Study of air infection risk in the operating theatre

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ABSTRACT
The ventilation system of a hospital operating theatre is designed to provide a comfortable and healthy environment for the patient and the surgical team. A healthy environment can be achieved by minimizing the risk of contamination through an appropriate filtration and air distribution scheme. The design and construction of operating theatres in Hong Kong, including the upgrading of the older ones, are based on the UK Health Building Notes and Health Technical Memoranda. Observations and field measurements in a case study found that the airflow and some design features did not comply with the specified requirements. CFD analysis was used to examine the significance.

INDEX TERMS
Air movement; Operating theatre; Ventilation

INTRODUCTION

In the operating theatre of a hospital, the means of ventilation that assists in health protection are room air distribution, pressurization, filtration and exchange. Infection control practices vary from place to place, depending on the cultural background, scientific research, financial constraints and for historical reasons. The major source of bioaerosols in the operating theatre is from the surgical team. When the surgical team is working near the operating table, everyone is subject to airborne infection risk, in particular the patient because of his weakness and the wound being exposed.

Low-velocity (laminar) airflow tends to minimize the spread of airborne contaminants and directs them towards the exhaust outlets. Consequently, the air-path infection risk can be reduced. Established design guidelines give comprehensive information about the ventilation requirements, as in the case of ultra-clean ventilation (UCV) design. Nevertheless, in many operating theatres, the air-conditioning provisions and actual ventilation performance do not exactly comply with the up-to-date engineering standards. Different forms of terminal devices, different diffuser discharge velocities, different levels of room pressurization, omission of partial wall and so on, do exist.

In Hong Kong, the engineering practice basically follows the UK Health Technical Memorandum (HTM) developed by the National Health Service Estates (1994). According to HTM 2025, the down flow of supply air should cover a minimum projected area of 2.8 m × 2.8 m. This floor area or zone is meant to be large enough to accommodate the operating site and instruments. The zone boundary enclosing the supply air diffuser should be provided with either a partial wall or a full wall (which, respectively, terminate at 2 or 1 m from the finished floor level). The discharge velocity at the diffuser is crucial to ensure that sufficient air reaches the operating plane (the level at which the patient lies on the operating table). HTM quotes this as 0.38 m/s at a minimum. The velocity at the operating plane should provide a washing effect such that the relatively large particles can be removed before they settle onto the surfaces. With a minimum of 0.2 m/s, any contaminant in air can be readily removed by this flow of air. An objective is to achieve levels of less than 10 BCP/m^3 (BCP

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standards for bacteria carrying particles) when conventional cotton clothing is used, so that the use of occlusive clothing or body exhaust system result in counts of less than 1 BCP/m^3.

About one-third of the operating rooms in a medium-size hospital in Hong Kong follow the UCV design. However, even in these rooms the air distribution and design features may not strictly adhere to the up-to-date HTM requirements. One main difficulty lies in the renovation work at the older hospitals, where the site constraint leads to the deviations. Table 1 shows the measured results of a sample of operating theatres from seven hospitals in Hong Kong. All were either newly constructed or renovated within the last 10 years. It can be seen that the supply air diffusers in the majority of these rooms are smaller than the current standard, and their discharge velocities are only within 42–82% of the specified 0.38 m/s.

Table 1 Survey of supply air diffuser in existing operating theatres

Hospital	Year of completion	Size of supply air diffuser (m × m)	Measured discharge velocity (m/s)
I	1993	2.4 × 2.4	0.24
		2.4 × 2.4	0.24
II	1996	2.4 × 2.4	0.27
III	1996	2.4 × 2.4	0.26
		2.4 × 2.4	0.22
		2.4 × 2.4	0.25
IV	1996	2.4 × 2.4	0.16
V	1999	3.0 × 3.0	0.28
		3.0 × 3.0	0.31
VI	2000	2.4 × 2.4	0.16
		3.0 × 3.0	0.17
VII	2000	3.0 × 3.0	0.18
		2.4 × 1.2	0.24

A CASE STUDY

One operating theatre in a private hospital was selected for investigation. The selected operating room was one of the four comprising the operating suite, which had been renovated 10 years ago. The four operating rooms were served by one central air-conditioning unit that ran 24 h a day.

Figure 1 shows an isometric view of a model of this operating theatre. The dimensions of the room were approximately 6.25 m × 5.0 m. The height of the false ceiling was 2.3 m. The perforated ceiling diffuser was recessed from the false ceiling surface by 0.4 m and covers a zone of 3.2 m × 2.4 m. A structural beam right across the room divides the perforated ceiling and the air plenum into two equal portions. It is at this beam position that the main and satellite operating lamps are hung. And because of this site restriction, there is no provision of a partial or full wall at the supply air diffuser. The room is maintained at a positive pressure. The room air discharges to the corridor through a low-level transfer grill as well as through the entrance door gaps. Pressure stabilizer is not provided.

Field measurements were taken to record the air velocities at the supply diffuser and the transfer grill. The measurements were made through the use of a hot-wire anemometer. In the direct measurement, the diffuser outlet surface was divided into a test grid consisting of 0.3 m × 0.3 m elemental squares. Face velocity readings were taken at 100 mm beneath the diffuser surface. The average discharge velocity was found to be 0.16 m/s, which was only 42% of the HTM specification.

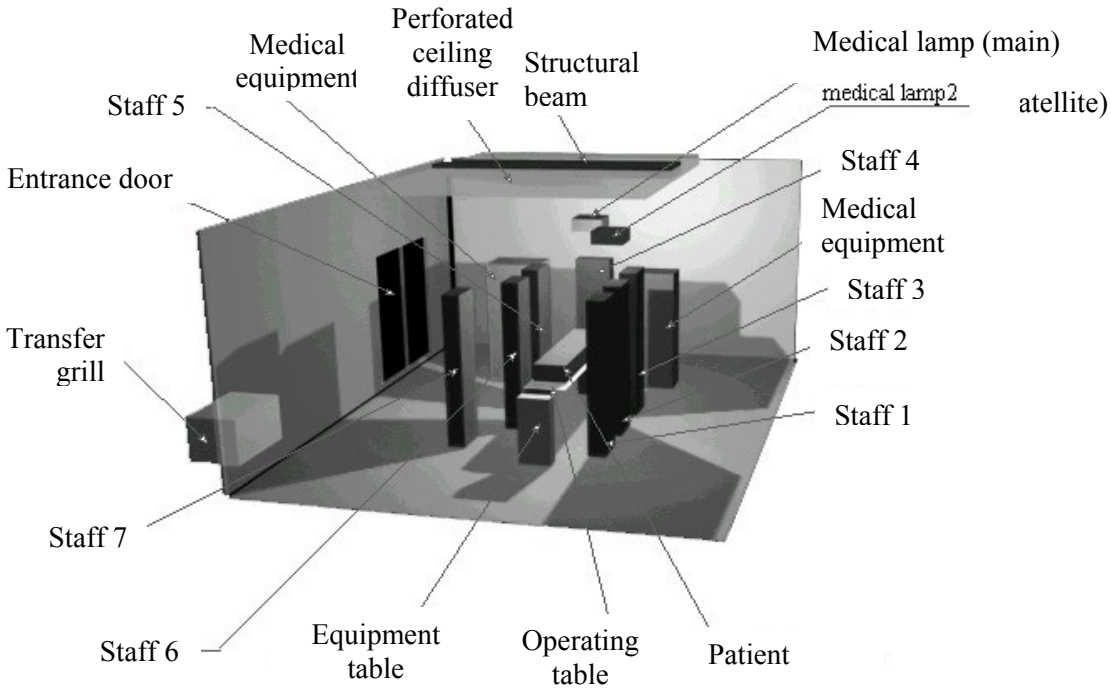

Figure 1 An isometric model of the operation theatre under study.

The software CFX4.3 (AEA, 1999) and the standard k–ε model were selected as the computational tools of the airflow and contaminant dispersion. The appropriateness of applying the software in vertical displacement type ventilation had been validated; its use in studying operating theatre airflow had been reported (Chow *et al*., 2000; Liu and Moser, 2002). In our CFD model, the locations of the surgical staff, medical lamps and equipment relative to the operating table were made with reference to the DIN 4799 specification (1990). A non-uniform 3D rectangular grid of 77 × 50 × 45 was used. Non-slip velocity and adiabatic boundary conditions were used for the solid surfaces, with heat fluxes and airborne pollutant sources added where appropriate. The people, medical equipment and lamps were treated as solid blocks. Uniform heat flux was assumed on all exposed surfaces of the first two, and provided only on the downward surface of the medical lamps. The release of the microbiological particles from each surgical staff was assumed to be at a rate of 100 BCP/min. Taking the fact that the surgical team is moving around, and the bacteria from the human body can be released from any part of the body surface (especially when the body is wet or when the staff is bending towards the patient), it was taken that the bacteria were released uniformly throughout the surface facing the operating table. The ceiling diffuser and transfer grill positions were set as inlet and outlet velocity boundaries. The door gaps were set as mass flow boundaries.

Simulations were executed under different operating conditions. It was found that the medical lamp positions, which can be adjusted by the surgical staff, have a remarkable effect on the airflow and the distribution of microbiological particles. The results of the following two cases are, therefore, selected for discussion:

Case 1: the position of the main lamp is directly above the head of the patient and the satellite lamp is at one side of the operating table.

Case 2: the main lamp and the satellite lamps are positioned at opposite sides of the operating table.

RESULTS

Temperature Stratification

The air temperature in the operating theatre can be adjusted up or down by the team members through a thermostat, which controls the supply air temperature level to the suite. The simulation results show that for both Case 1 and Case 2, the uniformity in temperature distribution can be reasonably maintained inside the room. The temperature range at the occupant zone is not more than 3°C. The vertical temperature stratification satisfies the ISO (1990) specification. There is no obvious difference in the level of thermal comfort between the two cases of medical lamp positions.

Airflow Pattern

The velocity distribution in Figure 2(a) and (b) shows the downflow pattern at the 'micro-environment' zone. Reverse flows occur at uppermost part of the room and up to the recessed space under the beam. The main difference between Case 1 and Case 2 is that opposite flow directions were found above the central position of the operating table. While a downward flow occurs in Case 1, a low-velocity upward flow pattern is observed in Case 2. The latter is probably because of the flow obstruction caused by the two medical lamps. However, the air stream passing across the patient comes from the ceiling diffuser for both cases, despite the flow recirculation under the beam. This indicates that the washing effect is still effective in this non-standard operating theatre. The upper corners of the room are the areas of flow stagnation.

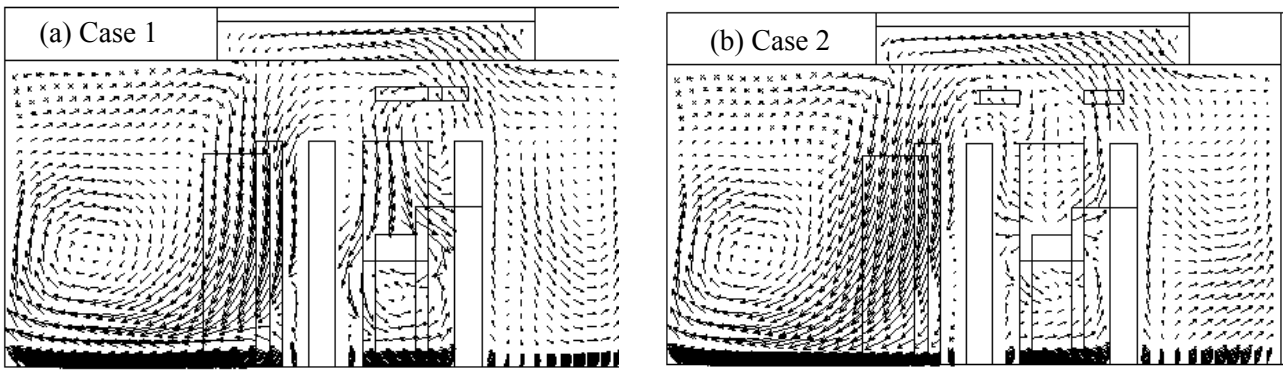

Figure 2 Velocity distribution.

Health Risk to Patient

In the simulation, the total amount of airborne bacteria released from the surgical team was 700 BCP/min. The results show that the bacteria concentration at the critical zone is below 10 BCP/m^3, and generally less than 7 BCP/m^3 at the patient's body. The contours can be found in Figure 3. The range is from 2.14 to 14.5 BCP/m^3 (6.75 BCP/m^3 on average) for Case 1, and from 0.3 to 7.05 BCP/m^3 (3.61 BCP/m^3 on average) for Case 2. Overall, Case 2 is better than Case 1. The concentration levels are not far from the HTM requirements on UCV design. This shows that the ventilation provision in the operating theatre is still effective for a number of general operations. For Case 1, a higher concentration can be seen at the head of the patient. Here the contribution is mainly from the surgical staff labelled 'Staff 4'in Figure 1. Inside the room, higher microbiological particle concentrations occur at regions outside the critical zone.

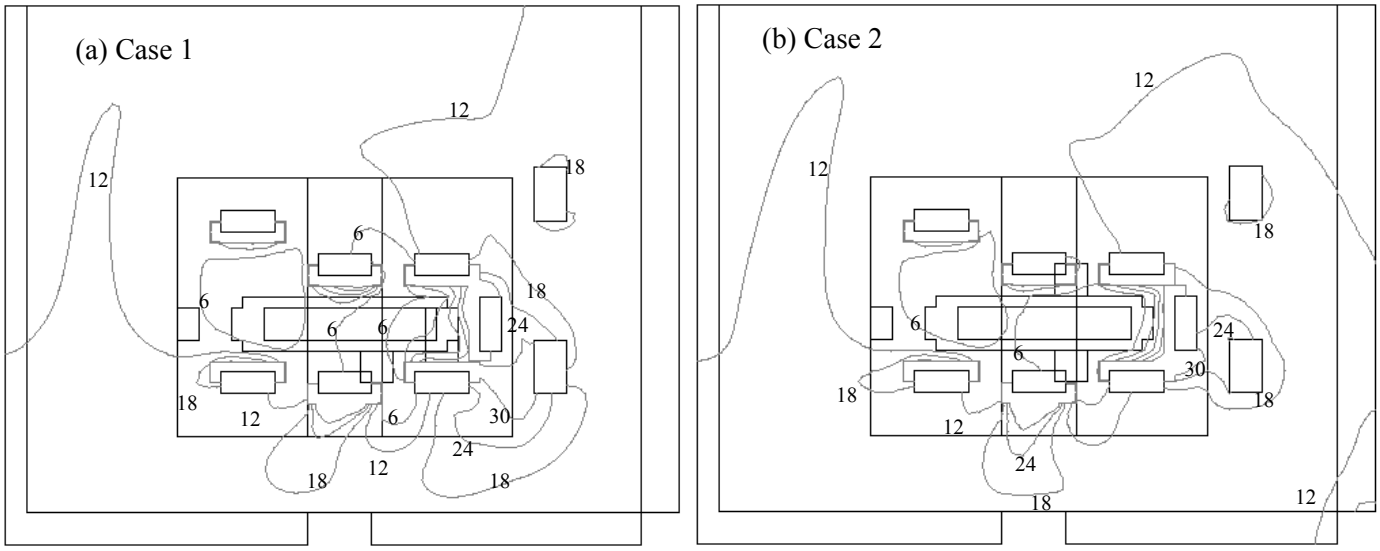

Figure 3 Airborne bacteria concentration in the non-standard operating theatre at the operating plane as a result of bacteria released from the surgical team.

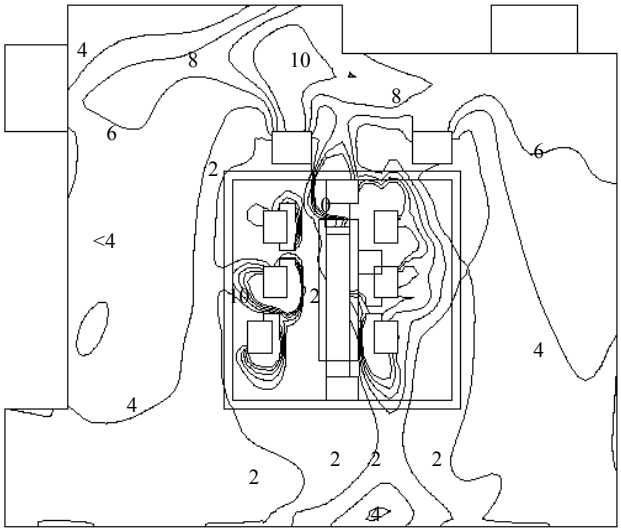

Figure 4 Airborne bacteria concentration in a standard operating theatre at the operating plane as a reference condition.

As a reference case, Figure 4 shows the simulation result based on one operating theatre in a new hospital in Hong Kong. The UCV design is in full compliance with the HTM requirements. The lamp positions were similar to Case 1. It can be seen that the concentration at the patient's body is from 2 to 10 BCP/m^3, with the maximum at the head position and decreasing gradually towards the feet. Inside the room, the concentration at this operating plane level is below 10 BCP/m^3, and is lower than 4 BCP/m^3 in most positions. Within the sterilized zone, bacteria concentration at the right-hand side is higher (i.e. greater than 10 BCP/m^3 at the positions of Staffs 1, 2 and 3). This is because, here, the satellite lamp blocked a portion of the supply air from reaching the operating plane. This reference case

confirmed that the airflow condition in the non-standard operation theatre under investigation is slightly inferior but still acceptable.

CONCLUSIONS

The ventilation systems in the older hospitals very often do not match the up-to-date professional standards. Careful planning of renovation work in the operating theatre is very important. The application of CFD can help to understand the adequacy and appropriateness of the ventilation design.

In the case study, the simulation results indicated that the level of thermal comfort in the entire room is satisfactory. However, the airflow scheme at the operation area has been affected, though the washing effect at the operation table can still be maintained. It is also found that the positions of the two medical lamps have a remarkable effect on the air-borne particulate dispersion. Hence, the medical staff should be cautioned about the possibility of developing a high airborne bacteria concentration region because of the unfavourable medical lamp positions.

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