Experimental Study on the Surgical Microenvironment in an Operating Room with Mixing Ventilation under Positive and Negative Pressure

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ABSTRACT

Due to the outbreak of Covid-19, negative pressure operating room (NPOR) are strongly recommended to be applied to prevent spreading virus from infected patients to adjacent rooms during surgery procedures. However, there have been few experimental studies on the effect of OR pressure difference on the surgical microenvironment. This study aims to experimentally investigate the airflow distribution in the surgical microenvironment in an OR under different pressure conditions. All measurements were performed in a full-scale laboratory, which has an area of 62 m^2, and a mixing ventilation. The air velocity and temperature in the surgical microenvironment of a lying patient were measured under positive pressure of 5 Pa, 10 Pa, 15 Pa and negative pressure of -5 Pa, -10 Pa and -15 Pa. The effect of heat generated by operating lamps was also considered. The results show that the airflow distribution around the surgical wound is dominated by thermal plume from the patient under the condition of both positive and negative pressure. In other areas of the surgical microenvironment, regardless the pressure difference conditions, the room airflow distribution by ventilation system is the dominant factor on surgical microenvironment. Variations in differential pressure can affect the temperature distribution around the surgical site, with a smaller differential pressure producing a slightly larger vertical temperature gradient.

INTRODUCTION

Surgical site infections (SSI) are infections that occur at or near surgical incision within 30 days of operation or 1 year (Mangram et al. (1999)). It is the 3rd commonly reported nosocomial infection accounting for 10 to 40% of all nosocomial infections (Singh, Singla, and Chaudhary 2014; Salkind and Rao 2011). Globally, SSI rates have been found to be from 2.5% to 41.9% (Singh, Singla, and Chaudhary 2014; Mawalla et al. 2011; Suetens et al. 2013). The improvements in the prophylactic and therapeutic antibiotic treatments of surgical patients have been achieved to reduce SSIs. The implementation of high-efficiency particulate air filters (HEPA) has also been proved to be an effective way to reduce the SSIs by supplying clean air to the OR (Cao, Storås, et al. 2018; Friberg 1998). Furthermore, some ventilation guidelines for ORs also require the application of a positive pressure relative to corridors or anaesthesia room to suppress the invasion of exogenous microorganisms (Control and Prevention (2003)).

However, since the SARS outbreak in 2003, some researchers have considered it necessary to set up special NPORs to treat those patients. The effect of a NPOR is to prevent infected patients from leaking airborne viruses through doors and windows and infecting other healthy people. Many computational fluid dynamic (CFD) studies have proved NPOR is a feasible solution (Chow et al. 2006a; Chow et al. 2006b). Since the outbreak of the COV-19 in 2019, NPOR has been proposed again to help address the need for safe surgery for patients with Cov-19 (Chen et al. 2020; Li et al. 2020; Luo and Zhong 2020; Wong et al. 2020; Al-Benna 2021; Arora et al. 2020; Ing et al. 2020). However, there are few experimental studies providing evidence on whether the conversion to negative pressure has any effect on OR performance.

A recent study defines the small zone close to the operating site as the surgical microenvironment; the rest of the operating zone may be defined as the surgical macroenvironment (Aganovic et al. (2017)). This study revealed that indoor airflow patterns and the use of various surgical facilities play an important role in determining air cleanliness in the surgical microenvironment. Other studies have revealed a close relationship between the surgical microenvironment and the patient's and physician's thermal plumes. It is suggested that the airflow distribution in the surgical microenvironment may be influenced by many factors. This study aims to investigate the airflow distribution in the surgical microenvironment in the positive and

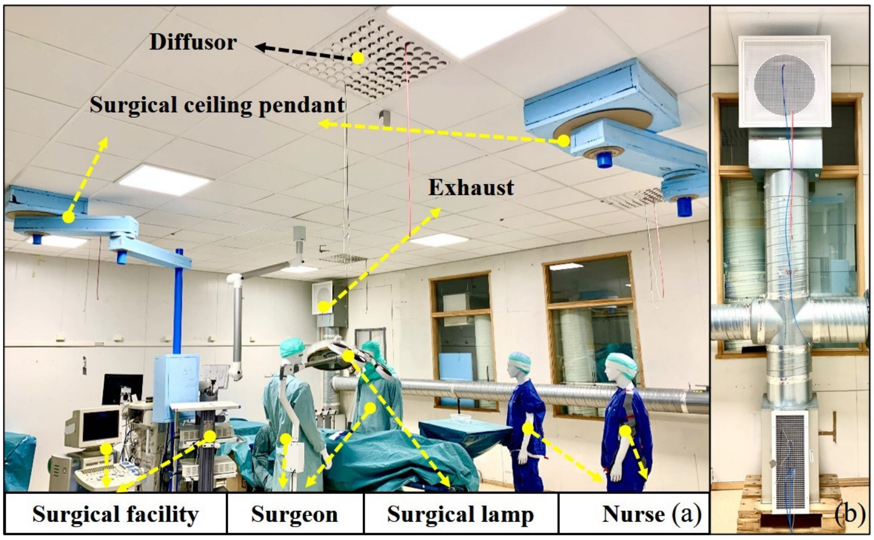

Figure 1. The Experiment set up (a) Layout of the OR, (b) The exhaust

negative pressure OR to identify the dominant of the surgical microenvironment.

METHODS

The OR lab

All measurements for this study are made in the operating room OR full-scale laboratory in the Department of Energy and Process Engineering, Norwegian University of Science and Technology (NTNU). The dimension of the laboratory is 8.73 m × 7.05 m × 3.25 m (length × width × height), and the volume of the laboratory is 200 m^3. The OR lab has similar layout and design with an actual OR equipped with a mixing ventilation system in St. Olavs Hospital (Cao, Nilssen, et al. (2019)). Figure 1 shows the layout and the design of exhausts in the lab.

Mixing Ventilation system

The OR lab is equipped with a mixing ventilation system with four diffusers (0.55 m× 0.55 m) and four lower-level air-exhaust outlets (0.175 m × 0.575 m), four higher level air-exhaust outlets (0.55 m × 0.55 m), as shown in Figure 1(b). Each lower exhaust grill is connected to a 0.6 m × 0.2 m × 0.315 m plenum box and each upper exhaust is connected to a 0.315 m × 0.4 m plenum box. The plenum box is equipped with a balancing damper and pressure outlets so that the airflow rate could be measured and controlled. A DPM model TT470 S (accuracy of ±2 Pa) was used for pressure measurements in the plenum boxes attached to the exhaust grills and air diffusers, which is converted to airflow rates. The measuring uncertainty with this method is 5%. The distribution of exhausted air between the higher and lower exhaust grills for each of the exhaust modules is approximately 1/3 and 2/3 respectively. The position of diffusers and exhausts are shown in Figure 2.

Experimental setup

The indoor air temperature and air change rate have a great influence on the thermal plume of the human body and the surgical microenvironment (Feng et al. 2020; Zhang et al. 2020). As many standards recommend a minimum temperature of 20 °C in the OR and minimum air change rate of 20 air changes per hour (ACH), so 20 °C and 20 ACH were chosen as the test condition in the study. The supply air temperature was 19.1 to 19.3 °C. The calorific value of all heat sources in the lab is shown in Table 1. According to ASHRAE standard (American Society of Heating and Engineers (2017)), the heat generated by a standing human at light labour is about 1.2-1.6 met, of which 1 met is 58.2 W/s·m^2. The surface area of the human body is about 1.8 m^2, so the calorific value of the human body between 126 W and 168 W is reasonable. The heat generation of the manikin used in this experiment is all within this range, and the skin surface area of the surgeon is larger than that of the nurses, so the heat generation is slightly higher than the nurses.

Table 1. Heat generation of equipment in the lab

Equipment	Heat generation
Operating lamp 1	111.5 W
Operating lamp 2	140.0 W
Head surgeon	166.8 W
Assistant surgeon	167.7 W
Assistant nurse	156.5 W
Distribution nurse	153.7 W

Measurement condition

This measurement focused on the surgical microenvironment. Two horizontal planes at the height of 1.2 m and 1.3 m were measured in the surgical microenvironment which is shown in Figure 3. Each plane was 2 m long and 0.5 m wide, the same size as the operating table, and located 0.05 m and 0.15 m above the patient's head. Measurement points were

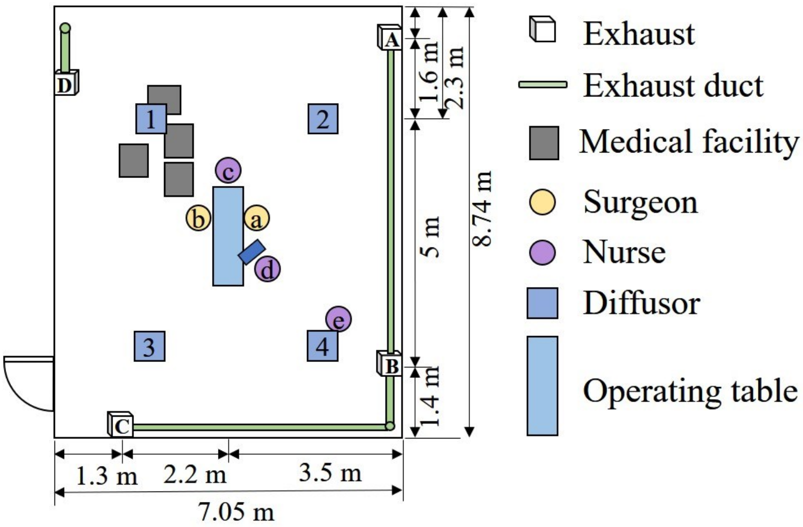

Figure 2. Layout of OR lab

divided by a transverse spacing of 0.1 m and longitudinal spacing of 0.2 m, then 11 × 6 = 66 is the total number of measurement points in this study. The AirDistSys5000 enables air temperature and low air-speed measurements at several points in spaces, as shown in Figure 4, and records the air turbulence intensity at each point. In this device, thermoanemometer transducers are equipped with a probe to track the velocity (accuracy of ±0.02 m/s) and temperature (accuracy of ±0.2 °C). This instrument supports simultaneous measurement of up to eight measurement points. In this study, six probes were used to simultaneously measure six points on the width of the operating table, with a distance of 0.1 m between each probe. After one measurement, move them 0.2 m along the long side of the operating table and repeat 11 times and then finish a measurement of a plane.

Table 2. Pressure difference of the OR room and ambient environment in six cases

Case	Pressure difference (Pa)
1	-15
2	-10
3	-5
4	5
5	10
6	15

Referring to the previous research on NPOR (Chow et al. 2006a; Chow et al. 2006b), we selected three kinds of negative pressure values, namely -5 Pa, -10 Pa and -15 Pa, and used three corresponding positive pressure 5 Pa, 10 Pa and 15 Pa for comparison. Therefore, six conditions of pressure differences are designed to be the cases in this study shown in Table 2. In order to ensure the same airflow rate, the supply airflow rate of different cases is the same, which is 3995 $m3{=}h$. The different negative pressure differences can be achieved by adjusting the exhaust airflow rate which are, from Case 1 to Case 6, 4546 m^3/h, 4382m^3/h, 4130 m^3/h, 3860 m^3/h, 3607 m^3/h and 3487 m^3/h, respectively.

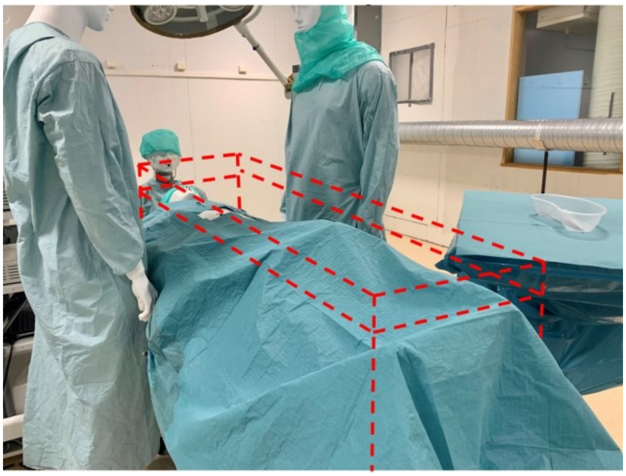

Figure 3. Measurement surfaces

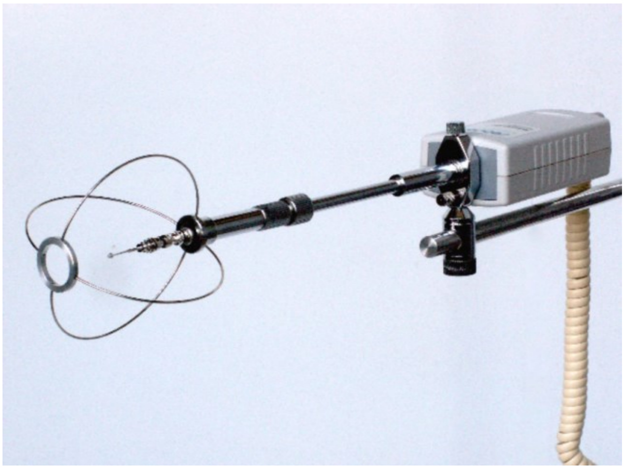

Figure 4. AirDistSys5000

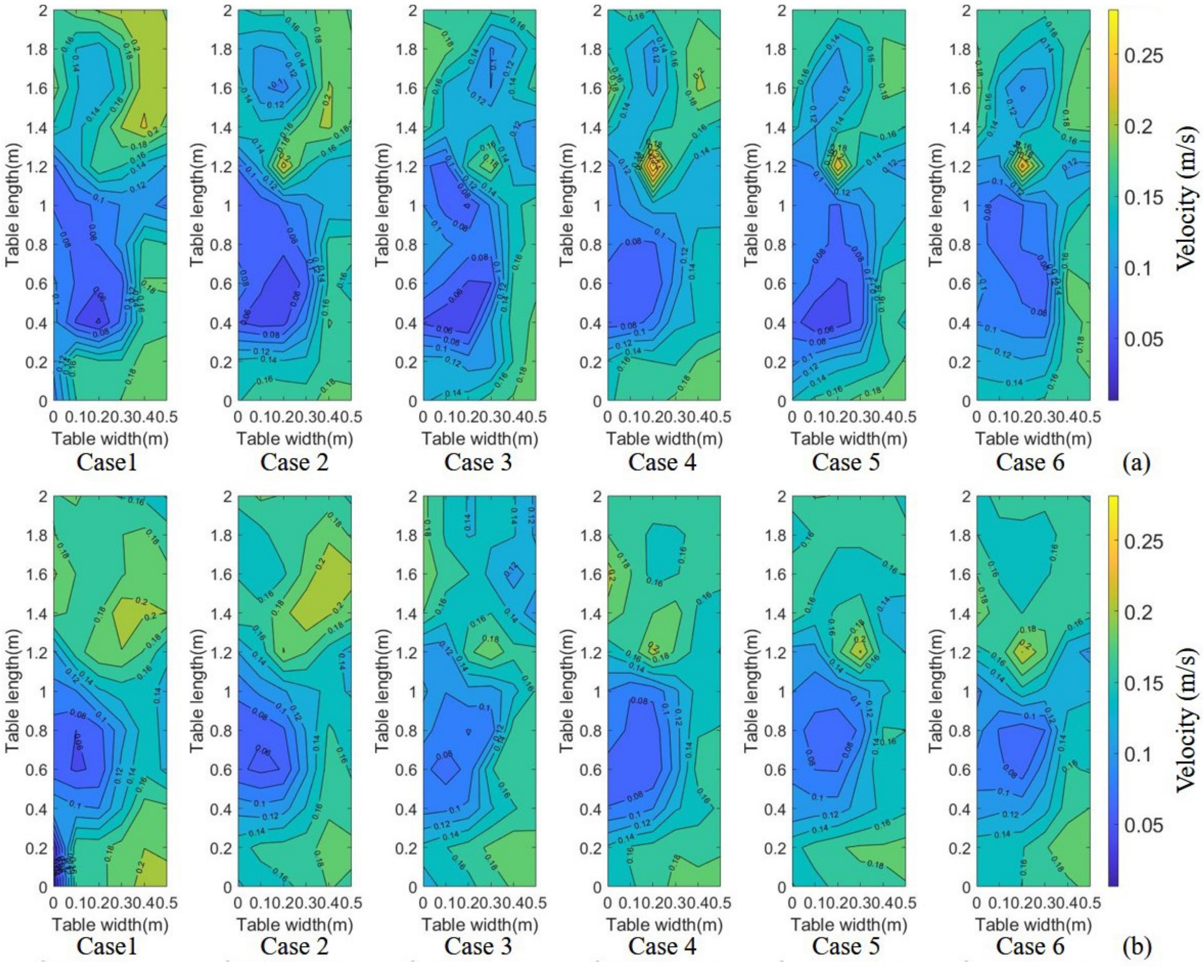

Figure 5. Results of the velocity distribution at two heights from the floor (a) 1.2 m (b) 1.3 m

RESULTS AND DISCUSSION

Velocity

In this study, the air velocity, air temperature, and turbulent intensity of airflow were measured in the surgical microenvironment every 2 seconds for 3 minutes. At each measurement point there are 90 data, and the average of those values was used for each point. The Contourf function in MATLAB is used to present these measured results. The velocity distribution

results of Case 1-6 are shown in Figure 5 in which (a) shows the results for a plane with a height of 1.2 m and (b) shows the results for a height of 1.3 m. The results show the effect of the thermal plume originating from the patient's surface due to the radiation heat transfer from the operating lamp. Another common feature in all cases is that there is a low-velocity zone above the left side of the head and above the left leg, where the airflow velocity is very low, in some cases less than 0.08 m/s. The results for a 1.3-m high plane corresponds to the results for the 1.2-m high plane, but with a lower velocity. They have a similar velocity distribution, and the velocity of the 1.3 m-high plane turns out to be about 0.02 m/s less than that of the 1.2 m-high plane. The pressure difference makes some differences in the velocity distribution. Some regions are more sensitive to pressure changes than others and exhibit different distribution characteristics. For the surgical site, under the condition of positive pressure (Case 4-Case 6), the thermal plume in the upper space dominates the airflow distribution in this area, and its velocity is much higher than that of the surrounding area. This phenomenon is not obvious at negative pressure, and even at -15 Pa the centre of the plume has shifted to other regions. On the contrary, the velocity of the airflow above the right side of the head is higher in the negative pressure condition and lower in the positive pressure condition. While the other regions were not sensitive to pressure, both the velocity and the distribution characteristics were similar in all cases.

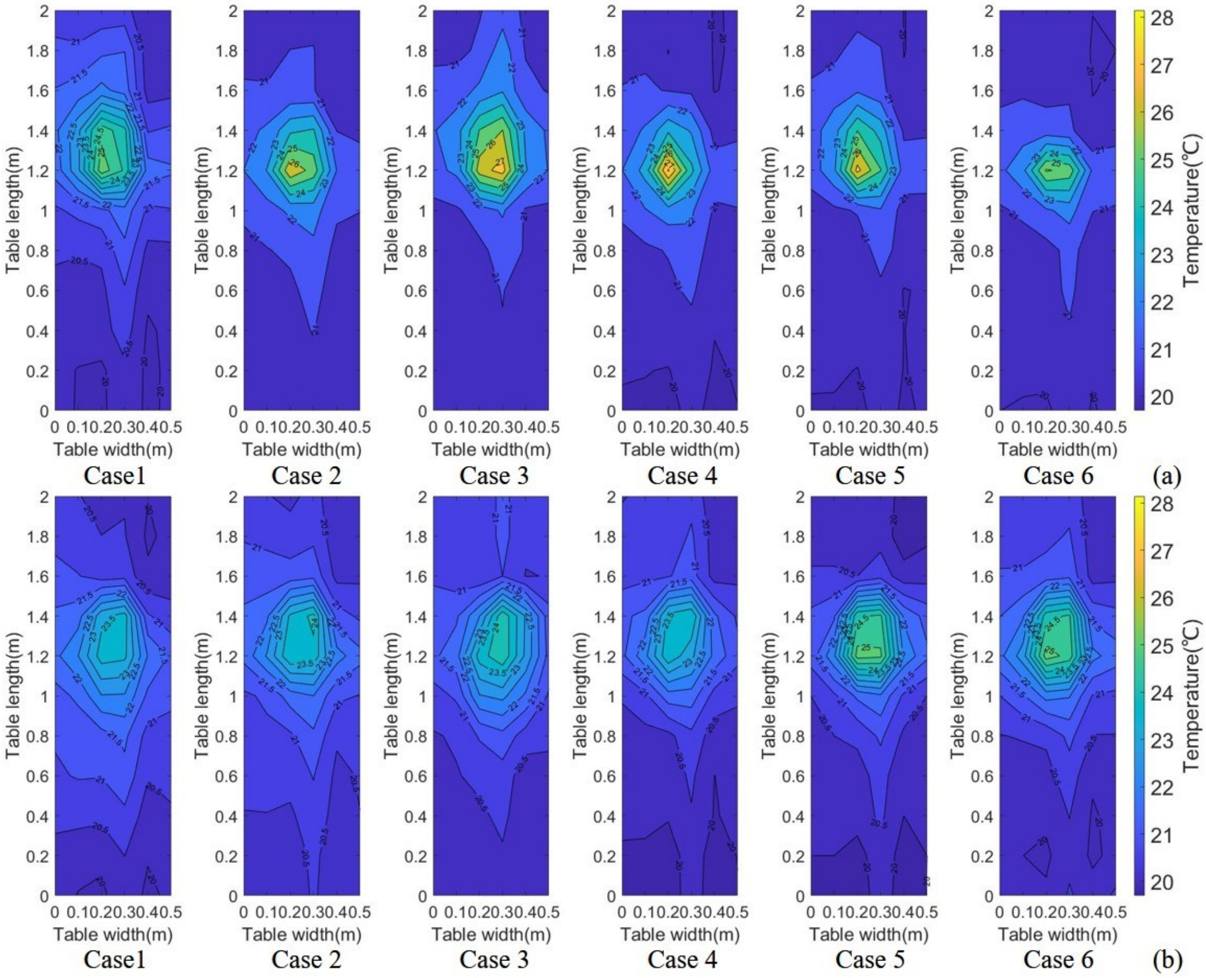

Figure 6. Results of the temperature distribution at two heights from the floor (a) 1.2 m (b) 1.3 m

However, although there are different phenomena between different cases, these differences do not show regular characteristic. So, it cannot be attributed to the difference of pressure difference. For one thing, the experiment was done over a few days, the weather condition was not exactly the same between these days. Different weather conditions will affect the air parameters outside the OR laboratory. For example, the change of outdoor temperature would lead to different wall temperatures in the OR laboratory. In addition, this experiment did not consider the change of air humidity in the laboratory. These factors need to be carefully examined in future studies.

Temperature

Figure 6 shows the temperature distribution of Case 1-Case 6, in which (a) shows the results of the plane at height of 1.2 m and (b) shows the results of the plane at the height of 1.3 m. The overall maximum temperature, which all appeared above the surgical site, ranging from 25 °C to 28 °C in the plane of 1.2 m, and 23.5-25.5 °C in the plane of 1.3 m. Since the error of measurement of indoor temperature is within 0.2 °C, the maximum temperature of the 1.3m-high plane is 1.5-2.5 °C lower than the maximum temperature of the 1.2 m-high plane.

From the temperature results of the 1.2 m-high plane, whether positive or negative pressure, the smaller the pressure difference, the higher the maximum temperature. When the pressure difference is -15 Pa, the maximum temperature in the plane is the smallest, which is 25 °C. The maximum temperature is around 26 °C under the pressure difference of -10 Pa and 15 Pa. when it comes to the pressure difference of -5 Pa and 10 Pa, the maximum temperature is around 27 °C, while this figure rises to 28 °C under the pressure difference is 5 Pa.

Comparing the results from two planes, the difference of maximum temperature between two heights is increasing with the decreasing of the absolute value of pressure difference. In the Case 1 and Case 6, the temperature difference between two heights is 1-1.5 °C, while this figure is 2 °C in the Case 2 and Case 5 and reaches to 3°C in Case 3 and Case 4. This value represents the temperature gradient in the vertical direction. The results show that the temperature gradient is only affected by the absolute value of pressure difference, and the positive and negative

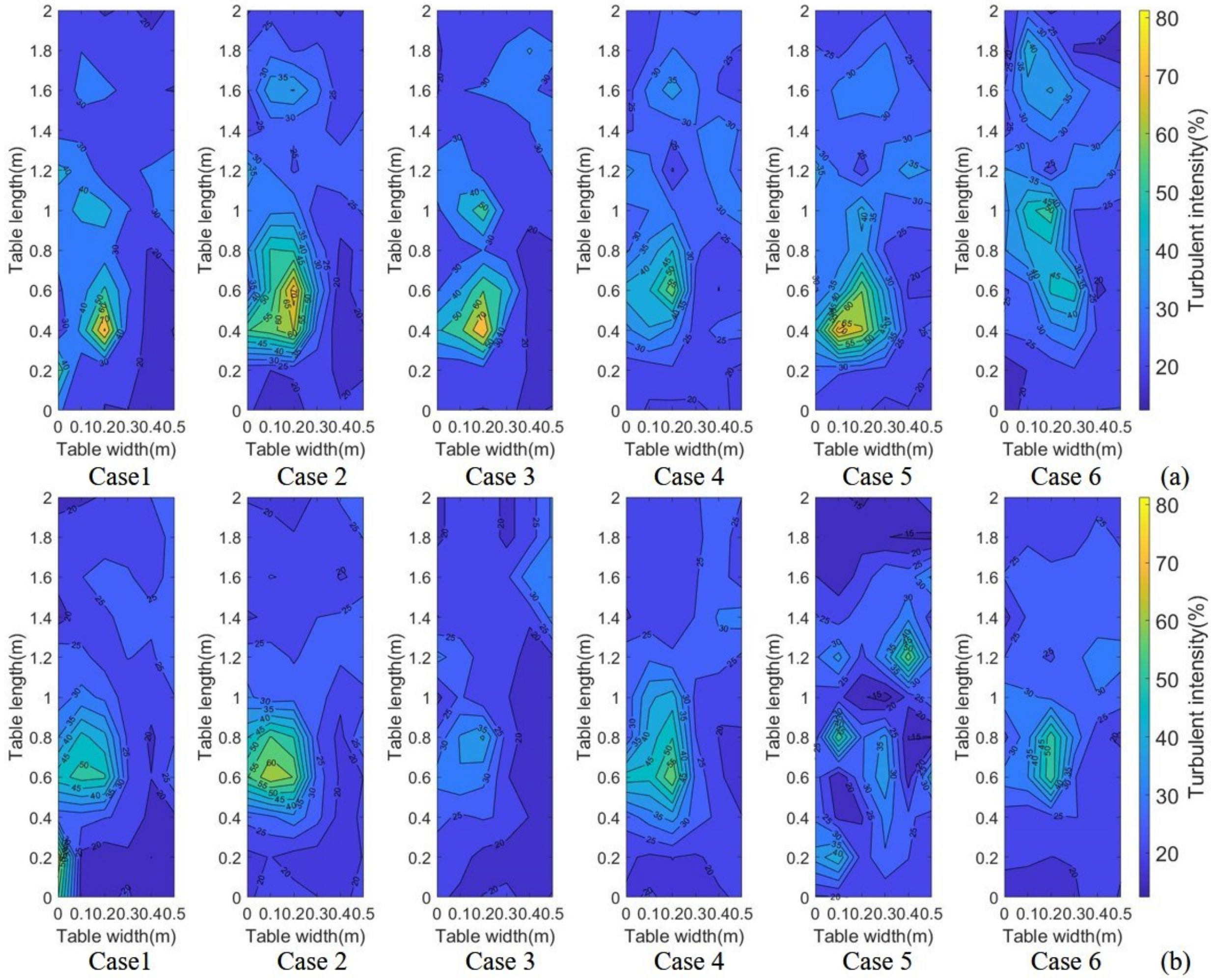

Figure 7. Results of the turbulent intensity distribution at two heights from the floor (a) 1.2 m (b) 1.3 m

pressure have little effect on it. It is worth noting that, in Case 1, there is an obvious low temperature zone on the right side of the head, which corresponds to the high-speed zone of the velocity result, indicating that the ventilation flow plays a very important role in this area.

Turbulent intensity

Figure 7 shows the turbulent distribution result at

two heights, (a) is 1.2 m (b) is 1.3 m. Turbulence intensity is defined as follows,

$$Tu = e/v \tag{1}$$

In which, e is the standard error of the velocity(m/s), v is the mean air velocity. Turbulence intensity is a quantity that characterizes the development intensity of turbulence.

As can be seen in Figure 7, the turbulence intensity varies between 15%-81%. The turbulence intensity in the 1.2 m plane is higher than that in the 1.3 m plane. In all the cases, the Peak value occurred on the upper left side of the leg, except Case 6, which appeared near the wound. This is due to the low average speed on the left side of the leg, less than 0.1 m/s. The maximum values were all above 70%, except for Case 4 and Case 6, which were 56% and 52%, respectively. In the case of negative pressure, the turbulence intensity of the 1.3 m-high plane is slightly lower than that of the 1.2 m-high plane, but they have similar distribution characteristics. However, under the condition of positive pressure, the results of the plane with a height of 1.2mand the plane with a height of 1.3 m are different. Compared with Case 4, the value difference of the maximum turbulence intensity at two heights is less than 2%. In Case 5, the turbulence intensity of the plane with a height of 1.3 m is more chaotic, with three peak points appearing, which are not seen in other cases. However, the peak value of Case 6 1.2 m high plane is smaller than that of all other working conditions, only 50%. It can be concluded that, compared with the negative pressure difference, the turbulence intensity in the vertical direction of the surgical microenvironment does not decrease under the positive pressure condition.

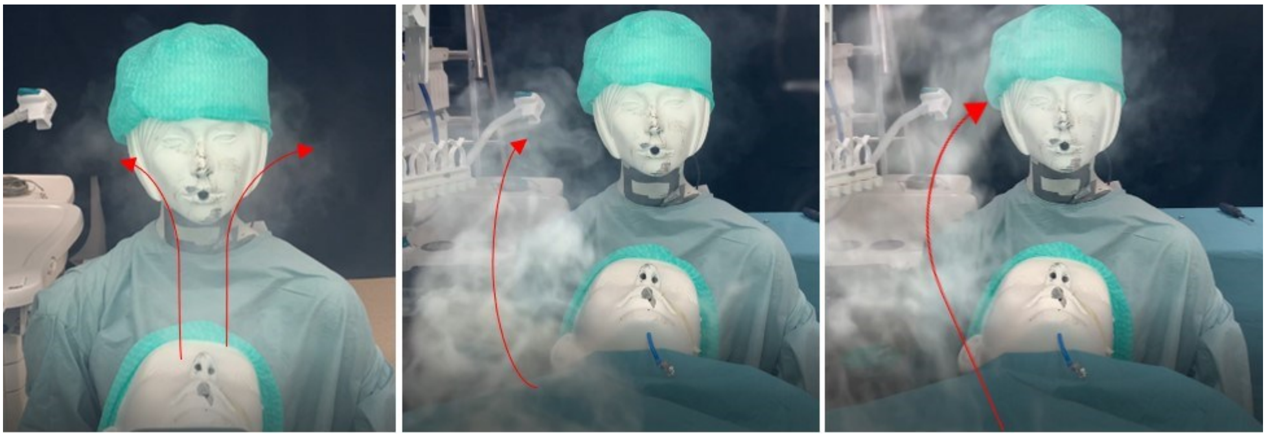

Figure 8 – Results of smoke visualization at 10 Pa(a)Thermal plume only (b) Ventilation only (c) Ventilation and thermal plume

Smoke visualization

To explore the airflow distribution of the surgical microenvironment, three cases were selected for smoke visualization. Figure 8 shows the smoke visualization results at -10 Pa. The smoke was jet out horizontally from 0.05 m above the patient's chest and eventually reaches the area above the patient's face to observe the airflow in the area above the patient's face. As can be seen in Figure 8(a), when only the heating device of the 'patient' was turned on (the ventilation system was turned off), the smoke came out of the chest area and spread slightly in front of the patient's face until it reached the anesthesiologist. As can be seen in Figure 8 (b), when only the ventilation system was turned on, the smoke dissipates from the patient's chest toward the patient's face and deviates to the left before reaching the face. As shown in Figure 8 (c), when the ventilation system and heating device of the thermal manikin were turned on at the same time, the movement of the smoke was like that when the ventilation system was turned on only, but a little upward. This is because of the upward flow of air from the thermal plume. Therefore, in the area within 0.15 m above the head, the airflow caused by ventilation is the main factor affecting the airflow distribution in this area within 0.15 m above the head.

CONCLUSIONS

This study experimentally investigated the airflow distribution of the surgical microenvironment in OR with mixing ventilation under 6 pressure difference conditions: -15 Pa, -10 Pa, -5 Pa, 5 Pa, 10 Pa, and 15 Pa.

For the surgical site, under the condition of positive pressure (Case 4-Case 6), the thermal plume in the space 0.15 m above the surgical site dominates the airflow distribution in this area, and its velocity is much higher than that of the surrounding area. This phenomenon is not obvious at negative pressure, and even at -15 Pa the centre of the plume has shifted to other regions. However, these differences of the velocities are not significant enough and does not shows regular characteristic. Due to the restriction of some conditions, the influence of other factors cannot be excluded and should be studied further.

The radiation heat transfer from the operating lamp heated the surgical site surface, which forms a strong thermal plume affecting the airflow near the wound as the main factor. This effect is stronger under positive pressure and slightly weaker under negative pressure. Other areas, such as the head and legs, are mainly affected by airflow of the room ventilation.

Whether it is positive or negative pressure has less effect on the temperature distribution in the surgical microenvironment than the effect of absolute value of the pressure difference. The increase of the absolute value of the pressure difference reduces the vertical temperature gradient and the maximum temperature. In general, the pressure difference has a slight effect on the temperature distribution. Therefore, how pressure difference affects transport of the contaminant in the surgical microenvironment should be further investigated. Besides, the airflow rate of ventilation system did not change in this study. Therefore, future study should pay attention to the influence of ventilation airflow rate on the microenvironment of the OR when designing the ventilation system of the NPOR.

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