i.e. an increase in the amount of clean outdoor air supplied to indoor volumes (ASHRAE, 2020; REHVA, 2020; National Health Commission of China, 2020, etc.). However, existing ventilation systems in buildings are designed for removal of heat and pollution loads that exist under normal conditions, i.e. when there is no pandemic. The air-handling units, ducting and air supply and exhaust terminals are dimensioned to be economic and energy-efficient and allow for little increase in the ventilation rate. Ventilation systems designed to supply large amounts of outdoor air during pandemic will not operate economically under normal conditions with a greatly reduced supply flow rate. Furthermore, they will not be feasible because of the high initial costs associated with large air handling units, the large and voluminous ducting systems they require. The outdoor air supply rate can be increased by installing additional (portable) units, such as window installed fans and small free-standing air handling units. In addition, high-efficiency filters, stand-alone air cleaners and ultraviolet germicidal irradiation (UVGI) units installed in rooms or in ducts can be used to provide the equivalent of clean air to rooms.

This study was performed based on an assumption that the risk of cross-infection is possible in spaces with existing mechanical ventilation systems that are designed for normal conditions (namely not for pandemics). We analysed some possible operation modes of space ventilation and the importance of several factors for reducing the risk of airborne transmission in buildings with mechanical ventilation. We propose an improved control strategy based on source control without the need to make changes to existing ventilation systems. The strategy will be especially useful during the period when COVID-19 lockdown measures are being relaxed, bringing many employees, pupils and students back to their workplaces. The strategy is applicable in spaces such as classrooms, offices, meeting rooms, conference rooms, etc. The proposed strategy can also be applied for reduction of occupants' exposure to indoor pollution in general.

2. The process of ventilation and exposure

Ventilation systems are designed to provide a certain amount of clean air to rooms depending on the number of occupants and the characteristics of the air polluting emissions. Present standards consider different ventilation categories, i.e. different amounts of supply air per person, for example 10 L/s person (EN 16798-1, 2019). Furthermore, some standards recommend supplying additional clean air to remove the pollution emitted by building materials, e.g. 1 L/s m^2. Ventilation systems can be operated either to continuously supply the maximum designed airflow rate or to change the supply airflow rate according to the number of room occupants (which is known as demand control ventilation). The ventilation operated in most buildings in practice aims to achieve complete mixing of the clean supply air with the polluted room air. This air distribution is known as mixing ventilation. When the risk of airborne infection exists, it is recommended to increase the ventilation rate and thus to increase the dilution of the polluted room air with an increased supply of clean air. The ventilation system should be operated to continuously supply the maximum possible airflow rate.

Although complete mixing of the air distribution in rooms is the intention, the room airflow interaction is very complex and complete mixing is seldom achieved (Müller et al., 2013). Even in the case of uniform velocity and temperature distribution, an infected person acts as a point source of pollution and the concentration of the pollution decreases with the distance from the source. Occupant exposure therefore depends on the distance to the infected person. In this connection, short-distance and long-distance exposure can be defined. The short-distance exposure, i.e. when the exposed occupant is close to the infected person, depends on the interaction of the free convection flow that exists around a human body, the transient flow of breathing and the background ventilation flow. This airflow interaction in the human body microenvironment is complex (Melikov, 2015) and has a major impact on short-distance exposure (Melikov and Ai, 2020). Research has shown that short-distance exposure in ventilated rooms occurs when the distance between the exposed occupant and the infected person is less than 1–1.5 m (Ai and Melikov, 2018, Ai et al., 2019). Long-distance exposure occurs at distances between occupants of more than 1–1.5 m when the pollution is more or less mixed with the air in the occupied zone. Long-distance exposure depends mainly on the room ventilation, especially the ventilation rate and the room airflow characteristics (air temperature, humidity, velocity, direction, etc.). As stated above, distancing of more than 1–2 m is recommended by the WHO and the governments of many countries in order to reduce the risk of cross-infection. Assuming that this recommendation is respected, in the following analyses only long-distance exposure is considered.

With a steady-state ventilation air supply and steady-state expiratory flows from occupants, there can be at least two typical and distinct scenarios of airborne cross-infection, depending on the schedule of the presence of the infected person in a room. The evolutions of the room concentration of expiratory airborne aerosols for the two scenarios are schematically shown in Fig. 1. Note that complete mixing of expiratory airborne aerosols and room air is assumed in this study, and the particle dynamics of airborne aerosols are not considered. After the infected person enters a room, the room concentration of the expired airborne aerosol starts to increase and thus the instantaneous exposure of the occupants to the aerosols increases. If the infected person stays in the room for long time, the concentration of expired airborne aerosols builds up until it reaches steady state (Fig. 1, continuous curve). However, if after certain time the infected person leaves the room, the concentration of aerosols starts to decay (Fig. 1, dotted line). The process of building-up from a low concentration of aerosols will start again when the infected person re-enters the room after some time. The build-up and decay will repeat every time the infected person enters and leaves the room. Under these transient conditions, the time-averaged exposure of occupants to expired airborne aerosols will be lower than the first scenario (Fig. 1, continuous curve). This method of source control is utilized in the present study. For both scenarios (continuous and intermittent source generation), the exposure depends on a number of factors, such as the schedule of the presence of the infected person in the room, the number of infected persons in the room, the

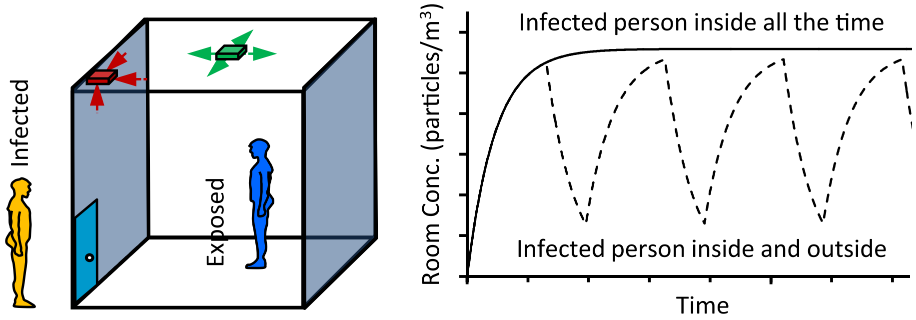


Fig. 1. Evolution of the whole room concentration during exposure caused by airborne cross-infection: (a) with a build-up to steady-state room concentration (with continuous presence of infected person) and (b) with alternating build-up and decay of the room concentration (with intermittent presence of infected person).

length of the periods during which each infected person is absent from the room, the designed occupant density, ventilation supply flow rate, volume of the room and number of occupants.

3. Method for the prediction and evaluation of exposure to expired airborne aerosols in a room

Assuming that the room air and the expired aerosols of the infected person(s) are well mixed, the development of the room concentration of pathogens is governed by the mass balance equation. The aforementioned evolutions of room concentration can be predicted by the solution of the mass balance equations for the build-up (Eq. (1)) and decay (Eq. (2)).

$$C_t = \frac{\dot{G}_r}{Q_s} + \left(C_{0b} - \frac{\dot{G}_r}{Q_s}\right) e^{-\mathrm{ACH}(t - t_{0,b})} \tag{1}$$

$$C_t = C_{0d} e^{-\mathrm{ACH}(t - t_{0,d})} \tag{2}$$

where C_t is concentration of expiratory airborne aerosols in the room at a certain time t, particles/m^3; $\dot{G}_r$ is generation rate of airborne particles from the infected person, particles/h; Q_s is the supplied ventilation flow rate, m^3/h; C_{0b} and C_{0d} concentration of expired airborne aerosols in the room at the beginning of the build-up ($t_{0,b}$) and decay ($t_{0,d}$), particles/m^3; and ACH is the air change per hour, h^{-1}, which is the ratio of the supplied ventilation flow rate (Q_s) to the volume of the room (V_r). It should be noted that the outdoor air is assumed as clean air without expiratory airborne aerosols.

Infection models, such as Wells-Riley model, are not used to evaluate the risk of airborne cross-infection, because such models account for ventilation considering only ventilation flow rate. Thus, the models cannot examine the effect of different ventilation strategies that have the same ventilation flow rate. Intake fraction is used to evaluate the risk of airborne cross-infection, which is defined as the proportion of air mass exhaled by the infected person that is then inhaled by the exposed person (Bennett et al., 2002). It has to be stated that the intake fraction correspond to dose. A higher intake fraction does not necessarily means a higher risk, if accumulation of a certain dose has not been achieved. However, for engineering applications, it is difficult for ventilation to be accurately operated and controlled based on dose, because of many influential factors such as variation of occupant density, schedule and time. This study therefore assumes that a higher intake fraction represents a high risk of cross-infection. The time-averaged intake fraction during a certain period can be written as:

$$IF = \frac{\int_{t_{in,0}}^{t_{in}} C_{in}(t) M_{in} dt}{\int_{t_{ex,0}}^{t_{ex}} C_{ex}(t) M_{ex} dt} \tag{3}$$

where $C_{in}(t)$ and $C_{ex}(t)$ are the concentration inhaled by the exposed person and the concentration exhaled by the infected person at time t, particles/m^3, respectively, where $C_{in}(t)$ is assumed to be the same with room concentration C_t and $C_{ex}(t)$ is the ratio of $\dot{G}_r$ to the pulmonary ventilation rate of the infected person Q_p; M_{in} and M_{ex} are the mass flow rates of the inhaled flow of the exposed person and the exhaled flow of the infected person, kg/h, respectively; M_{in} and M_{ex} are assumed to be the same; $(t_{in} - t_{in,\,0})$ and $(t_{ex} - t_{ex,\,0})$ are the exposure period of the exposed person and the period of time during which the infected person is present in the room, respectively (in hours).

Eqs. (1), (2) and (3) can be used to determine the importance of the factors defined above and thus to determine the appropriate ventilation strategy. In the following section, the proposed method of source control is applied to determine the operation strategy of ventilation in a typical school classroom that will lead to a reduced risk of airborne cross-infection.

4. Case study: Classroom ventilation

The basic design conditions of the classroom to be considered follow the European standard EN16798-1:2019 (2019). The floor area of 81 m^2 is designed for 15 people with an occupancy density of 5.4 m^2/person. The supply airflow rate is the sum of the air volume required for each occupant defined in four categories (Cat I - 10 L/s/person, Cat II - 7 L/s/person, Cat III - 4 L/s/person, Cat IV - 2.5 L/s/person) plus corresponding to the categories additional airflow rate (L/s/m^2 of the floor area) for removal of pollution generated from building materials for three types of buildings depending on their emission levels. For the source, only an asymptomatic or pre-symptomatic person, i.e. an infected person without noticeable symptoms but capable of infecting other occupants, is considered, as it is reasonable to assume that symptomatic people will stay at home. The rate of generation of aerosols during breathing (with and without a mask) and while talking at different levels of loudness have been reported (Yan et al., 2018; Asadi et al., 2019). We used some of the reported data to perform the calculations. The source characteristics used for calculation of the intake fraction are: pulmonary ventilation - 6 L/min, breathing cycle - 10 cycles/min, and emission - 2554 particles/breath. Note that different people (e.g., super spreaders) could generate very different numbers of aerosols and the infectivity of the viruses will be different depending on their type and the stage reached in the course of the infection. However, in this study the use of a certain number, 2554 particles/breath, to perform calculations would not influence the relative differences between analysed modes of operation.

It has been reported that in order to cause infection a certain minimum number of viruses (i.e., a dose) is needed. The dose depends on both exposed concentration and exposure time. Considering that the number of virus-laden aerosols generated during breathing and talking is not high, an occupant would have to remain in a classroom for a long period in order to receive a sufficient number of aerosols to result in an

Table 1
A list of evaluated cases with different boundary conditions; all cases have in total five lessons and four breaks, except for Case 7, which has three lessons and two breaks.

	No. of occupants	Occupant density (m^2/person)	Height of ceiling (m)	Length of lesson (min)	Length of breaks (min)	Supply flow rate (L/s)	ACH (h^{-1})
Case 1	15	5.4	3.0	30	15	231 (Cat I)	3.4
Case 2	15	5.4	3.0	30	15	61.8 (Cat IV)	0.9
Case 3	15	5.4	3.0	30	15	0 (No ventilation)	0
Case 4	15	5.4	3.0	30	20	231	3.4
Case 5	15	5.4	3.0	45	15	231	3.4
Case 6	15	5.4	3.0	45	20	231	3.4
Case 7	15	5.4	3.0	50	30	231	3.4
Case 8	15	5.4	3.0	30	15 Occupants in room during breaks	231	3.4
Case 9	15	5.4	3.5	30	15	231 (Cat I)	2.9
Case 11	15	5.4 (2 infected occupants	3.0	30	15	231 (Cat I)	3.4
Case 12	30	2.7	3.0	30	15	381 (Cat I)	5.6

infection. We therefore performed analyses for a half school day with five lessons and four breaks in between. The case of a lesson lasting 30 min followed by a 15 min break and a ventilation airflow rate of 10 L/s person +1 L/s/m^2 for removal of building generated pollution (Category I, EN16798-1) was used as a reference case. The time-averaged intake fractions during the five lessons for different other cases were calculated. The results are presented and compared in the following.

The list of the evaluated cases with their detailed boundary conditions is given in Table 1. Case 12 represents a possible existing condition. In this case, the ventilation system for the classroom is designed following EN 15251:2007 (2007), which recommended 2 m^2 floor area per person (2.7 m^2/person was used in this study). Case 2 represents an extreme condition without ventilation supply of outdoor air to the room. Detailed analyses were performed to identify the importance of the following parameters: 1) supplied ventilation flow rate; 2) source control; 3) length of the lesson; 4) length of the break between lessons; 5) volume of the room; 6) number of infected persons; 7) design occupancy density. Furthermore, the effect of an additional supply of clean air (by for examples windows fans or air cleaners) to the room all the time or during only the breaks was studied (as listed in Table 2). For simplicity, the importance of the length of the lessons, the length of breaks and the additional ventilation air supply are discussed only for category I, i.e. 10 L/s person +1 L/s/m^2 for removal of building material emissions. For the purpose of comparison, the corresponding air change rate (ACH) is listed in Table 1.

The results are shown in Fig. 2. The results shown in Fig. 2(a) confirm that the intake fraction decreases with an increase in the ventilation rate. However, in order to be energy efficient, the mechanical ventilation systems in existing buildings are designed to supply only enough air to ensure occupants' health and comfort when pandemic is not present. It is therefore not possible to increase the supply airflow much above what is prescribed for Cat I to reduce the risk of cross infection. During a pandemic, additional clean air supply systems (window fans, stand-alone induction units, etc.) can be used. A large increase in the supply airflow rate will cause some important problems, including increase of draught and noise discomfort. Similar problems exist when additional ventilation systems are used. It is generally accepted that source control is the first step to be considered in ventilation design. Usually, source control can be applied by removing any symptomatic infected persons from the room. However, this is not possible in the case of asymptomatic persons. In this case, source control can be achieved by asking all occupants to leave the room. As shown in Fig. 2(b), in the case of classrooms, asking students to leave the room during breaks between lessons (Case 1) reduced the risk of airborne cross-infection by 35% compared to when the students stayed in the room during the breaks (Case 8). It is easy to apply this approach in practice, not only for classrooms in schools, but also for meetings, conferences, etc.

At a constant generation rate, the airborne aerosol concentration in a room will increase until it reaches steady state. The time-averaged intake fraction will therefore depend on the exposure time, especially before steady state has been reached. The comparison of Case 1 with Case 5 reveals a 14% increase in the intake fraction when the lecture time increases from 30 min to 45 min with a 15 min break between the lessons (Fig. 2(b)). Any increase in the break time also will help to reduce the time-averaged exposure. Note that the results are valid only if the infected person leaves the room during the break. If the person stays in the room (Case 8, or 'NB' in Fig. 2(b)), the intake fraction increases by 35%. Obviously, evacuating the room during the breaks is more important for reduction of the risk of cross-infection than a decrease in the duration of each lesson. The relative importance of the length of the lesson and the break duration can be evaluated by comparing the intake fraction for Cases 1 and 4, and Cases 5 and 6, which are '30 + 15' and '30 + 20', and '45 + 15' and '45 + 20', respectively. When the lesson time is 30 min, increasing the break time by 5 min reduces the intake fraction by 6% and in the case of 45 min lessons by 4%. It may be concluded that the impact of a reduction of the lesson time and an increase of the break time on the intake fraction is comparable.

Table 2
A list of evaluated cases with different boundary conditions. "A" and "B" denote respectively that increased ventilation was used continuously or only during the breaks (all occupants were out of the room during breaks in both cases).

	No. of occupants	Occupant density (m^2/person)	Height of ceiling (m)	Length of lesson (min)	Length of breaks (min)	Additional supply airflow rate (L/s)	Total supply airflow rate (L/s)	ACH (h^{-1})
Case 1	15	5.4	3.0	30	15	0	231	3.4
Case 12	15	5.4	3.0	30	15	250 (A)	481	7.1
Case 13	15	5.4	3.0	30	15	750 (A)	981	14.5
Case 14	15	5.4	3.0	30	15	1250 (A)	1481	21.9
Case 15	15	5.4	3.0	45	15	250 (B)	481	7.1
Case 16	15	5.4	3.0	45	15	750 (B)	981	14.5
Case 17	15	5.4	3.0	30	15	1250 (B)	1481	21.9

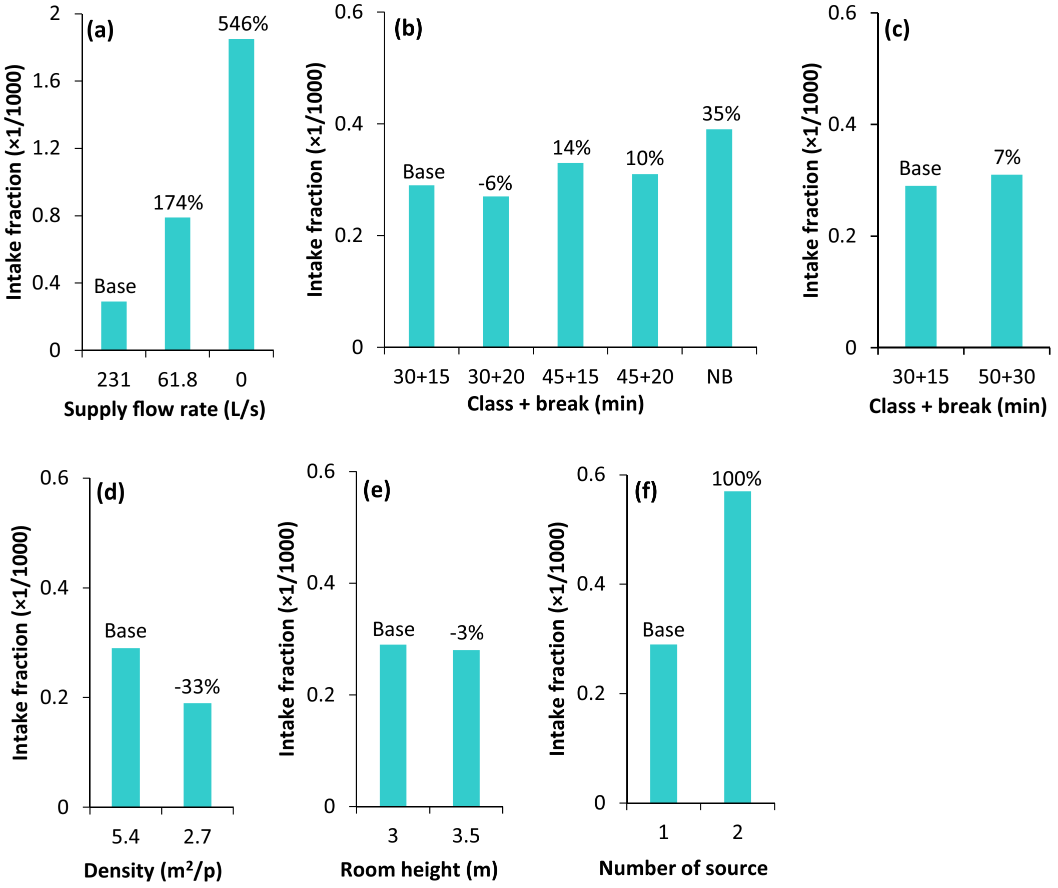


Fig. 2. The influence of various parameters on the time-averaged intake fraction during a half day: (a) supply airflow rate, (b) schedule of lessons and breaks when the total length of either lessons or breaks is different (see Table 1 for detail), where NB denotes No Break or students staying in the classroom during breaks, (c) schedule of lessons and breaks when the total duration of lessons and breaks together is unchanged, (d) occupant density, (e) room height, i.e. of room volume, and (f) number of infected persons present in the room. Case 1 as shown in Table 1 was taken as the reference case and the percentages above the bars are percentage increases of intake fraction in comparison to this reference case.

The above analyses were performed at slightly different total lengths of five lectures with four breaks in between. Analyses were performed to study the impact of the number (or division) of lessons and breaks on the intake faction with a fixed total time, selected to be 210 min. The intake fraction in the case of five lessons of 30 min with four 15 minute breaks in between and in the case of three 50 minute lessons with two 30 minute break in between is compared in Fig. 2(c). The results show that with an unchanged total time the intake fraction is increased by 7% when the number of lectures decreases and their length increases.

The impact of the number of occupants on the intake fraction will be different and there are two possibilities when the number of infected occupants is fixed. The first possibility is that the supply airflow rate remains unchanged but the number of occupants changes. The second possibility is that the supply airflow rate changes according to any change in the number of occupants, i.e. a 10 L/s person clean air supply is maintained when the number of occupants changes. With the first possibility, the change in the number of occupants with an unchanged supply airflow rate will not have any impact on the intake fraction. With the second possibility, increasing the number of occupants with a corresponding increase in the supply airflow rate (with social distancing maintained) will lead to a decrease in the intake fraction (Fig. 2(d)). The results show that an increase in the number of room occupants from 15 persons to 30 persons (Case 1 and Case 12) while maintaining a supply airflow rate of 10 L/s person will decrease the intake fraction by 33%. With goal of reducing the intake fraction it is thus better to operate the ventilation system at the maximum possible supply airflow rate even when the number of occupants decreases.

The impact of the room volume on the intake fraction can be seen from the results shown in Fig. 2(e) by comparing Cases 1 and 9 (Table 1). The only difference between the two cases compared in the

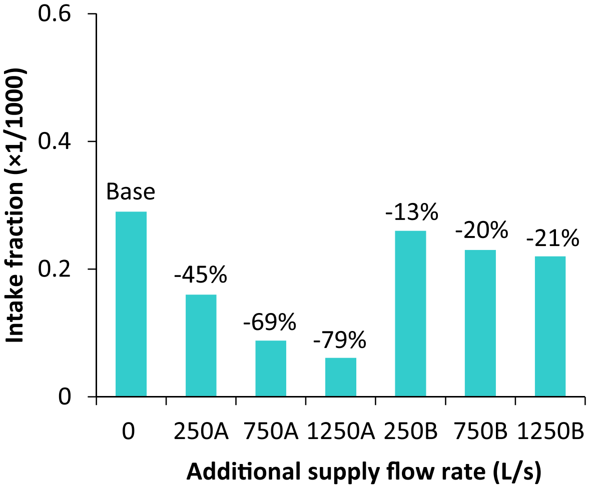


Fig. 3. The influence of additional ventilation on the time-averaged intake fraction during a half day. The basic case has no additional supply of outdoor air; 250A denotes 250 L/s additional supply flow rate all the time and 250B denotes 250 L/s additional supply flow rate during breaks only; the Case 1 as shown in Table 1 was taken as the reference case and the percentages above the bars are percentage increases in the intake fraction in comparison to this reference case.

figure is the height of the ceiling, 3 and 3.5 m, which makes 16.7% difference in the room volume, which is 283.5 m^3 and 243 m^3, respectively. The intake fraction decreases by 2.8% when the room volume is increased by approximately 17%. The results suggest that with the same ventilation rate the risk of cross infection will be lower in spaces with a larger volume, such as those with a higher ceiling.

The above-mentioned analyses were performed for the case of only one infected person being present in the room. The presence of more than one infected person will lead to a proportional change in the intake fraction, and a proportional change in the risk of airborne transmission (Fig. 2(f)).

Considering the negative impact of draught and noise on learning (and on the performance of occupants in general), the importance of an increase of the supply airflow rate of clean air to the room was studied in two scenarios: first, the additional air supply took place continuously, i.e. during both lessons and breaks, and second, the additional air was supplied only during the breaks (when all the occupants were out of the room). The combinations of parameters studied are listed in Table 2. The calculations were performed under the condition that during the breaks the occupants all leave the room. The results are shown in Fig. 3.

The results support the common assumption that in general the increase of the supply airflow rate of clean air reduces the intake fraction and that a continuous supply of additional clean air during both lessons and breaks is much better than if it occurs only during breaks. This is demonstrated by the fact that the case in which five times more air is supplied during the breaks only (1250B; case 17, Table 2), the intake fraction was much higher than in the case of continuous operation of ventilation when the increase in the clean air supply rate was only 100% (250A - Fig. 3; Case 12 - Table 2). This means that an additional outdoor air supply during breaks only can be a method to reduce airborne cross infection, but, if possible, a continuous supply of additional ventilation is much more efficient.

5. Recommendations

Based on the results of the present study the following recommendations on how to reduce the risk of airborne infection in rooms with mechanical ventilation are made:

- Ventilation systems supplying clean outdoor air should be operated continuously with the maximum supply airflow rate. It is recommended that steady-state conditions in the room in terms of the supply airflow rate should exist at the time when occupation begins, i.e. the ventilation should be in operation before any occupants enter the room;
- Occupants should be asked to leave the room every hour for a short break of 10–20 min. In the case of classrooms, meeting rooms, conference rooms, etc. all occupants should leave the room periodically. In the case of open-plan offices the occupants may not all leave at the same time.
- Short room occupation times with long breaks are recommended; a shorter occupation time prevents the room concentration from building up to the highest level, and a longer break between periods of occupation allows the room concentration to decrease as much as possible and allows the use of additional high-noise ventilation equipment. Even if the total duration of occupied and break periods together remains the same, it is recommended to have short occupied and break periods.
- With the same supply airflow rate, a reduction in the number of room occupants will not reduce the risk of airborne infection while the number of infected occupants present remains unchanged. An increase in the number of occupants (provided the recommended distancing is maintained) with a proportional increase in the supply airflow rate (i.e. with an additional supply of air) will reduce the intake fraction and probably the overall risk of airborne transmission provided that the number of asymptomatic infected persons present remains unchanged. However, increasing the number of occupants should be avoided as it may increase the number of infected persons present. Source control is very important (e.g. by monitoring occupants temperature) as well as by making occupants more aware of their responsibility to stay at home if symptomatic.
- Supply of additional air to the room with stand-alone air-handling units, window fans, etc. is recommended, at least during breaks. Possible draught and noise problems due to the high supply air velocity will limit the increased supply airflow rate. In this case the additional equivalent ventilation rate can be complemented with a stand-alone room air cleaner, efficient filtration of air recirculation, and air disinfection. The need to heat any additionally supplied air is another limitation during winter.
- A moderate increase of the room volume (room height) in newly constructed buildings provides a decreased risk of airborne infection, but not much.

The above recommendations relate to the operation of ventilation. In addition, the distance between occupants' workstations should be at least 1.5 m in order to avoid short-distance airborne cross-infection (Ai and Melikov, 2018). This requirement should be applied even when people are not talking. When a separation distance of 1.5 m cannot be maintained, transparent partitions between occupants seated beside each other should be considered. Wearing masks (possibly of highest-grade) in offices and during meetings is recommended, especially when it is difficult to take breaks, sufficiently high ventilation rate cannot be guaranteed, or social distancing cannot be respected. Occupants should be encouraged to avoid singing, shouting, talking loudly, reading aloud and being physically active in offices (classrooms) as much as is reasonably possible. For examples, singing lessons should be cancelled, and in-class discussion and debate and other forms of teaching involving a lot of talking should be reduced as much as possible. Workstations should be arranged as face-to-back (Ai and Melikov, 2018). Occupants should be encouraged to reduce the chance of face-to-face orientation at all times. In order to reduce exposure to air contaminated by infected customers, staff in places such as shops, supermarkets and restaurants should have a relatively separate and well-ventilated place to which they can retire periodically and whenever there are no customers present.

The effectiveness of using outdoor air supply and intermittent occupancy in combination with air filtration, air cleaning and air disinfection in reducing the risk of airborne transmission is not evaluated in this study. We considered complete mixing of air and exhaled aerosols in rooms. However, airflow pattern and dynamics of aerosols are important for the distribution of aerosols and the exposure of each occupant in rooms. Results of such detailed predictions of airflow pattern and dynamics of aerosols are difficult to apply in practice because of many influential factors, which cannot be controlled, such as location of exposed and infected occupants, size and number distributions of exhaled aerosols, etc.

CRediT authorship contribution statement

A.K. Melikov: Conceptualization, Methodology, Writing - original draft, Funding acquisition. **Z.T. Ai:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Funding acquisition. **D.G. Markov:** Methodology, Formal analysis, Investigation, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the Ramboll Foundation Denmark and by the National Natural Science Foundation of China (No. 51908203). The valuable comments of Dr. David Wyon are highly appreciated.

References

Ai, Z.T., Melikov, A.K., 2018. Airborne spread of expiratory droplet nuclei between the occupants of indoor environments: a review article. Indoor Air 28 (4), 500–524.

Ai, Z.T., Hashimoto, K., Melikov, A.K., 2019. Influence of pulmonary ventilation rate and breathing cycle period on the risk of cross-infection. Indoor Air 29 (6), 993–1004.

Asadi, S., Wexler, A.S., Cappa, C.D., et al., 2019. Aerosol emission and superemission during human speech increase with voice loudness. Sci. Rep. 9, 2348. https://doi.org/10.1038/s41598-019-38808-z.

ASHRAE, 2020. Position Document on Airborne Infectious Diseases, Approved by the Board of Directors, January 19, 2014. Reaffirmed y the Technology Council, February 5, 2020. https://www.ashrae.org/file%20library/about/position%20documents/airborne-infectious-diseases.pdf.

Bennett, D.H., McKone, T.E., Evans, J.S., et al., 2002. Defining intake fraction. Environ. Sci. Technol. 36 (9), 206A–211A.

EN 15251, 2007. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics, EN 15251:2007. European Committee for Standardization, Brussels.

EN 16798-1, 2019. Energy Performance of Buildings – Ventilation for Buildings – Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics – Module M1-6, EN 16798-1:2019. European Committee for Standardization, Brussels.

Ghinai, I., Woods, S., Ritger, K.A., et al., 2020. Community transmission of SARS-CoV-2 at two family gatherings — Chicago, Illinois, February–March 2020. MMWR Morb. Mortal. Wkly Rep. 69, 446–450.

Knibbs, L.D., Morawska, L., Bell, S.C., Grzybowski, P., 2011. Room ventilation and the risk of airborne infection transmission in 3 health care settings within a large teaching hospital. Am. J. Infect. Control 39 (10), 866–872.

Li, Y., Leung, G.M., Tang, J., Yang, X., Chao, C., Lin, J.Z., et al., 2007. Role of ventilation in airborne transmission of infectious agents in the built environment-a multidisciplinary systematic review. Indoor Air 17, 2–18.

Lu, J., Gu, J., Li, K., Xu, C., Su, W., Lai, Z., et al., 2020. COVID-19 outbreak associated with air conditioning in restaurant, Guangzhou, China, 2020. Emerg. Infect. Dis. https://doi.org/10.3201/eid2607.200764 In press.

Melikov, A.K., 2015. Human body micro-environment: the benefits of controlling airflow interaction. Build. Environ. 91, 70–77.

Melikov, A.K., Ai, Z.T., 2020. Short-distance airborne transmission of respiratory pathogens: role of breathing zone airflow interaction, lecture at the sixth webinar in the series on the spread of infectious diseases in indoor environments. The International Society of Indoor Air Quality and Climate (May 5).

Morawska, L., Cao, J., 2020. Airborne transmission of SARS-CoV-2: the world should face the reality. Environ. Int. 139, 105730.

Müller, D., Kandzia, C., Kosonen, R., Melikov, A.K., Nielsen, P.V., 2013. Mixing Ventilation. Guide on Mixing Air Distribution Design, REHVA 2013. p. 114.

National Health Commission of China, 2020. Guidelines on the operation of air-conditioning and ventilation systems in office buildings and public spaces during the outbreak of COVID-19. (in Chinese), Accessed on May 23 at. http://www.nhc.gov.cn/jkj/s5898bm/202005/2d89c552f9804f39bb4f44a9d826b2cd.shtml.

Park, S.Y., Kim, Y.M., Yi, S., Lee, S., Na, B.J., Kim, C.B., et al., 2020. Coronavirus disease outbreak in call center, South Korea. Emerg. Infect. Dis. https://doi.org/10.3201/eid2608.201274 (In press).

Read, R., 2020. A choir decided to go ahead with rehearsal. Now dozens of members have COVID-19 and two are dead. Los Angeles Times Published March 30, 2020. Accessed on May 20 at. https://www.msn.com/en-us/news/us/a-choir-decided-to-go-ahead-with-rehearsal-now-dozens-of-members-have-covid-19-and-two-are-dead/ar-BB11Tjim.

RHEVA, 2020. COVID-19, 2020. Guidance. https://www.rehva.eu/activities/covid-19-guidance (Retrieved 3 April 2020).

Smieszek, T., Lazzari, G., Salathe, M., 2019. Assessing the dynamics and control of droplet- and aerosol-transmitted influenza using an indoor positioning system. Sci. Rep. 9, 2185.

Yan, J., Granthama, M., Pantelic, J., Bueno de Mesquit, P.J., Alberta, B., Liua, F., Ehrman, S., Milton, D.K., EMIT Consortium, 2018. Infectious virus in exhaled breath of symptomatic seasonal influenza cases from a college community. PNAS 115 (5), 1081–1086 January 30, 018.