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Influence of environmental conditions on airborne infection risk in ward

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Abstract: In order to study the influence of parameters on airborne transmitted diseases in a hospital ward, a pollutant decay equation and a Wells-Riley model are adopted to study the relationship between the airborne infection risk and the parameters such as the ventilation rate, the number of susceptible persons and the volume of the ward. The results show that the airborne infection risk can be reduced by increasing the ventilation rate. For two wards with the same air change per hour (ACH) but different volumes, the ventilation rate in a large room is higher than that in a small one. The number of the infected persons in the ward increases with the increase in the susceptible persons when the ACH is a constant. Therefore, the ventilation rate in the ward is not only estimated by the ACH but also related to the volume of the ward and the number of the susceptible persons.

Key words: airborne transmitted diseases; air change per hour (ACH); ventilation rate

The global transmission of tuberculosis (TB) during recent decades, the outbreak of severe acute respiratory syndrome (SARS) in 2003, the current pandemic of influenza A(H1N1)[1] and the possible pandemic of highly pathogenic emergency diseases in the future remind us that airborne infection remains a serious threat to human health[2]. In the current literature, conclusive evidences show that ventilation can help control airborne infection[2-6]. The ventilation and the airflow pattern in a room have a close relationship with airborne transmitted diseases such as measles, TB and SARS.

Centres for Disease Control and Prevention, USA are the first to develop the guideline for preventing and controlling airborne transmitted diseases[7]. Based on the guideline, various guidelines, such as ASHRAE[8], CDC[9], AIA[10], are published to control airborne infections. The air change per hour (ACH) can reflect the process of the concentration decay of pollutants.

Herein, we propose a new method to calculate the ventilation rate based on the actual number of the susceptible persons and the room size. The purpose of this study is not to recommend a reasonable value of the minimum ventilation rate, but to discuss the advantages of a new way of determining the ventilation rate and control the pollution of indoor air in ASHRAE 62.1—2004[11].

1 Methodologies

1.1 Mechanism of airborne infection

Airborne transmission refers to the passage of micro-organisms from a source to a person through aerosols, resulting in infection of the person with or without consequent disease[2]. Pathogen-laden droplets are released into the air when patients talk, cough or sneeze. The droplets with a diameter of less than 100 μm are found to evaporate very rapidly[12] and then become droplet nuclei with a diameter of less than 5 μm[7]. Some pathogen-laden (virus or bacteria) may die or lose infectivity in this process but others attaching to the droplet nuclei may remain infective. These droplet nuclei of small sizes and low deposition velocities suspend in the air because of gravity and drag forces, and then they are inhaled by the susceptible persons through the noses or pharynxes and finally reach the lungs. According to the mechanism of airborne infection, airborne transmitted diseases can be controlled and the droplet nuclei can be diluted or even removed with a suitable ventilation rate.

1.2 Concentration decay equation

The relationship between the ventilation rate and the concentration decay of the calculated pollutants can be expressed as a concentration decay equation. We assume that the pathogen concentration in the outdoor air is zero and there is no source in the room. Thus, the concentration decay equation can be simplified as

$$\frac{\mathrm{d}c}{\mathrm{d}t} = -nc \tag{1}$$

$$\frac{c}{c_0} = \exp(-nt) \tag{2}$$

where t is the ventilation time; c is the pathogen concentration at time t; n is the ventilation rate; c_0 is the initial pathogen concentration.

1.3 Wells-Riley model

The ventilation rate is defined as the volume of the outdoor air supplied to the room per unit time. A high ventilation rate can reduce the infection risk of the airborne transmitted diseases. The relationship between the ventilation rate and the infection risk of the airborne transmitted diseases can be expressed by the Wells-Riley model proposed by Riley et al. in 1978[13]; that is,

$$P = \frac{C}{S} = 1 - \exp\left(-\frac{Ipqt}{Q}\right) = 1 - \exp\left(-\frac{Ipqt}{nV}\right) \tag{3}$$

where P is the infection risk; C is the number of infected persons appearing in the next generation; S is the number of the susceptible persons; I is the number of the infectors in the infectious stage; p is the pulmonary ventilation rate; q is the quanta of the airborne infection produced per infector per hour; $Q = nV$ is the room ventilation rate; n is the air change

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per hour (ACH); V is the room volume; T is the exposure time.

This model is based on the concept of the quantum of infection which was introduced by Wells in order to estimate the infection risk of airborne transmitted diseases in 1955[3]. Wells defined a quantum of infection as the dose of the infectious droplet nuclei. Based on this model, Riley et al. [13] successfully predicted an outbreak of measles in a suburban elementary school near Rochester, NY. Many other investigations[13-16] evaluated the infection risk of several airborne transmitted diseases and even estimated the relationship between the airflow pattern and the spatial distribution of the infection risk.

2 Results

2.1 Effect of ACH on pathogen concentration

The ACH is suitable for analyzing the concentration decay of the calculated pathogens in the indoor air. According to Eq. (2), the variation in the concentration decay of the calculated pathogens with different ACHs can be obtained, as shown in Fig. 1. When the ACH is 6 times/h, the pathogen concentration decreases to 8% within 25 min. But the same effect can be obtained within 12.5 min when the ACH is 12 times/h. It can be seen that a higher ACH can cause a faster decay of the pathogen concentration in the indoor air.

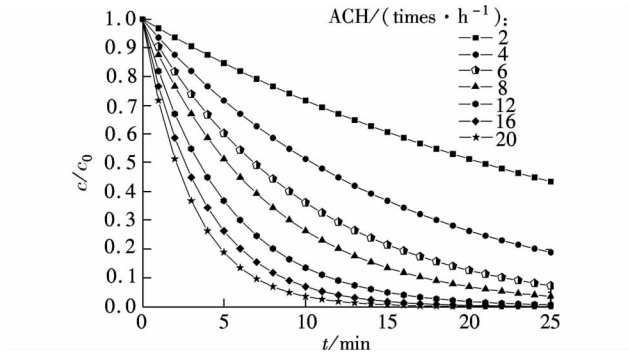

Fig. 1 Concentration decay of calculated pathogens

2.2 Effect of ACH on infection risk

The ACH is commonly used to denote the ventilation rate. Fig. 2 shows the variation in infection risk with different ACHs. This study is carried out in a room with a volume of 90 m^3 (6 m × 5 m × 3 m). The room is assumed to contain an infector with a quanta value of 12 quanta/h for 2 h. And the pulmonary ventilation rates of all the susceptible persons in the room are 0.3 m^3/h. It can be seen that with the increase in the ACH, the infection risk of the susceptible persons decreases under the same exposure conditions. The reason is that a higher ACH means the room is ventilated with more outdoor air. Moreover, a good ventilation effect can be obtained by increasing the ventilation rate in a poorly ventilated room. However, the ventilation effects are not obvious in the following situations: 1) The room's ventilation rate is high and the number of quanta released by an infector is at the normal level, e.g., q = 12 quanta/h. According to Fig. 2, the infection risk decreases less than 1% when the ACH increases from 14 to 16 times/h. So the infection risk of a well ventilated room cannot decrease drastically with the increase in the airflow rate. 2) The quanta produced by an infector (either person or animal) are very high. According to Fig. 2, when the quanta value of autopsy outbreak is not less than 2 000 quanta/h[17], more than 89% of the susceptible persons are still infected even though the ACH in the room is 6 times/h.

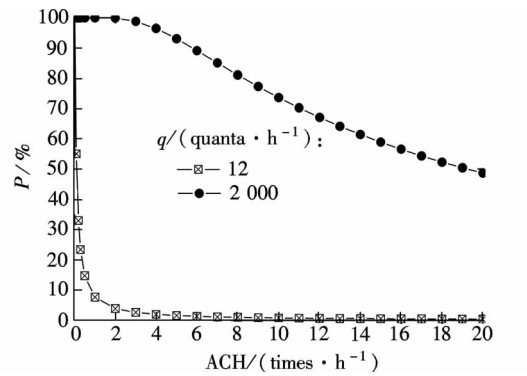

Fig. 2 Variation in infection risk with different ACHs

2.3 Effect of room size on infection risk

The ventilation rate does not reflect the impact of the room size on the infection risk. For instance, the ACH in a room with a volume of 135 m^3 (7.5 m × 6 m × 3 m), named room 1, is 6 times/h; that is, the absolute ventilation rate of room 1 is 810 m^3/h. However, with the same ACH, the absolute ventilation rate of a room with a volume of 90 m^3 (6 m × 5 m × 3 m), named room 2, is 540 m^3/h. Both the two rooms are assumed to contain an infector with a quanta value of 12 quanta/h for 2 h. And the pulmonary ventilation rates of all the susceptible persons in the room are 0.3 m^3/h. The infection risk in room 1 is 0.88% while that in room 2 is 1.32%. If the infection risk in room 1 is 1.32%, the ACH in the room only needs to reach 4 times/h and the absolute ventilation rate decreases by 270 m^3/h. Consequently, with the same ACH, the ventilation rate in room 1 is higher than that in room 2. The high ventilation rate is beneficial in diluting or even removing the pathogens in the indoor air and control the spread of the airborne infection. However, the excessive ventilation rate leads to great energy consumption and high operating costs. If the ventilation rate is estimated by the room size, the infection risk, the energy consumption and the operating costs can be reduced.

2.4 Effect of actual number of susceptible persons on infection risk

In order to evaluate the actual number of new infection cases, Eq. (3) can be modified as

$$C = \left[1 - \exp\left(-\frac{Ipqt}{Q}\right)\right]S = \left[1 - \exp\left(-\frac{Ipqt}{nV}\right)\right]S \quad (4)$$

Fig. 3 shows the relationship between the number of new cases and the ACH. The room with a volume of 90 m^3 (6 m × 5 m × 3 m) is assumed to contain an infector with a quanta value of 2 000 quanta/h for 2 h. And the pulmonary ventilation rates of all the susceptible persons in the room are 0.3 m^3/h. It should be noted that with the same ACH of 10 times/h (900 m^3/h), the number of new cases in the room

with 30 susceptible persons is 22.09, while that with 5 susceptible persons is only 3.68. That is, with the same ventilation rate and infection risk, the number of the infected persons increases with the increase in the number of the susceptible. Obviously, the more the secondary cases are, the more the new cases generated in next generation are. Consequently, the disease outbreak spreads fast. Therefore, the actual number of the susceptible persons in the room is an important factor in the spread of the airborne infection. If the ventilation rate is estimated by the actual number of the susceptible persons in the room rather than the ACH, the spread velocity of the disease may be slowed down.

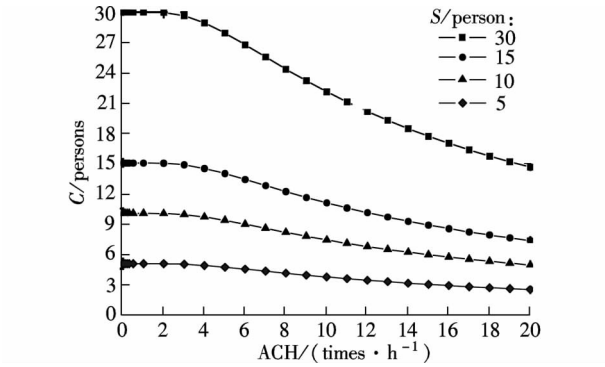

Fig. 3 Variation in infected persons with different ACHs

3 Discussion

A high airflow rate helps to prevent the spread of airborne transmitted diseases and reduce the concentration of the droplet nuclei in the indoor air. The ACH is commonly used in the guidelines of infectious diseases while the impact of the floor areas and the number of the persons in the room are considered in the ASHRAE 62.1—2004[11] for civil buildings. From this study, conclusions can be drawn as follows:

1) The ventilation rate estimated by the ACH does not reflect the influence of the room size. With the same ACH, the ventilation rate in a large ward is higher than that in a small ward. Even though the ACH in the small ward is higher than that in the large ward, the airflow rate in the small ward may still be low. Therefore, the ventilation rates in these two wards may be different because of different sizes even if the ACHs are the same.

2) The ventilation rate estimated by the ACH does not consider the impact of the actual number of the susceptible persons. This means that no matter how many susceptible persons in the ward, the airflow rate is always a fixed value for a certain ACH. With the increase in the number of the susceptible persons, the new infected cases increases and, thus, a disease outbreak spreads fast.

According to the discussion mentioned above, limitations are found. Therefore, some modifications should be made. That is, the ventilation rate is related to the room size and the actual number of the susceptible persons in the ward.

4 Conclusion

There are some reasonable methods for determining the minimum ventilation rate based on the room size and the actual number of the susceptible persons instead of the ACH. A large room can provide much more outdoor air than a small one with the same ACHs and the number of the infected cases increases with the increase in the actual number of the susceptible persons. The analysis of the concentration decay provides a deep insight into the relationship between the concentration decay of the pathogens and the ventilation rate. It also shows that plenty of outdoor air can prevent the airborne infection. However, there is a lack of sufficient evidence to choose the ideal ventilation rate. Further studies focus on how to effectively specify the minimum ventilation rate and reduce the risk of cross-infection for airborne infection in a general hospital ward.

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病房环境条件对空媒传播疾病感染风险的影响

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摘要:为了研究病房内各种参数对空媒传播疾病的影响,利用浓度衰减方程和 Wells-Riley 方程研究分析了通风量、易感染人员数量、病房尺寸等参数与空媒传播疾病感染风险的关系. 分析结果显示:增加病房内的通风量可以有效地降低空媒传播疾病的感染几率;对于换气次数相同但面积不同的 2 个病房而言,大病房的通风量大于小病房的通风量;换气次数相同时,病房内的感染人数随易感染人员数量的增加而增加. 因此,病房内所需的通风量不仅与换气次数(ACH)有关,还与病房面积和病房内易感染人员数量有关.

关键字:空媒传播疾病;换气次数(ACH);通风量

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