Prevention of surgical site infection under different ventilation systems in operating room environment

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HIGHLIGHTS
• The effectiveness of four different ventilation systems was compared in depth.
• Airflow and bacteria-carrying particles concentration were quantitatively analyzed.
• Vertical laminar airflow with high airflow rate could not achieve desired effect.
• Temperature-controlled airflow ventilation could guarantee air cleanliness.

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ABSTRACT
Biological particles in the operating room (OR) air environment can cause surgical site infections (SSIs). Various ventilation systems have been employed in ORs to ensure an ultraclean environment. However, the effect of different ventilation systems on the control of bacteria-carrying particles (BCPs) released from the surgical staff during surgery is unclear. In this study, the performance of four different ventilation systems (vertical laminar airflow ventilation (VLAF), horizontal laminar airflow ventilation (HLAF), differential vertical airflow ventilation (DVAF), and temperature-controlled airflow ventilation (TAF)) used in an OR was evaluated and compared based on the spatial BCP concentration. The airflow field in the OR was solved by the Renormalization Group (RNG) k-ε turbulence model, and the BCP phase was calculated by Lagrangian particle tracking (LPT) and the discrete random walk (DRW) model. It was found that the TAF system was the most effective ventilation system among the four ventilation systems for ensuring air cleanliness in the operating area. This study also indicated that air cleanliness in the operating area depended not only on the airflow rate of the ventilation system but also on the airflow distribution, which was greatly affected by obstacles such as surgical lamps and surgical staff.

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1 Introduction
Following the severe acute respiratory syndrome (SARS) and influenza H1N1 viral infections, the outbreak of corona virus disease 2019 (COVID-19) in China has once again drawn worldwide attention to infectious diseases. The process of biological particles such as viruses, bacteria, and fungi releasing and spreading into the air is one of the main transmission methods of infection (He et al., 2017). Therefore, a clean air environment is essential to prevent infection, particularly in the operating room (OR) where a patient’s wounds are exposed; if airborne bacteria enter the wound, surgical site infections (SSIs) can result. SSIs are the second most common cause of healthcare-associated infections (HAIs) in Europe and the United States (Allegrenzi et al., 2016). SSIs consider-
ably increase hospital stays, mortality rates and health care costs. On average, the length of a hospital stay can be increased by 9.7 days because of SSIs, and the cost of each additional stay is approximately $20,000 (Lissovoy et al., 2009). Mortality associated with SSIs can reach 3% (Awad, 2012). Relevant literature indicates that the amount of particles and bioaerosols in the air environment is positively related to the risk of infection (Lidwell et al., 1983; Humbal et al., 2018).

During surgery, the surgical team has been found to be the main source of contaminants such as bacteria (Hoffman et al., 2002). Bacteria are mainly attached to skin scales or granules shed by the surgical staff (Woods et al., 1986). The bacteria-carrying particles (BCPs) released by the surgical staff can contaminate the wound by deposition and can also indirectly contaminate the wound through contaminated instruments. Hansen et al. (2005) noted that the number of bacteria counted with colony-forming units (CFU) was related to particles larger than 5 μm. Memarzadeh and Manning (2002) suggested that the diameter of BCPs was approximately 10 μm. In addition, they also suggested that the diameter of infectious particles in the operating room (OR) ranged from 5 to 10 μm (Memarzadeh and Manning, 2003). Microorganisms associated with human disease and carryover prefer to adhere to particles with aerodynamic diameters ranging from 4 to 20 μm (Noble et al., 1963). The number of particles released by the human body is different and can be related to many factors, such as the bearing, movement and posture of a person. Noble (1975) indicated that a person can produce approximately 1000 BCPs per minute through shedding skin fragments under moderate physical activity. Hughes and Anderson (1999) found that a person can shed 10,000 skin fragments, 10% of which carry microorganisms, while participating in sports activities. Rui et al. (2008) detected the shedding of 200 CFU/min for each person’s upper body and 400 CFU/min for the lower body. In the work of Sadrizadeh, the number of BCPs released by a surgical staff was 4 CFU/s (Sadrizadeh et al., 2014a). Tammelin et al. (2012, 2013) showed that different garments may cause different amounts of BCPs to be released, which had a large effect on the BCP concentration in the clean room.

A ventilation system and indoor air distribution not only maintains indoor temperature and humidity and improves the thermal comfort of the occupants but also provides a clean environment for occupants (Reponen et al., 1989; Gao et al., 2020). There is a strong correlation between the ventilation system and the concentration of air contamination, and an effective ventilation system can significantly reduce the incidence of infection (Lidwell et al., 1983; Skaaret, 1986; Stacey and Humphreys, 2002). The most commonly used ventilation in an operating room is laminar airflow ventilation. In laminar airflow ventilation, a large area air supply diffuser provides a uniform flow of clean air flow through the surgical area to remove microbial contaminants from the surgical area. In reducing airborne bacteria, many studies have shown that laminar airflow ventilation is more effective than turbulent mixed airflow ventilation, which is based on the principle of dilution (Diab-Elschahawi et al., 2011; Hirsch et al., 2012; Fischer et al., 2015). Laminar airflow ventilation includes vertical laminar airflow (VLAF) ventilation and horizontal laminar airflow (HLAF) ventilation. In VLAF ventilation, the airflow passes through a high-efficiency air filter on the ceiling and then flows along parallel streamlines at high velocity and low turbulence through areas where the surgical field and sterile objects are exposed. Although the flow pattern is not an exact laminar airflow, the highly powered airflow will continue to carry away the BCPs produced by the surgical staff. Many experimental studies and numerical simulations have demonstrated that the VLAF system effectively protects the operating area in ORs against high concentrations of BCPs based on good design parameters (Memarzadeh and Manning, 2002; Chow and Yang, 2004; Diab-Elschahawi et al., 2011; Oguz et al., 2017). However, the performance of VLAF is easily affected by many factors, such as air supply velocity, the obstruction of surgical lamps, the movement of surgical staff, and the thermal plume of the surgical staff (Chow and Yang, 2003, 2005; Chow et al., 2006; Chow and Wang, 2012; Cao et al., 2018). These factors will result in the disruption of laminar flow, forming eddies and reducing the VLAF cleaning efficiency. HLAF is a good alternative to VLAF because it avoids the obstruction of surgical lamps and surgical staff. In HLAF ventilation, the airflow passes through a high-efficiency air filter on the sidewall and then passes through the operating area to achieve air cleaning in the operating area (Ahl et al., 1995; Friberg and Friberg, 2005; Liu et al., 2009; Sadrizadeh et al., 2014b). However, this ventilation system has strict requirements for ventilation design parameters and the layout of the operating room.

On the basis of the abovementioned laminar airflow ventilation with a large amount of airflow through the operation area, differential vertical airflow (DVAF) ventilation is used in modern ORs. A DVAF system consists of 25 filters that ensure unidirectional airflow in the operating area. Three central filters above the operating table supply air at the highest airflow velocity, while six filters near them use a moderate airflow velocity. The remaining 16 filters use the lowest airflow velocity. Romano et al. (2015) experimentally and numerically demonstrated that a DVAF system was effective in reducing the BCP concentration above an operating table based on good design parameters. Moreover, a new OR ventilation system called temperature-controlled airflow (TAF) ventilation was studied (Alsved et al., 2018). The air supply diffusers were located at the center and surrounding area of the ceiling. A uniform airflow was sent from the central diffusers, and the temperature was 1.5°C lower than the airflow supplied from the surrounding diffusers.
Alsved et al. (2018) compared the differences in BCP concentrations in critical areas of ORs under turbulent mixing airflow, laminar airflow, and TAF at a certain design parameter. It was found that the laminar airflow ventilation and the TAF ventilation systems were able to maintain a clean indoor environment, while the turbulent mixing ventilation system could not. In addition, Wang et al. (2018) simulated and compared the above three systems using computational fluid dynamics (CFD). The results showed that the TAF ventilation system was reliable and effective.

Previous studies evaluating the cleanliness efficiency of VLAF, HLAF, DVAF and TAF in ORs with the same simplified supply diffuser conditions have been very limited and not comprehensive. Therefore, the purpose of this study was to compare the airflow patterns and BCP distributions in the operating areas of ORs under four different ventilation systems and to determine the most effective ventilation system in ORs with special obstacles and high cleanliness requirements. CFD was employed to control the different working conditions and obtained relatively accurate results, which were verified by the corresponding experimental data. In addition, this study aimed to increase the knowledge of each ventilation system and provide guidance for the design and usage of ventilation systems in ORs.

2 Case study

The model description of the ORs is shown in Fig. 1. The dimensions of the OR were 7 m (length) × 6 m (width) × 3 m (height). Four ventilation systems (VLAF, HLAF, DVAF and TAF) were considered in the OR. The airflow in the OR was discharged by five exhausts, which were located at the three sidewalls. The size of exhaust 3 was 1.2 m × 0.5 m, and the bottom edge was 0.15 m away from the floor. The size of the remaining exhausts, whose bottom edges were 0.2 m away from the floor, was 1 m × 0.4 m.

VLAF was applied to the OR, as shown in Fig. 1(a). The supply diffuser was composed of 25 terminal high-
efficiency particulate filters, each of which had a net area of 0.56 m × 0.56 m, and the total size of the supply diffuser was 2.8 m × 2.8 m. The airflow rate of the system was 10080 m³/h, which corresponds to an air change per hour (ACH) of 80. Clean air was supplied to the OR at the same velocity by each high-efficiency particulate filter and then exhausted from the air exhausts. The HLAf for the OR is shown in Fig. 1(b). The size of the supply diffuser was the same as that of the VLAF, but the air supply direction was different. The airflow rate was 7560 m³/h (i.e., 60 ACH).

The OR with DVAF is shown in Fig. 1(c). The supply diffuser of the system was the same size as the first two, but the air supply velocity was different. Sixteen high-efficiency particulate filters on the outside of the supply diffuser provided clean air at a low velocity, while the middle six high-efficiency particulate filters delivered air at a medium velocity. Three internal high-efficiency particulate filters provided air at a high velocity. The airflow rate of the system is 6300 m³/h (i.e., 50 ACH), with a high velocity of 0.41 m/s, a medium velocity of 0.29 m/s, and a low velocity of 0.16 m/s. Fig. 1(d) displays the TAF. The supply diffuser in the center of the OR consists of 9 high-efficiency particulate filters with a size of 1.68 m × 1.68 m. There were 8 supply diffusers located on both sides of the ceiling of the OR. Each supply diffuser had a size of 0.56 m × 0.56 m. The cooler air was sent to the operating area from the central supply diffuser, and the warmer air was sent to the periphery of the operating area by the supply diffuser around the ceiling. The system had the same airflow rate as the DVAF, and each high-efficiency filter in the system had the same airflow velocity. The major characteristics of the four ventilation systems are shown in Table 1.

The operating table was located in the center of the OR. The size of the bottom support was 0.4 m (length) × 0.4 m (width) × 0.6 m (height), and the dimensions of the table were 2 m (length) × 0.6 m (width) × 0.2 m (thickness). There were two instrument tables on each side of the operating table. The dimensions of instrument table 1 were 1.2 m × 0.45 m × 0.9 m (height), and the dimensions of instrument table 2 were 0.8 m × 0.45 m × 0.9 m (height). Two cylindrical surgical lamps had a diameter of 0.6 m and a thickness of 0.1 m. Each surgical lamp emitted a heat flux of 300 W/m² from its downward surface. There were two pieces of medical equipment in the OR, and their sizes were 0.5 m × 0.3 m × 1.5 m (height) and 0.5 m × 0.3 m × 1.2 m (height). Each piece of medical equipment emitted a heat flux of 250 W/m² from the exposed surfaces. There were eight surgical staff members and one patient in the OR. Seven surgical staff members were around the operating table for patient treatment, and another staff member was the circulating nurse standing in the surrounding area of the OR. For each scenario, four surgical staff members were in bending postures, while the other surgical staff members were in upright postures. The surgical staff were 0.4 m × 0.2 m × 1.7 m (height), and each surgical staff emitted a heat power of 100 W from their exposed surfaces (Chow and Wang, 2012). The BCPs were released from the surfaces of each surgical staff member. Each person had a BCP release rate of 200 CFU/min for the upper body and 400 CFU/min for the lower part of the body. This was based on the data of Rui et al. (2008). The BCPs had an aerodynamic diameter of 12 μm and a density of 1000 kg/m³ (Sadrizadeh et al., 2016). Since the activity of the patient was limited to lying on the operating table and his or her body was well covered, the heat and BCPs released by the patient were not considered. The simulation parameters of the OR are shown in Table 2.

### Table 1: Major characteristics of the four ventilation systems

| Ventilation system | Supply diffuser locations | Airflow velocity | Airflow temperature |
|------------------|--------------------------|-----------------|-------------------|
| VLAF             | Middle of the ceiling    | Uniform         | Uniform           |
| HLAf             | Middle of the sidewall   | Uniform         | Uniform           |
| DVAF             | Middle of the ceiling    | Internal supply air velocity (high), Middle supply air velocity (medium) | Uniform |
| TAF              | Middle of the ceiling    | Uniform         | Middle supply air temperature (high) |
|                  | Periphery of the ceiling |                 | Periphery supply air temperature (low) |

### 3 Mathematical model

#### 3.1 Airflow phase model

In the indoor airflow turbulent simulation, the RANS (Reynolds-averaged Navier-Stokes) method was applied in this study. The Renormalization Group (RNG) k-ε turbulence model in the RANS method has been widely used in indoor airflow simulations and has been proven to be effective (Chen, 1995). The general form of the governing equation can be written as:

\[
\frac{\partial (\rho \Phi)}{\partial t} + \nabla \cdot (\rho \Phi \mathbf{V}) = \nabla \cdot (\Gamma \nabla \Phi) + S_\Phi, \tag{1}
\]

where \( \rho \) is the air density, \( \mathbf{V} \) is the air velocity vector, \( \Phi \) represents each of the three velocity components, \( \Gamma \) is the effective diffusion coefficient of \( \Phi \) and \( S_\Phi \) is the source term.

For the boundary conditions used in the simulation,
velocity quantities at the wall were obtained under a no-slip condition. All air inlets were set as velocity inlets with a turbulent intensity of 5%. All exhausts were set as pressure outlet boundaries, with pressure at +25 Pa and a turbulent intensity of 5% (Chow and Wang, 2012). The air supply temperature of the VLAF, HLAF and DVAF systems was taken as 20°C. The center air supply temperature of the TAF system was 18.5°C, and the surrounding air supply temperature was 20°C (Alsved et al., 2018). An enhanced wall function was used to treat the turbulence characteristics of the near wall region. The exposed surfaces of the surgical staff and medical equipment and the downward surface of surgical lamps were set as heat flow boundary conditions. The heat was uniformly released from the surfaces. The other surfaces were set as adiabatic boundary conditions. The Boussinesq model was applied by considering the thermal buoyancy effect, and the radiation exchange between the surfaces and all walls was processed by the discrete ordinate (DO) radiation model. All surfaces and walls with opaque gray radiation sources had an emissivity of 0.95 for radiative heat transfer (Chow and Wang, 2012).

\[ \frac{d \rho u \rho}{dt} = \frac{18 \mu C_D R e}{\rho \rho_p d_p^2} (u_i - u_p) + g_i \left( 1 + \frac{\rho}{\rho_p} \right) F_{ai}, \]  

where \( u_i \) and \( u_p \) are the instantaneous velocity of fluid and particles, respectively, \( \mu \) is the molecular viscosity of fluid, \( \rho \) and \( \rho_p \) are the density of fluid and particles, respectively, \( d_p \) is the particle diameter, \( R e \) is the particle Reynolds number, \( C_D \) is the drag coefficient, \( g_i \) is the gravitational acceleration in the \( i \) direction, and \( F_{ai} \) is the additional force exerted on the particles.

The dispersion of the particles was simulated using the DRW model due to the effect of eddy diffusion. The DRW model assumed that the fluctuating velocity was characterized by a Gaussian distributed random velocity fluctuation. Due to the stochastic nature of the DRW model, it was necessary to calculate a sufficient number of trajectories to achieve statistical convergence. Through analysis, the concentration of the particles was numerically stable at approximately \( 1.9 \times 10^6 \) trajectories.

The simulation procedure first calculated the turbulent airflow field, then added the discrete phase particles and finally solved the coupled flow. When the particles arrived at the exhausts of the OR, the particles escaped, that is, the exhausts were set to the escape boundary condition. Due to the strong adhesion of the rigid surfaces, the particles were captured when they hit the rigid surfaces without sufficient energy to bounce (Hinds, 1999); thus, the surfaces were set to a trapped boundary condition.

Three different grids were tested for grid independence. The grids include a coarse grid (2359512 cells), a medium grid (3341771 cells), and a fine grid (4231448 cells). The VLAF system was tested, and there were no significant

### Table 2  Simulation parameters of the operating room

| Objects                                    | Surface area (m²) | Heat flux (W) | Inflow velocity (m/s) |
|--------------------------------------------|-------------------|---------------|-----------------------|
| Staff                                      | 2.12              | 100           |                       |
| Operating table (upper surface)            | 1.2               |               |                       |
| Instrument table 1 (upper surface)         | 0.54              |               |                       |
| Instrument table 2 (upper surface)         | 0.36              |               |                       |
| Medical equipment 1                        | 1.98              | 250           |                       |
| Medical equipment 2                        | 1.59              | 250           |                       |
| Lamp (lower surface)                       | 0.283             | 300           |                       |
| Exhaust 1,2,4,5                            | 0.4               |               |                       |
| Exhaust 3                                  | 0.6               |               |                       |
| Supply (VLAF)                              | 7.84              |               | 0.357                 |
| Supply (HLAF)                              | 7.84              |               | 0.268                 |
| Supply (DVAF)                              | 0.9408 (high speed) | 0.41        |                       |
|                                            | 1.8816 (medium speed) | 0.29      |                       |
|                                            | 5.0176 (low speed) | 0.16         |                       |
| Supply (TAF)                               | 2.8224 (central)  | 0.328         |                       |
|                                            | 0.3136 × 8 (surrounding) | 0.328   |                       |
differences in the airflow fields between the three grids. Taking into account the cost of calculation and the accuracy of the calculation results, the medium grid was adopted. For the convergence of numerical calculation, the residual value and stability of the variables were observed, and the imbalance error of total mass and energy through the inlet and exhausts was less than 1%. In addition, two exhausts were defined as monitoring surfaces to check for variable stability.

LPT was performed by the discrete phase model (DPM) in FLUENT. The spatial CFU concentration was used as a measure of BCPs, and the BCP concentration in space was calculated by using the DPM Concentration, which is the total concentration of the particles in all phases in a cell. For the comparison among systems, 18 sample points were taken above the centerlines of the operating table and instrument tables (the locations of the sample points are shown in Fig. 2). Sample points 2 and 5 are located at 10 cm and 30 cm, respectively, above the centers of the operating table and instrument tables. The distances of the sample points at the same height above the operating table, instrument table 1 and instrument table 2 are 67 cm, 40 cm, and 27 cm, respectively. Then, the BCP concentration of each sample point under the four ventilation systems was compared to evaluate the effect of different ventilation systems on the control of BCPs.

3.3 Mathematical model validation

To validate the above mathematical model of airflow, we used the experimental data of airflow distribution on the full-scale ISO Class-5 cleanroom in a hospital by Yang et al. (2015). At the same time, the experimental data by Chen et al. (2006) were used to validate the LPT method and DRW model.

3.3.1 Hospital-based ISO Class-5 cleanroom

The cleanroom consisted of a patient care area and a bathroom. The layout of the cleanroom and location of each measurement point are shown in Fig. 3(a). The cleanroom dimensions were 3.3 m (X) × 2.5 m (Y) × 3.1 m (Z), of which the dimensions of the bathroom were 1.5 m (X) × 2.5 m (Y) × 1.4 m (Z). In the patient care area, the clean air treated by the high-efficiency filter was sent into the room through the supply diffuser on the ceiling and was discharged from the air exhausts on both sides of the lower part of the room. The dimensions of the supply diffuser were 3.1 m (X) × 1.5 m (Z) plus 1.6 m (X) × 1.3 m (Z), and the dimensions of the air exhausts were 0.3 m (Y) × 0.75 m (Z). The airflow rate was 6950 m³/h. In the bathroom, a part of the airflow was sent from the ceiling supply diffuser, and the remaining airflow was infiltrated from the door gap. Finally, the airflow was discharged from the air exhausts on the wall. To ensure that the toilet pollutants do not enter the patient care area, the pressure of the patient care area was higher than that of the bathroom. The airflow rate of the door gap was 100 m³/h, and the door gap size was 0.02 m (Y) × 0.8 m (Z). The dimensions of the ceiling supply diffuser and the air exhaust in the bathroom were 0.5 m (X) × 0.5 m (Z) and 1.8 m (Y) × 0.2 m (Z), respectively. The airflow rates of
the supply and exhaust were 325 m³/h and 425 m³/h, respectively. The standard k-ε model, the RNG k-ε model, and the realizable k-ε model were used to simulate the airflow distribution. The simulation results were compared with the measured data.

The results of the simulation and measurement data are shown in Fig. 3(b). The comparison results showed that all three models were in good agreement with the measurement data. In addition, the RNG k-ε model was slightly more accurate than the other two models. Therefore, the RNG k-ε model was used to carry out this study.

3.3.2 LPT and DRW model validation

The data used for validating the LPT and DRW model were measured in a chamber with dimensions of 0.8 m (X) × 0.4 m (Y) × 0.4 m (Z), as shown in Fig. 4(a). The sizes of the air inlet and outlet in the chamber were both 0.04 m × 0.04 m, and their center positions were X = 0 m, Y = 0.2 m, Z = 0.36 m and X = 0.8 m, Y = 0.2 m, Z = 0.04 m. The air supply velocity was 0.225 m/s. The particles were mixed into the supply airflow at a steady rate by a solid particle disperser. The diameter and density of the particles were 10 μm and 1400 kg/m³, respectively. The same model as the test was built, and a numerical study was conducted under the same conditions of air supply and particle release as the test.

The LPT and DRW models were applied to simulate the particle dispersion. Through calculation and comparison, the concentration of the particles becomes numerically stable at approximately 16000 trajectories. The experimental and simulated values of the particle normalized concentration at different X positions in the center plane are shown in Fig. 4(b). It can be seen that the trend of the particle normalized concentration with the height in the simulation results was in good agreement with the test results, and most of the simulation results were within the error range of the test results. Therefore, the LPT and DRW models were successfully validated.

4 Results and discussion

4.1 Effect of designed airflow rate on air and BCP concentration distribution

The airflow field and BCP concentration distribution of the four ventilation systems at the designed airflow rate were
simulated and analyzed. Figure 5(a) shows the velocity vector and BCP concentration distribution for different planes in the OR using VLAF. The same velocity airflow was supplied from the ceiling diffusers and accelerated by gravity. Due to the obstruction of the surgical lamps, the airflow direction changed during the descent, and an eddy was formed beneath the surgical lamps. Under the leading action of the airflow, a large eddy was formed at a position of approximately 10 cm above the patient. The BCP concentration in the eddy zone was high, and the main source of BCPs was the surgical staff in the bent position on the right side of the operating table and not the surgical staff under the surgical lamp. This was due to a close airflow formed in front of the left surgical staff that washed away the BCPs. There was also a high BCP concentration above instrument table 1 because instrument table 1 was located behind the surgical staff. An airflow flushing effect was formed on the surface of instrument table 2; therefore, the BCP concentration above the surface of instrument table 2 was low.

The velocity vector and BCP concentration distribution of different planes in the OR under HLAF are shown in Fig. 5(b). The same velocity airflow was sent out by the air supply diffusers on the wall, but the airflow did not maintain a horizontal direction in the height direction due to the influence of gravity. The upper airflow was blown downwards toward the operating table, forming a high-speed airflow layer of approximately 10 cm above the
The high-speed airflow layer greatly reduces the BCP concentration. However, an accumulation area of BCPs was formed above the high-speed airflow layer due to the low air velocity and the existence of eddies. On the surface of instrument tables 1 and 2, the horizontal airflow provided a washing effect, so there was low BCP concentration on the surface. The short-distance horizontal laminar airflow could provide excellent protection for patients and instruments in the operating area at a limited height but could not work for higher elevations of the OR.

Similar to VLAF, the airflow changed direction under DVAF. The velocity vector and BCP concentration distribution for different planes in the OR under DVAF are shown in Fig. 5(c). It can be seen that the airflow at different velocities was sent out by the ceiling air supply diffusers, and the airflow velocity was accelerated under the action of gravity. Similar to VLAF, the airflow changed direction.

Fig. 5 Velocity vector and BCP concentration distribution for (a) VLAF, (b) HLAF, (c) DVAF, and (d) TAF.
after being obstructed by the surgical lamp, squeezing the adjacent airflow and resulting in an eddy under the surgical light. However, above the operating table, high-speed airflow predominated. Although there was a small eddy in front of the bending staff, the airflow above the patient was vertically downward. Therefore, the concentration of BCPs above the patient was very low. Because of the difference in airflow between the inside and the outside, it can be seen that a good airflow displacement effect was formed above the surface of instrument Tables 1 and 2, so the air was very clean.

The velocity vector and BCP concentration distribution of different planes in the OR under TAF are shown in Fig. 5(d). The colder airflow was sent out by the center ceiling air supply diffusers, and the airflow was affected by only one surgical lamp during the descent. Warmer airflow was supplied from the surrounding diffusers. Two small eddies were formed under the surgical lamp due to the effect of the central and peripheral airflow. Due to the limited size of the eddies, the effect on the airflow above the patient was not significant. Thus, similar to the DVAF system, although there was a small eddy in front of the bending surgical staff, vertically downward airflow was formed over the patient. The concentration of BCPs above the patient was very low. There were no eddies on the surfaces of instrument tables 1 and 2, so there was low BCP concentration above instrument tables 1 and 2.

To facilitate a quantitative analysis and comparison of the capacity of BCP contamination controls for different systems in the operating areas, BCP concentrations at each sample point in the OR utilizing different ventilation systems were analyzed and are shown in Fig. 6. There was a significant difference in BCP concentration at each sample point between different systems. It can be seen that the DVAF system and the TAF system achieve high air cleanliness above the operating table. The BCP concentrations of the six points were less than 10 CFU/m³, and some points were less than 0.01 CFU/m³. The results also showed that the spatial distributions of BCP concentrations above the operating table for the VLAF and HLAF systems were significantly different. For the VLAF system, the intermediate concentration was high, and the concentration on both sides was low. For the HLAF system, the concentrations at the first three points were all low, with two of them below the recommended limit, but the BCP concentration of the last three points reached 200 CFU/m³ or more.

The air cleanliness of instrument table 1 of the DVAF system was the best, and the BCP concentration was less than 0.01 CFU/m³. The air cleanliness above instrument table 1 of the TAF system achieved the recommended limit value. The air cleanliness of instrument table 1 of the VLAF and HLAF systems did not meet the demand, which was quite different from the first two systems.

For the contamination situation above instrument table 2, the TAF system performed better, and the concentration of only one point exceeded the recommended limit value. The BCP concentrations at points 1, 2 and 4 in the DVAF system were less than 10 CFU/m³, while the concentrations at other points exceeded the recommended limit value. The concentration values of the first three points above instrument table 2 in the HLAF system were low, while the concentration of the last three points was much higher. It was apparent that the surface of instrument table 2 had good airflow replacement. The concentration of points except points 1 and 3 above instrument table 2 of the VLAF system exceeded the recommended limit.

4.2 Effect of different ACHs on air and BCP concentration distribution

To further evaluate the efficiency of the four ventilation systems, five different ACHs of 40, 50, 60, 70 and 80 were used. The supply air velocity was changed to obtain different ACHs.

For the VLAF system, as shown in Fig. 7(a), there was a significant difference in the trend and magnitude of change between each point with increasing ACH. The range of BCP concentrations at the point above instrument table 1 was the largest, and the range of BCP concentrations at the point above instrument table 2 was the smallest. When the ACH was 70, the BCP concentration at each point above the operating table and instrument table 2 was much higher.

![Fig. 6](image-url) The BCP concentration at each sample point (10 CFU/m³ was the recommended limit for clean operating areas).
than 10 CFU/m³, and the concentration of each point above instrument table 1 was less than 10 CFU/m³. In other ventilation ACHs, the BCP concentration at each point varied greatly. It can be seen that the air cleanliness in the operating area under the VLAF system cannot be evaluated only by the ACHs. This was because obstructions such as surgical lamps and surgical staff destroy the vertical downward laminar airflow, resulting in many eddies and a failure of the washing effect.

For the HLAF system, as shown in Fig. 7(b). Above the
operating table, when the ACH was less than 60, the BCP concentration of each point was greater than 10 CFU/m³. When the ACH was equal to 60, the BCP concentration at points 1, 2 and 3 was low, but there was a high BCP concentration at points 4, 5 and 6. When the ACH was greater than 60, the BCP concentration at each point was within 12 CFU/m³. This indicated that there was a significant spatial difference in the airborne BCP concentration above the operating table among different ACHs. When the ACH was 60, an air flow layer was formed above the patient, and the air flow layer provided a good washing action, so the BCP concentration was low. However, due to the low airflow velocity above the air layer, the BCP concentration was high. When the air change rate was less than 60, the oblique downward air flow was too low to reach above the patient. This resulted in a high BCP concentration. When the air change rate was greater than 60, a large portion of the obliquely downward air flow reached the patient, forming a very thick air layer, so the BCP concentration at the six points above the patient was very low. The BCP concentration above instrument table 1 was high because instrument table 1 was located on the side of the surgical staff, and the BCPs emitted by the surgical staff pass through instrument table 1 during the process of being discharged from the air outlet. In addition to instrument table 1, the concentration above instrument table 2 decreased as the ACH increased.

For the DVAF system, as shown in Fig. 7(c), above the operating table, the BCP concentration at points 1, 3, 4 and 6 at each ACH was less than 10 CFU/m³, but the BCP concentration at points 2 and 5 increased as the ACH increased. This could be caused by the eddy above the patient. Above instrument table 1, the BCP concentration was highest when the ACH was 60. The BCP concentration at each point above instrument table 2 increased as the ACH increased. This is because the airflow sent out from the air diffusers above instrument table 2 was affected by the eddy under the operating lamp.

For the TAF system, as shown in Fig. 7(d), the BCP concentration above the operating table and instrument tables was very low, not exceeding 50 CFU/m³. This is mainly because the airflow was affected by only one surgical lamp, and the airflow above the patient formed a good laminar flow. In addition, due to the temperature gradient of the central and surrounding supply air, the cold airflow fell vertically, and the air in the surrounding area had a good dilution effect. It can be seen that when the ACH was changed, the performance of the TAF system was less affected.

4.3 Effect of different ventilation systems on removal efficiency of human emission particles

The removal fraction of BCPs in different systems under different ACHs is shown in Fig. 8. The removal fraction can be defined as the ratio of the amount of indoor BCP discharge to the total amount produced. It can be seen that the greater airflow rate in the OR cannot achieve the better effect of removing indoor BCPs. The VLAF and TAF systems reached maximum removal fractions at an ACH of 60, which were 78.9% and 69.5%, respectively. The HLAF and DVAF systems reached maximum removal fractions at an ACH of 70, which were 83.7% and 73.8%, respectively. The greater the proportion of BCPs removed, the fewer particles deposited on the surface of the interior. When the ACHs were 40 and 50, the removal fraction of VLAF was the largest, indicating that the BCP removal effect was the best of the four ventilation systems under low ACHs. However, the removal fraction of HLAFT was the highest when the ACHs were 60, 70 and 80, indicating that at high ACHs, the BCP removal effect was the best of the four ventilation systems.

![Fig. 8 Removal fraction of BCPs from the human body by different ventilation systems.](image-url)
5 Conclusions

In this study, an RNG $k$-$

\$\epsilon$ turbulence model and an LPT/DRW model were used to quantitatively calculate the airflow distribution and the dispersion of BCPs in four different ventilation systems: vertical laminar airflow ventilation (VLAF), horizontal laminar airflow ventilation (HLAF), differential vertical airflow ventilation (DVAF), and temperature-controlled airflow ventilation (TAF). An analysis and comparison of the performances of the four ventilation systems were carried out based on the BCP concentration of the 18 points. At each operating table or instrument table, three sample points were selected at a height of 10 cm above the table, and another three corresponding points at 30 cm above the table were also selected for analysis.

Due to obstructions such as surgical lamps and surgical staff, the VLAF system failed to provide a vertical downward laminar airflow. This resulted in a high BCP concentration in the operating area, and this situation was not improved as the airflow rate increased. In the HLAF system, when the airflow rate was greater than a certain value, an ultraclean environment was obtained near the patient and the surfaces of the instrument tables. Once the airflow rate decreased below this value, the air cleanliness deteriorated. When the DVAF system was at a lower airflow rate, the operating area achieved an ultraclean environment. However, the BCP concentration exceeds the recommended limit as the airflow rate increases. Because of the lower BCP concentration in the operating area under different airflow rates, the performance of the TAF system was the best among the four ventilation systems.

The results also showed that the BCP concentrations in the operating area under the four ventilation systems were significantly different. In addition, the degree of air cleanliness in the operating area depended not only on the airflow rate of the ventilation system but also on the airflow distribution. The airflow distribution was greatly affected by the surgical lamps and surgical staff. Hence, the position of the surgical lamps should be considered during the design and use of an operating room.

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