Numerical Study of the Influence of Bedside Curtains on Human Exhaled Contaminants Distribution in a Two-bed Ward

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Abstract. Bedside curtains are widely used in multi-bed wards to protect the privacy of patients. However, it may change the distribution of airflow and lead to cross infection. A numerical approach is applied to investigate contaminant distribution in a two-bed ward with downward ventilation. Tracer gas such as CO_2 is applied to simulate the exhaled contaminants by two lying patients. The contaminant concentration distributions with and without bedside curtains are compared. The results show that bedside curtains have great impacts on the airflow throughout the ward, which leads to a significant difference in the trajectory of expiratory flow between patients. Without curtains, the supply air can reach almost all the ward except the aera bed 1. Curtains mounted without grille almost completely block the airflow to bed 1, most of the airflow along with the continuous air supply of the whole ward without passing through bed 1, while the exhaled flow of patient 2 is blocked by the curtain, which cannot be directly returned to the outlet, but is affected by the eddy current caused by fresh air and spread to the end of bed 2. The expiratory airflow of patient 1 will also spread to the whole ward, which will lead to cross-infection. Most of the supply air can pass through the grille on the upper part of the curtain to reach the upper space of bed 1, and a small part of the airflow is blocked and bounced by the curtain. The exhaled flow of patient 2 follows the bounced air back to the faces of patient 2, and then follows the supply air throughout the whole ward. Expiratory airflow of patient 1 moves upward at first and then spread to the whole ward along with the supply airflow. The study can provide a reference for wards to construct a healthy indoor environment.

Keywords. contaminant distribution, exhaled contaminants, numerical simulation, cross infection, ward

1 Introduction

In this COVID-19 epidemic, a large number of infected people entered the hospital for treatment, and a part of health care workers (HCW) were also infected during the treatment. In addition, there was a small amount of cross-infection in the hospital. In addition to the severe acute respiratory syndrome (SARS), Middle East respiratory syndrome (MERS), tuberculosis and other infectious diseases that have appeared before, airborne diseases are getting more and more attention[1]. The emission and spread of bioaerosol particles in the air is one of the important causes of cross-infection. The risk of cross-infection in hospital wards is closely related to the form of airflow, medical curtains and the concentration of bioaerosol particles. In China, fan coil plus fresh air system is the most widely used in hospitals, especially in the wards.

Ventilation is mainly to reduce the concentration of bio-aerosol particles in the ward and provide fresh air, and the installation of medical curtains is not only to protect the privacy of patients, but also to protect the patients and medical staff in the ward from other patients in the ward Infection. Excellent airflow organization and medical curtains play a very important role in reducing the risk of cross-infection. Tracer gas and simulation studies have shown that the ventilation[2,3] and the presence of medical curtains[3-6] affect the risk of air cross-infection between two patients. Nielsen et al.[7] found that when a personalized ventilation system is used, a sufficiently high partition can block the penetration of the expiratory airflow. Similarly, medical curtains in two-bed wards can reduce the possibility of one patient inhaling another patient's expiratory airflow and reduce the risk of cross-infection between the two patients. Installing medical curtains between hospital beds can reduce the risk of spreading between patients after adjacent patients release bioaerosols[6]. Noakes[3] found that when the partition was installed, the bioaerosol on other surfaces around another patient was significantly reduced.

In this study, a numerical simulation method was used to evaluate the diffusion of droplets in a two-bed ward with a fan coil unit and an independent fresh air system. The main purpose of this study is to simulate the diffusion of human exhaled pollutants under the action of ventilation airflow and determine whether the medical curtain can really protect two patients and medical staff in a double-bed ward.

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2 Methodology

2.1 Physical model

Taking a two-bed ward in Wuhan as the research object, the air distribution of air conditioning and the expiratory track of patients in the ward under three conditions were studied to verify whether the medical curtains played a protective role. Fig. 1 shows the geometric model of the two-bed ward. The size of the two-bed ward is 8.5 m × 3.5 m in area and 2.9 m in height. It is composed of the bathroom and the main body of the ward, and the bathroom door is always open. There are two beds (2 m × 0.9 m in area and 0.6 m in height), two patients, two nightstands and other furniture in the ward. In case 1, there is no bed-side curtain in the ward. In case 2 and case 3, medical curtains are installed between the two beds, and the distance between the bottom of the medical curtain and the ground is 0.4 m, the difference is that case 3 has grilles at the top of the curtain, as shown in Fig. 2.

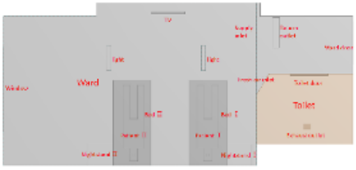

Fig. 1. View of the two-bed ward.

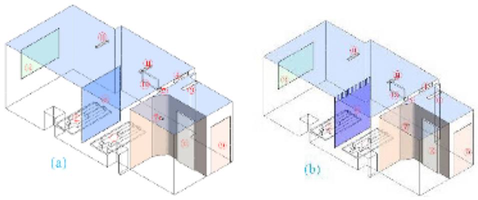

Fig.2. Layout of the two-bed ward.

①patient 1 ②patient 2 ③window④supply inlet⑤fresh air inlet⑥ return outlet⑦exhaust outlet⑧medical curtain⑨ward door⑩toilet door ⑪light ⑫TV

2.2 Numerical model

The Renormalization Group (RNG) k- ε model is used for the simulation. In this simulation, the temperature change is small, the density change is small, and the Boussinesq approximation is adopted. The SIMPLEC algorithm is selected. The pressure adopts the second-order scheme and the momentum equation adopts the second-order upwind scheme. In order to accelerate the convergence speed of calculation, the first-order upwind scheme is used for turbulent kinetic energy and turbulent dissipation rate. All equations are solved by FLUENT software.

For solving the dispersion of CO_2, the species transport model is used[8]:

$$\frac{\partial(\rho Y_i)}{\partial t} + div(\rho \vec{U} Y_i) = -div(\vec{J_i}) + R_i + S_i \qquad (1)$$

Where Y_i is the local mass fraction of CO_2, $\vec{J_i}$ is the diffusion flux of CO_2, R_i is the net rate of production, which is 0, S_i is the rate of the source.

This study uses the discrete phase model based on Lagrangian method (Discrete Phase Model) to study the movement, distribution and interpersonal transmission behavior of cough droplets. In the simulation, the droplet diameter of cough and exhale is 8.5 μm and 0.4 μm, while the number of droplets are 1000000 and 525 [9].

2.3 Boundary conditions

In order to determine the supply air volume and temperature, the cooling load of the ward was calculated before the numerical simulation. The supply inlet is defined as the velocity inlet with a temperature of 16°C, the fresh air inlet is defined as the velocity inlet with a temperature of 21.5°C, and the mouths are defined as a velocity inlet with a speed of 1m/s[10] and a temperature of 34°C[11-13]. Both the return outlet and the exhaust outlet are set to outflow. The human body adopts the thermal boundary condition with a constant temperature of 34°C. The partition wall between the toilet and the ward is coupled with heat transfer, and the other walls set the thermal boundary condition of fixed heat flux according to the calculation results of cooling load.

To simplify the problem, the two patients are seen as lying flat on the bed, exhaling through their mouth, the initial velocity of the exhaled air is 1m/s, the direction is vertical and upward, and the temperature is 34.7℃[14], including humidity compensation[15]. Tracer gas method is a common method for analyzing pollutant diffusion and airflow patterns[16. In this study, CO_2 was used as a tracer gas to simulate pollutants in breathing. The concentration of carbon dioxide produced by the patient's breath is 40,000ppm.

There is an exhaust outlet in the ceiling of the toilet in the two-bed ward. The supply air and fresh air are mixed with the air in the ward, most of the air flows back to the return air, part of it goes into the toilet and is discharged outdoors through the exhaust outlet in the toilet ceiling.

When the volume fraction of particles is less than 10%-12%, particles can be treated as discrete phases. The calculation of discrete phase can be divided into two kinds, uncoupled and coupled. Uncoupled method means that after the calculation of continuous phase flow field is converged, particles are added to track the model after post-processing, which is equivalent to simplifying the model, without considering the influence of discrete relative continuous phase, which can greatly save computer operation time. Coupling method refers to the convergence of flow field calculation first. Then the particles are added and calculated together to converge..

2.4 Evaluation index

The protective effect of medical curtain is evaluated by the following indices:

Deposition rate on object i: $DR_i = \frac{N_{t_i}}{N}$

removal rate on object i: $RR_i = \frac{N_{e_i}}{N}$

suspension rate:$SR = 1 - \sum_1^n DR_i - \sum_1^m RR_i$

total deposition rate: $DR = \sum_1^n DR_i$

total removal rate: $RR = \sum_1^m RR_i$

Where N_{t_i} is the number of droplets trapped by the surface of the object i; N_{e_i} is the number of droplets escaping from the opening i; N is the total number of droplets produced by patients.

2.5 Grid sensitivity

The computational domain is mainly discretized by unstructured tetrahedral grids system with refinement around the boundaries such as mouths, heat sources, openings and medical curtain. 0.77million, 1.07 million, 1.54 million and 1.86 million grids are used to solve the flow field to verify the grid independence. Fig. 3 compares the temperature, speed and CO_2 mass fraction of 10 sampling points on the ward line segment under different grid numbers. In order to ensure the accuracy of calculation and save computing resources, all simulations choose a meshing method with a grid number of 1.07 million.

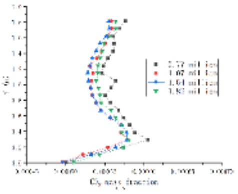

Fig.3. Grid independence verification.

3 Results and discussion

3.1 CO_2 distribution

Fig. 4 shows the CO_2 distribution at Y=0.9 m (patients' breathing aera), Y=1.1 m (accompanying staff breathing aera) and Y=1.5 m (HCW's breathing area) during exhalation in three cases. In case A (without bed-side curtain), The highest CO_2 concentration in the patients' breathing area is 0.028, The average CO_2 mass score is 6.79×10^{-4}, the highest CO_2 concentration in the respiratory area of the escort is 0.011, the average CO_2 mass score is 6.97×10-4, the highest CO_2 concentration in the respiratory area of the medical staff is 0.0058, and the average CO_2 mass score is 6.63×10^{-4}. In case 2 (with bed-side curtain), The highest CO_2 mass fraction in the respiratory area of patients was 0.03, and the average CO_2 mass fraction was 6.57×10^{-4}. The highest CO_2 mass fraction in the respiratory area of accompanying staff was 0.013, and the average CO_2 mass fraction was 6.71×10^{-4}. The highest mass fraction of CO_2 in breathing zone of HCW was 0.0084, and the average mass fraction of CO_2 was 6.90×10^{-4}. In case 3, The highest CO_2 mass fraction in the respiratory area of patients was 0.031, and the average CO_2 mass fraction was 6.76×10-4. The highest CO_2 mass fraction in the respiratory area of accompanying staff was 0.012, and the average CO_2 mass fraction was 6.96×10^{-4}. The highest mass fraction of CO_2 in breathing zone of HCW was 0.0068, and the average mass fraction of CO_2 was 7.10×10^{-4}.

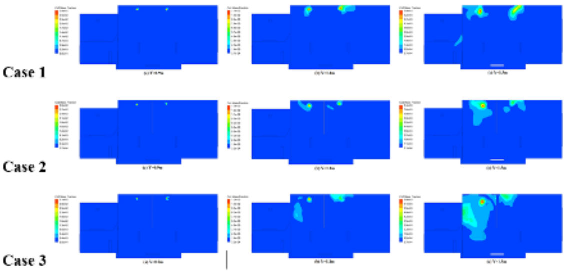

Fig.4. CO_2 distribution in the ward.

3.2 Droplet diffusion

The diffusion of exhale droplets and cough droplets after 50 seconds, 100 seconds, 150 seconds and 200 seconds is shown in Table 1 and Table 2. In Case 1, the DR of expiratory droplets and cough droplets between patients at 200 seconds are 11.43% and 2.28%, respectively. In Case 2, the DR of expiratory droplets and cough droplets between patients at 200 seconds are 8.57% and 0.94%. As shown in Fig. 5, 41,280 and 131,890 cough droplets of patient 1 and patient 2 trapped on the medical curtain, respectively, with a capture rate of 8.66%. The expiratory droplets of patient 1 and patient 2 fell on the medical curtain, respectively, with a capture rate of 1.43%. In Case 3, the trap rates during exhalation and cough were 10% and 1.48%, respectively. As shown in Fig. 6, 35,270 and 183,180 cough droplets of patient 1 and patient 2 fell on the medical curtain, respectively, with a trap rate of 10.92%. Patient 1 and patient 2 had 10 and 30 expiratory droplets on the medical curtain, respectively, with a trap rate of 3.81%.

Table 1. Diffusion of expiratory droplets.

Case	Time (s)	DR (%)	RR (%)	SR (%)
Case 1	50	22.27	0	77.73
	100	46.36	2.73	50.91
	150	61.36	8.64	30
	200	67.27	11.82	20.91
Case 2	50	26.36	0	73.64
	100	47.73	1.36	50.91
	150	64.55	5	30.45
	200	73.18	6.82	20
Case 3	50	38.18	0	61.82
	100	61.36	0	38.64
	150	76.36	0	23.64
	200	83.18	0.091	15.91

Table 2. Diffusion of coughing droplets.

Case	Time (s)	DR (%)	RR (%)	SR (%)
Case 1	50	78.26	1.18	20.56
	100	86.24	2.21	11.55
	150	90.43	3.06	6.51
	200	92.61	3.76	3.63
Case 2	50	90.08	0.34	9.58
	100	94.23	0.91	4.86
	150	96.16	1.29	2.55
	200	97.08	1.50	1.42
Case 3	50	71.43	0.30	28.27
	100	83.35	1.45	15.20
	150	89.10	2.81	8.09
	200	91.91	3.71	4.38

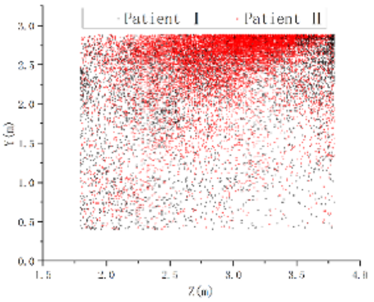

Fig.5. Deposition position of cough droplets on the medical curtain in Case 2.

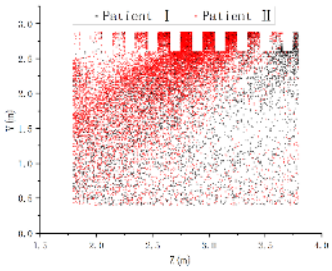

Fig.6. Deposition position of cough droplets on the medical curtain in Case 3.

3.3 Discussion

When exhaling and coughing, the droplets that fell on the patients and the beds were the least in Case 2, only 8.57% and 0.94%, respectively, because the complete medical curtain has completely blocked the direct cross propagation of drops in case 2. There is no block between the two beds in the case A, so the droplets produced by the patient 2 can follow the airflow to reach the patient 1and the bed1. The medical curtain in case 3 has a grille, so the droplets generated by the patient 2can follow the airflow reaches the surface of the patient 1and bed1 under gravity.

In Case 2 and Case 3, the deposition of cough droplets on the medical curtain is similar. The cough droplets are mainly deposited on the middle and upper part of the medical curtain, which is mainly affected by the cough airflow, and the cough airflow velocity is 10m/s, The momentum is large enough to bring the tiny cough droplets up to the ceiling. One part is trapped by the ceiling and the other part collides with each other. Under the influence of the indoor airflow, they move towards the medical curtain, and finally most of them are deposited on the medical curtain Of course, due to the large number of droplets produced per cough, about 106 droplets are produced per cough [9], and a large number of droplets are inevitably deposited on the edge of the medical curtain. And the droplets on the medical curtain mainly come from patient 2. This is because the indoor airflow flows from patient 2 to patient 1. When the airflow passes through the grilles on the upper part of the medical curtain, the droplets will be trapped.

4 Conclusions

This study predicts the comfort of the mankind and the diffusion of exhaled pollutants under the fan-coil unit (FCU) with fixed inlet and outlet of the independent fresh air system. The following conclusions can be drawn from the results of the numerical simulation:

•The recommended ventilation is in hospital is from top to bottom. However, due to the constraints of space layout and other factors, the return air outlet was installed on the ceiling of the two-bed ward in this study, the air distribution in the ward is up-supply up-return mode. Therefore, the pollutants exhaled by the patients are first dispersed in the ward and cannot be directly discharged outdoors. Therefore, HCW should take personal protection when entering the ward to avoid infection;

•The medical curtain can protect patient 1 from the infection of patient 2, and the protective effect is more obvious when the curtain has no grille. However, patient 2is relatively more likely to be infected by patient 1.

•Medical curtains may be contaminated by hazardous microorganisms, the problem can be overcome by impregnation of antibacterial substances onto curtain surfaces.

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