The impact of air change rate on the air quality of surgical microenvironment in an operating room with mixing ventilation

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Abstract:

Transmission of airborne microbe-carrying particles（MCPs）is one of the key factors causing surgical site infection during surgical procedures. In operating rooms (ORs) with mixing ventilation, air change rate may determine the microbe-carrying particles transmission and indoor air quality in the surgical microenvironment. This study focuses on the impact of the air change rate on the air quality in the surgical microenvironment in ORs. Experimental measurements of MCPs were carried out in a full-scale operating room laboratory (OR Lab) with different air change rates: 10 ACH, 15 ACH, 20 ACH, and 26 ACH. Nitrous oxide, N_2O, was used as tracer gas to simulate MCPs from five surgical staff. The N_2O concentration (C_r) in the OR under fully mixed condition and local ventilation index (ε_v) were used to evaluate the ventilation efficiency of the OR. The experiment results verified that the air change rate is a direct factor to the concentration of MCPs in ORs. The higher exposure risks of surgical incision in the surgical microenvironment may be mitigated with the increasing ACH. The current most commonly recommended 20 ACH should be improved regarding the air quality of surgical microenvironment in a mixing ventilated OR. Significant difference of contaminant concentration among the air-exhaust outlets indicates the location of medical equipment and contaminant sources may affect the efficiency of exhaust. This research contributes to the new guidelines for ventilation system design of ORs.

Keywords: air change rate, mixing ventilation, operating room, surgical microenvironment, air quality

1 Introduction

Surgical site infection (SSI), one of the most predominant infection categories in hospital-acquired infections, not only brings extra physical pain to patients, but also leads to great psychological depression. SSI prolongs hospital stay and increase postoperative costs, morbidity and mortality [1]. SSI is the third most common class of hospital-acquired infection and ranks amongst the leading causes of death within the surgical patient population [2]. In terms of surgical factors, transmission of airborne microbe-carrying particles (MCPs）is one of the key factors contributing to the development

of SSI [3] It has been proven that bacteria living on the skin of the staff and the patient is the most important source of causing SSI [4]. However, the presence of Staphylococcus aureus (S aureus) in the nose is now considered a well-defined risk factor for subsequent infection [5]. Evidence to date shows that rates of infection are higher in carriers than in non-carriers: people with large numbers of S aureus microbes in their nose have a risk of health care-associated infection that is three to six times higher than for non-carriers and low-level carriers among some specific population groups [6]. Nasal carriage by people who can cause outbreaks of surgical-site infections or other nosocomial infections is known to be an external source of contamination. Persons who carry S aureus in their nares and have upper respiratory tract infections may spread this microorganism to numerous surgical staff members and patients via various respiratory activities, such as breathing, coughing and speaking.

No matter stopping MCPs from their source or to their target infection sites causing SSI, anti-microbial medicines are widely chosen as the bacteria killer. This might affect the effectiveness of anti-microbial medicines for the patients in the future. There is ever-increasing attention on the irrational use of antibiotics which could affect the whole ecological system on the Earth. Therefore, physical mechanism for preventing patients from surgical site injections are preferred when it is possible. Dedicated room air distribution methods, such as mixing ventilation and laminar airflow systems are commonly adopted for creating a clean surgical environment for operating rooms (ORs) [7].

Air change rate is an important factor to evaluate the ventilation efficiency of air distribution. Air changes per hour (ACH) is expressed as the volumetric air flow rate through the space divided by the volume of the space, as a result it is obtained the number of times the air in the room. The standard minimum ACH in ORs installed with mixing ventilation in different countries varies a lot, from 12 ACH to 25 ACH [8-12]. The most commonly recommended number of air changes per hour is about 20 ACH to maintain the OR at a positive pressure relationship with adjacent rooms, while the outdoor air requirements for acceptable indoor air quality must be at least 51 m^3/h person according to ASHRAE Standard [10]. The lower limit of 20 ACH relied heavily on the early study by Galson [13] in 1960s, where they started the industry dialog about total air changes needed in ORs to minimize post-operative infection rates. Goddard [14] experimentally derived curves that quantify the relationship between air change rates and bacterial count. He stated that increasing air change rate from 20 ACH to 25 ACH reduced bacteria CFU (colony forming units) per cubic foot of room air from 3.8 to 2.5, which was treated as a great improvement of the room air cleanness.

The optimal layout of air-exhaust outlets may have both high-level/ceiling outlets and low-level mounted exhausts at every corner of an OR [15]. Such a layout is proposed not only for removing contaminant most efficiently, but also for contributing to a uniform air circulation inside the space [15]. However, only few studies have been done regarding the effect of air change rate on the air quality of surgical microenvironment in ORs. This study focuses on the impact of the air change rate on the air quality of the surgical microenvironment in ORs. Experimental measurements of airborne MCPs were carried out in a full-scale operating room laboratory (OR Lab) with different air change rates: 10 ACH, 15 ACH, 20 ACH, and 26 ACH. In our experimental measurement, four low level air-exhaust outlets and four high level air-exhaust outlets on the walls were mounted in the OR Lab. Trace gas, nitrous oxide (N_2O), was used to simulate airborne MCPs in ORs [16], which was released from the height of the surgical staff's nose to simulate the microorganism released by respiratory activities. Particles in the fine size range are less influenced by deposition mechanisms and have the most similar behavior to

the tracer gas [17]. Tang et al. [18] reported in their review article that airborne particles smaller than 5-10 μm can be simulated with tracer gas, as they often stay suspended in the air for long time. Noakes et al. [19] showed good agreement between the behavior of N_2O tracer gas and 3-5 μm particles in a hospital isolation room with mixing air distribution. This study was based on these studies that N_2O has been reported to a good proxy to simulate MCPs smaller than 5 μm in size.

2 Experimental measurements

2.1 Test chamber and experimental setup

All experimental measurements were performed in a full-scale OR Lab with the dimensions of 8.73 m(x)×7.05 m(y)×3.25 m(z) at the Department of Energy and Process Engineering of NTNU (Norwegian university of science and technology), as shown in Figure 1. N_2O was used to simulate airborne MCPs in ORs. The OR Lab with mixing ventilation system was equipped with four air-supply inlets (Swegon EAGLE Cb 400-600 with ALSd 315-400 plenum box, 0.55m×0.55m), four lower level air-exhaust outlets (Swegon PELICAN CE HFa 400-600 with ALSd 315-400 plenum box, 0.175m×0.575m) and four higher level air-exhaust outlets (Swegon GRLc 600-200 with TRGd 600-200-315-K plenum box, 0.55m×0.55m), as shown in Figure 2.

Figure 1. A photograph of a full-scale OR Lab and the wound

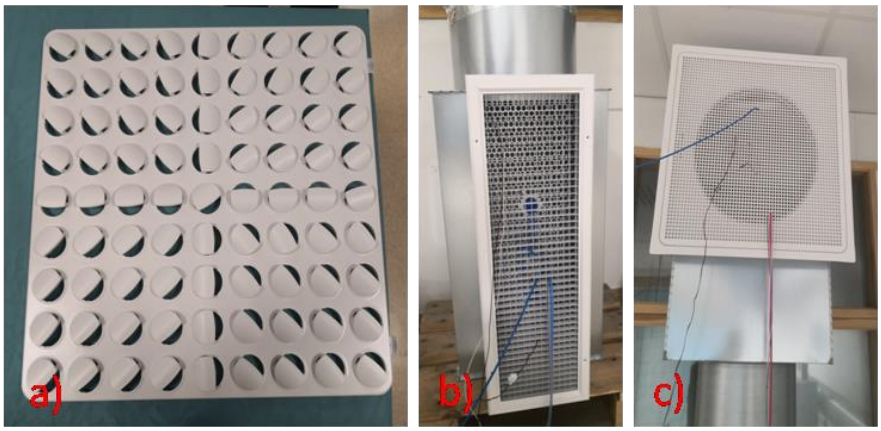

Figure 2. a) air-supply inlet; b) lower level air-exhaust outlet; c) higher level air-exhaust outlet

The ALSd plenum box was equipped with a balancing damper and pressure outlets so that the airflow rate could be measured and controlled. The DPM model TT470 S (accuracy of ±2 Pa) was used for pressure measurements in the ALSd plenum boxes attached to the exhaust grills and air diffusers, which was converted to airflow rates. The measuring uncertainty with this method is 5%. The eight air-exhaust outlets were separated into four modules close to the four corners of the room, and each module contained a lower level air-exhaust outlet and a higher level air-exhaust outlet. The supply air flow rates from the four inlets were in total 2002 m^3/h, 2995 m^3/h, 3995 m^3/h, and 5188 m^3/h for two scenarios, respectively. The air flow rate of four inlets were kept nearly balanced during the measurement. After converting the supply air flow rates to ACH considering the volume of the OR Lab (200 m^3), the ACHs for the four cases were then 10ACH, 15 ACH, 20 ACH, and 26 ACH respectively. The distribution of exhausted air between the higher and lower exhaust grills for each of the exhaust modules was approximately 1/3 and 2/3 respectively. The exhaust air flow rates needed to create a positive pressure were1920 m^3/h, 2957 m^3/h, 3949 m^3/h, and 5101 m^3/h. Normally, the OR is maintained at a positive pressure with respect to corridors and adjacent areas [8-12]. Hence, the air volume of the OR Lab was set to have more supply air than exhaust air, which created a slightly high pressure inside the OR Lab than outside to avoid any leakage of other contaminated air.

A thermal manikin was used to simulate a patient lying flat on an operating table of 0.84m height in the OR Lab. A detailed description of the thermal manikin can be found in Cao et al. [20] The manikin's surface temperature was measured by an infrared thermo detector (Bosch PTD 1, Pobert Bosch GmbH, Leinfelden-Echterdingen, Germany), which was in the range of 32–34°C during the experimental measurements. The patient was covered with a blanket, but the wound on the stomach (Figure 1, size 0.2 m×0.2 m) was directly exposed to the room air. The five-membered surgical staff was simulated by heated cylinders with a diameter of 0.4m. The height of surgical staff standing with a bend posture on the side of the operating table was 1.72m. The height of two other surgical staff standing near the medical instrument table was 1.75m. A surgical staff was assumed to have a sitting posture in front of the patient with a height of 1.32m. In Figure 1, three surgical staff were covered with green gowns and another two surgical staff were covered by blue light surgical clothing. Imitation of surgery staff using geometrical shapes with a certain convective heat loss has been done in previous studies [21]. In order to imitate the convective heat loss from the staff, light bulbs are placed inside the cylinders, each bulb with a power of 100W for standing surgical staff [22-24].The heat loss of human body in sitting posture is less than that in standing posture [25,26], thus the power of bulb was 75W in the 1.32m height cylinder. Besides the thermal manikin and the cylinders, there were other heating sources including operating lights, computers and medical equipment. In order to replicate a realistic OR, extra two group fluorescent lamps and one 300W tubes were added to imitate the various heat sources of medical equipment. The two group fluorescent lamps, each group including two 28W tubes, were added attached the walls. The 300W tube was close to the medical equipment. Thermocouples temperature sensors (HIOKI LR8400) were used to measure the supply and exhaust air temperature. The design of temperature in ORs is 20–24°C according to the ASHRAE Standard [10]. Therefore, during the measurement, the supply and exhaust air temperature was 23.0±0.5°C and 24.0±0.5°C, respectively.

2.2 Measurement procedure

A multipoint sampler and doser (Innova 1303, Brüel & Kjær, Ballerup, Denmark) coupled to a multi-gas monitor (Innova 1302, Brüel & Kjær, Ballerup, Denmark) were used for releasing and

measuring tracer gas concentrations. Tracer gas N_2O was continuously released from Innova 1303 through five plastic tubes with internal diameter of 3 mm that were fixed at the height of 1.5 m for four standing surgical staff and 1.08 m for the sitting surgical staff, as shown in Figure 1. The tubes were fixed nearly at the height of the noses of the surgical staff. Before the measurement, the background concentration of tracer gas N_2O was kept below 0.93mg/m^3. The sampling time of Innova 1302 was 60 s/channel, and six channels were measured in sequence, thus giving a period of 6 minutes between measurements in the same location. The total sampling time for one case was 90 minutes. The calibration of the doser system was performed using the PC software Lumasense, which also flushed the doser system so that the Innova 1303 only contains the desired calibration-gas. According to the manufacturer, the repeatability of the Innova 1302 measurements is ±1% under standard conditions, and the dosing calculation accuracy of the Innova 1303 is ±2%. During the measurement, the average N_2O flow rate was kept at 586 mg/min for four standing surgical staff and 71 mg/min for the sitting surgical staff. These flow rates were selected by controlling the pressure of Innova 1303 with working range from 3 bar to 4.5 bar. The flow rate being less in one tube was due to the restriction of Innova 1303, in which four tubes release gas with the same rate and the remaining one releases differently. The less flow rate was applied to the sitting surgical staff instead of other standing staff. Because the sitting surgical staff had less exposed surface, they were expected to release less MCPs. Since the total amounts of released trace gas are different from case to case, normalizations are done for all cases to make the comparison feasible.

The effect of four different air change rates (10 ACH, 15 ACH, 20 ACH, and 26 ACH) was investigated on the contaminant diffusion. Because of the limitation of sampling channels, the study consists of 8 experimental cases grouped in two scenarios to measure the concentration of contaminants in the surgical microenvironment (Point 1–6), and four air-exhaust outlets (Point 7–10) and an air-supply inlet (Point 11), which are summarized in Table 1 and the location of the measuring points is shown in Figure 3. The contaminant concentration of the surgical microenvironment was of primary interest, which was measured in Scenario 1 including cases A1, B1, C1, and D1. In Scenario 1, all measurement points were located close to the surgical site. Point 1, Point 2, and Point 3 were located above the patient. Point 4 and Point 5 were above different instrument tables symmetrically located at two sides of the surgical site. Point 4 was at the side having less surgical staff and Point 5 was beside two surgical staff. Point 6 was above the instrument table which was closest to the patient and surgical staff. Scenario 2 was designed for investigating contaminant concentration of different four air-exhaust outlets and monitoring contaminant concentration of an inlet, including Case A2, B2, C2, and D2. Point 7 and Point 8 were at the corner that was very close to the medical equipment. Point 9 and Point 10 were at the corner without any obstacle of the medical equipment. The N_2O concentration was repeatedly measured at Point 1 to observe the consistency of ventilation conditions in all cases. The N_2O concentration at Point 11 was used to calculate the reference concentration C_r expressed in the equation (2).

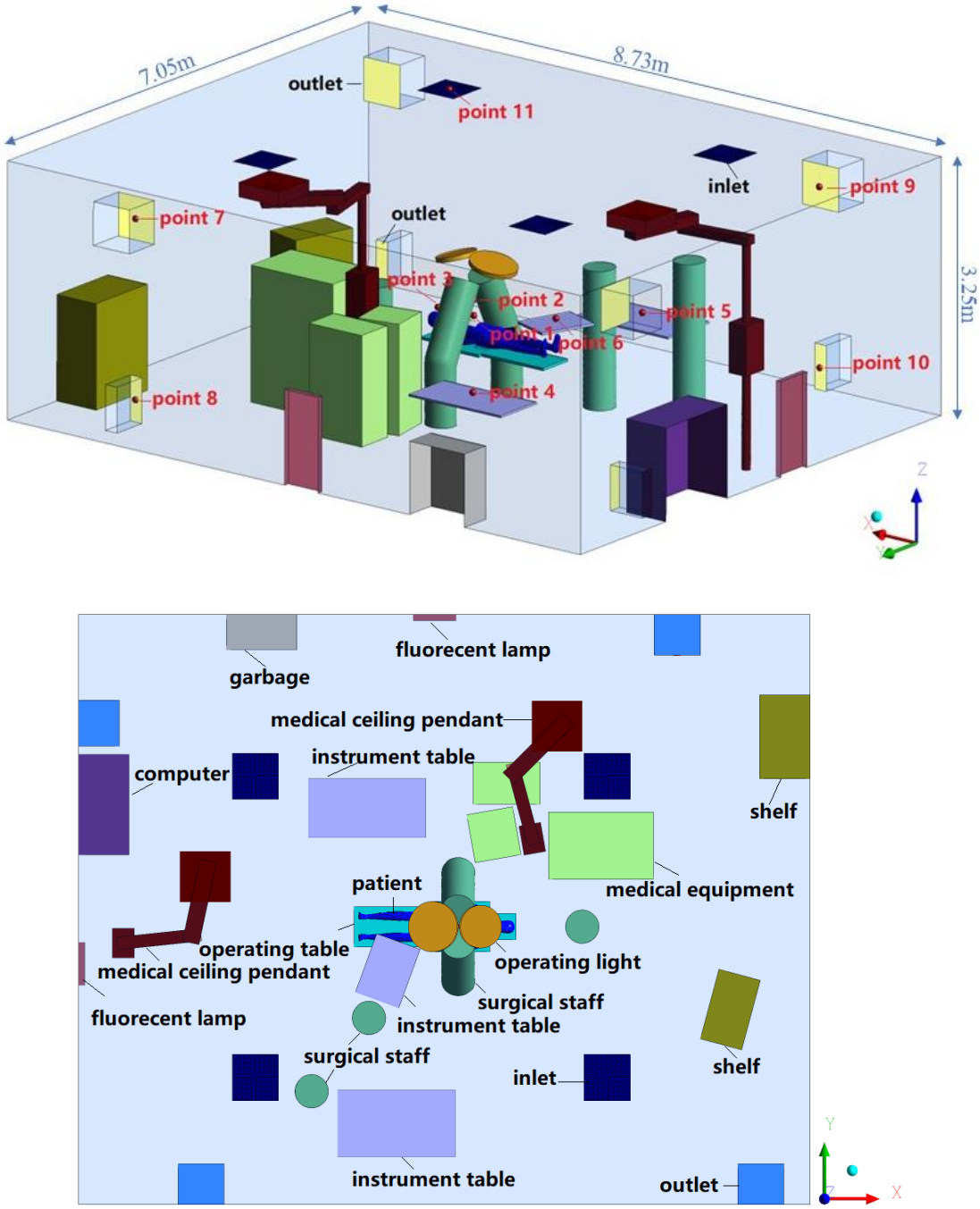

Figure 3. The 3D (top panel) and 2D (base panel) top-down views of the OR Lab, where the locations of all measurement points are illustrated（Point 1: above the centre of the wound 5cm. Point 2: above the centre of the wound 20cm. Point 3: above the patient's head 5cm. Point 4–6: above the centre of the instrument table 5cm. Point 7-10: on the centre of four outlets. Point 11: on the centre of an inlet. Tracer gas N_2O was released from five surgical staff.)

Table 1 Experimental conditions in different cases

Scenario	Case	Air change rate (ACH)	Test point
Scenario 1	A1	10	Point 1–6
surgical microenvironment	B1	15	Point 1–6

	C1	20	Point 1–6
	D1	26	Point 1–6
Scenario 2	A2	10	Point1 and Point7–11
four outlets and an inlet	B2	15	Point1 and Point7–11
	C2	20	Point1 and Point7–11
	D2	26	Point1 and Point7–11

2.3 Date analysis of mixing ventilation

Assume a completely mixed system with the same boundary conditions as in the experimental setup. Then, the relationship between ventilation rate and indoor air quality under non-steady state can be expressed by the equation (1) [27]:

$$\dot{V}C_s + \dot{M} = \dot{V}C_r + V\frac{dC_r}{d_t} \quad (1)$$

Where, $\dot{V}$ is the ventilation rate, m^3/h; $\dot{M}$ is the contaminant source strength, mg/h; C_s is the supply air concentration, mg/m^3; C_r is the exhaust concentration, mg/m^3; V is the free volume of the room, m^3. The analytic solution to equation (1) is equation (2):

$$C_{r(\tau)} = C_s + \frac{\dot{M}}{\dot{V}} - (C_s + \frac{\dot{M}}{\dot{V}} - C_{r(0)})e^{(-n\tau)} \quad (2)$$

Where, n=$\dot{V}/V$ and τ is time in hours. If the room air is fully mixed, the concentration at any point of the room will be equal to that of the exhaust air, hence the equation can be used to calculate the ideal concentration at any point in the room with a set of given conditions.

To measure the quality of the air distribution, and with that, how well the contaminants at a point in the room is ventilated by the supply air, the local ventilation index (ε_v) can be used by the equation (3):

$$\varepsilon_v = \frac{\overline{C_P}}{\overline{C_E}} \quad (3)$$

Where, $\overline{C_P}$ is the tracer gas mean concentration at measurement points, mg/m^3 and $\overline{C_E}$ is the contaminant concentration of the exhaust air, mg/m^3. When the room air is fully mixed by the contaminants, $\overline{C_E}$ equals to the exhaust concentration C_r. If ε_v>1, it indicates that the contaminant is in an airflow recirculation zone, which means the contaminant isn't diluted directly by the supply air. If ε_v<1, the contaminants are diluted directly by supply airflow. when the measurement point is at one outlet, short-circuiting is occurring in the measurement outlet, which means a large proportion of supply air flows directly to the measurement outlet. ε_v=1, the room air is fully mixed by the contaminants for fully mixing conditions.

2.4 Uncertainty analysis

The uncertainty of data was analysed in accordance with ISO guidelines [28]. The sample standard uncertainty is calculated as the combination of the maximum uncertainty of the measurement (random error) and the uncertainty of the instrument (range drift). The range drift of the multi-gas monitor Innova 1302 was ±2.5% of measured value per three months. For any given measurement point, the standard uncertainty u_c of the tracer gas concentration was calculated as in equation (4):

$$u_c = \sqrt{u_{rw}{}^2 + u_r^2 + u_a^2 + u_d^2} \quad (4)$$

Where, u_{rw} is standard uncertainty due to reproducibility (standard deviation); u_r is standard uncertainty due to repeatability; u_a is standard uncertainty due to instrument accuracy; u_d is standard uncertainty due to drift.

The absolute expanded uncertainty U with a coverage factor of 2 defines an interval with 95% confidence and is shown in equation (5):

$$U = 2 \cdot u_c \quad (5)$$

The uncertainty of the local ventilation index is based on the absolute expanded uncertainties of measured tracer concentration at 95% confidence.

3 Results and discussions

3.1 N_2O concentration of surgical microenvironment

Figures 4–6 show the measured N_2O concentration at scenario 1 (surgical microenvironment). As a reference, the N_2O concentration C_r of the OR Lab under fully mixed condition was calculated and plotted as a red dash line in Figure 4 and Figure 5. In the surgical microenvironment, lower N_2O concentration is preferred. First, the N_2O concentration at all measuring points before the opening of tracer gas was kept at background level, which means that the experiments were well ventilated. The N_2O concentration starts increasing until it became stable after approximately 24 minutes of tracer gas release. This period was named the starting phase. Second, a clear decay of tracer gas concentration at all points was measured after the tracer gas was closed. And the value went to background level after about 12 minutes in the end. This indicates that the air circulation in the OR Lab is in order. This period is called the ending phase. In between the starting and the ending phase, the stable phase was defined. The N_2O concentration at points in Scenario 1 is displayed in Figure 4. Point 1 was 5 cm above the centre of the wound of the patient, which was of the most interest. The values at this point were depicted using green lines in all figures. With different air-change rates, they were all slightly above the reference concentration. This agreed with our understanding that the ventilation mixes with the air less perfectly when it was close to a physical boundary such as the patient.

Point 2 was designed to investigate the possibility of a decrease in the N_2O concentration by adjusting the height of operating site. Point 2 was placed 15 cm high above Point 1. It can be seen from Figure 4 that the N_2O concentration at Point 2 varies differently at the stable phase compared to Point 1. However, it was not clear enough to identify which point was preferable among Point 1 and Point 2. The preference referred to a significant lower concentration at one point compared to the other. The surgical site is always adjustable according to the height of the operating doctor. It is worth investigating whether the height of the surgical site will affect the concentration of contaminants. In addition, the surgical site and/or the patient as a physical boundary would possibly affect the concentration of contaminant at different distances from the surgical site. Therefore, we expected statistical differences at these two points. However, the statistical similarities of these two measuring points indicated that the variation of N_2O concentration due to the adjustment of surgical site was small and could be ignored under all different air change rates. This situation was preferable. It supported the surgical staff being comfortable without losing cleanness of the wound zone.

Point 3 was measured at the head of the patient. This point was considered due to the risk of bacteria invading the patient's body through the mouth or through the nose. In Case A1 with 10 ACH and Case B1with 15 ACH, the N_2O concentration was barely higher than the reference concentration. When the air change rate was increased to 20 ACH (Case C1), the N_2O concentration became less than 10 mg/m^3 lower than the reference concentration. It went above the reference concentration again when the air change rate was further increased to 26 ACH (Case D1). And concentration at Point 1–3 was closer to the reference concentration during all the cases.

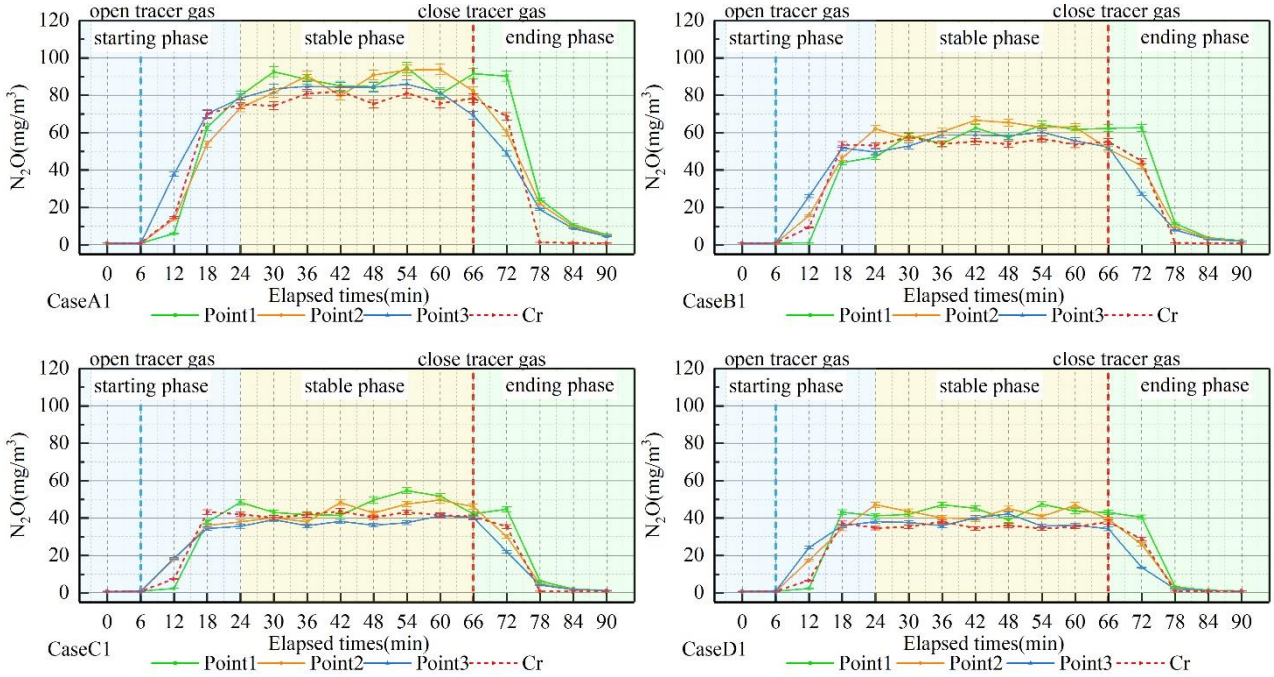

Figure 4. The N_2O concentration at Point 1–3 in Scenario 1

Figure 5 shows the N_2O concentration at Point 4–6, which were measured above three instruments tables. It can be seen that N_2O concentration at Point 4 is lower than values at two other points in the stable phase for all cases. Furthermore, the N_2O concentration at Point 4 was the lowest at all measured points except Case C1, where the lowest N_2O concentration was at the head of the patient. In addition, the N_2O concentration at Point 4 lay beneath the reference curve. The N_2O concentration at Point 6 in the stable phase is generally high compared to the values at the other points. Among Point 4–6 in the surgical microenvironment, the N_2O concentration at Point 5 and Point 6 was the highest and also higher than the reference concentration. In the ending phase, the variable of concentration at Point 4–6 decreased while increasing the air change rate. Point 4 and Point 5 were located above two equipment tables symmetrical to the surgical sites. We expected similarities of values at these two points. However, a much higher N_2O concentration was observed for all cases at Point 5 than at Point 4. After investigating the settings more carefully, it was found that there were more surgical staff closing to Point 5. There were three surgical staff on the Point 5 side of the surgical site and only one surgical staff on the Point 4 side of the surgical site. Since tracer gas was released through each tube fixed on surgical staff, it is reasonable to observe higher concentration at Point 5 compared to Point 4 because of closer and more amount of contaminant sources.

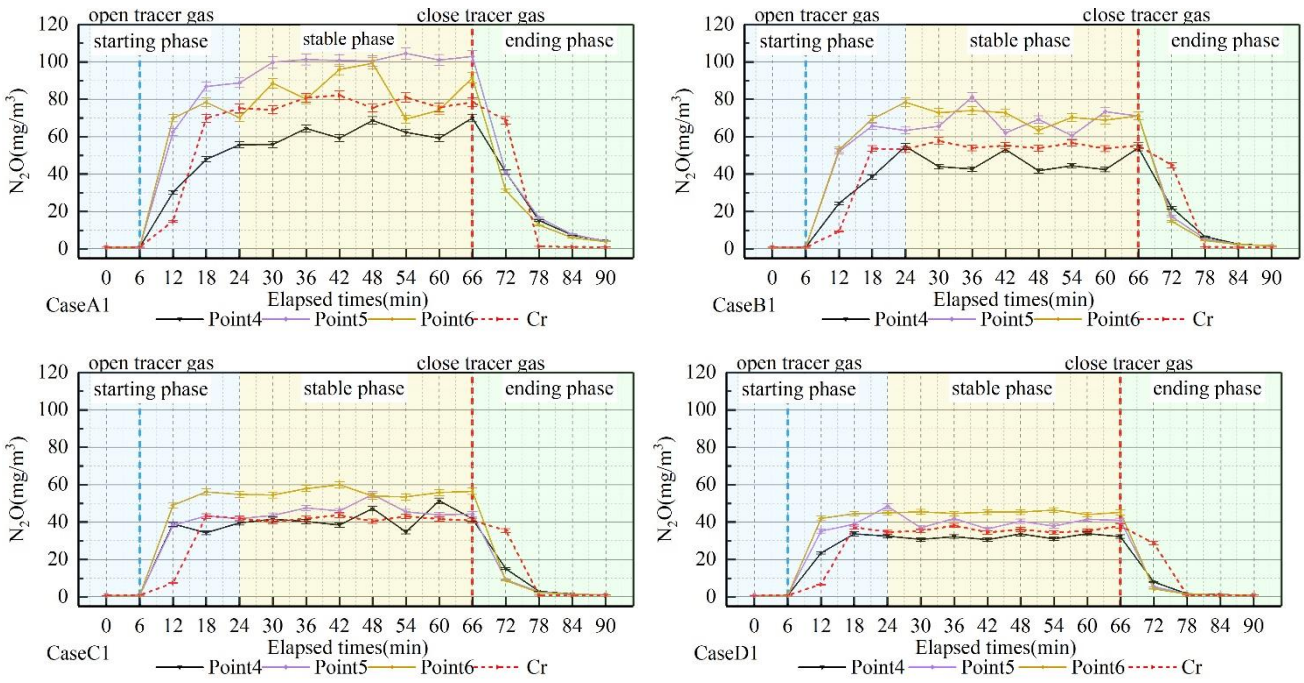

Figure 5. The N_2O concentration at Point 4–6 in Scenario 1

The N_2O concentration with different air change rates (Case A1–D1) is shown in Figure 6. For Point 1–6 in each case, the statistics (the mean and standard deviation) are estimated by the values in the stable phase. It can be clearly seen that the N_2O concentration decreases as the air change rate increases. The higher exposure risks of surgical incision in the surgical microenvironment may be mitigated with the increasing ACH. Considering the air change rates of four cases – 10 ACH, 15 ACH, 20 ACH, and 26 ACH, the increments of air change rate from Case A1 to Case B1 and from Case B1 to Case C1 are the same, which is 1 ACH less than the increment from Case C1 to caseD1. The increments of air change rates are almost in a sequential order. Yet, the corresponding decrements of N_2O concentration at Point 1–6 are not as even as the increments of air change rates. Starting from the lowest air change rate, the mean values of N_2O concentration drops the fastest from 10 ACH to 15 ACH and slower towards the highest air change rate. When the air change rate was 10 ACH, the expectations of mean values at different points range from the minimum of about 60 mg/m^3 (Point 4) to the maximum of about 100 mg/m^3 (Point 5). Whereas when the air change rate is 26 ACH, the expectations of mean values varied from about 30 mg/m^3 (Point 4) to about 40 mg/m^3 (other points). The variation of N_2O concentration is larger for the case under lower air change rate compared to the case under higher air change rate, which means the N_2O concentration is more stable for Point 1–6 under higher air change rate than under lower air change rate. Besides, the mean standard deviation values of N_2O concentration is the smallest for 26 ACH, which means the air quality is improved a lot. Results of point 1–6 show that 26 ACH is better than 20 ACH in the surgical microenvironment. Therefore, the current most commonly recommended 20 ACH should be improved regarding the air quality of surgical microenvironment.

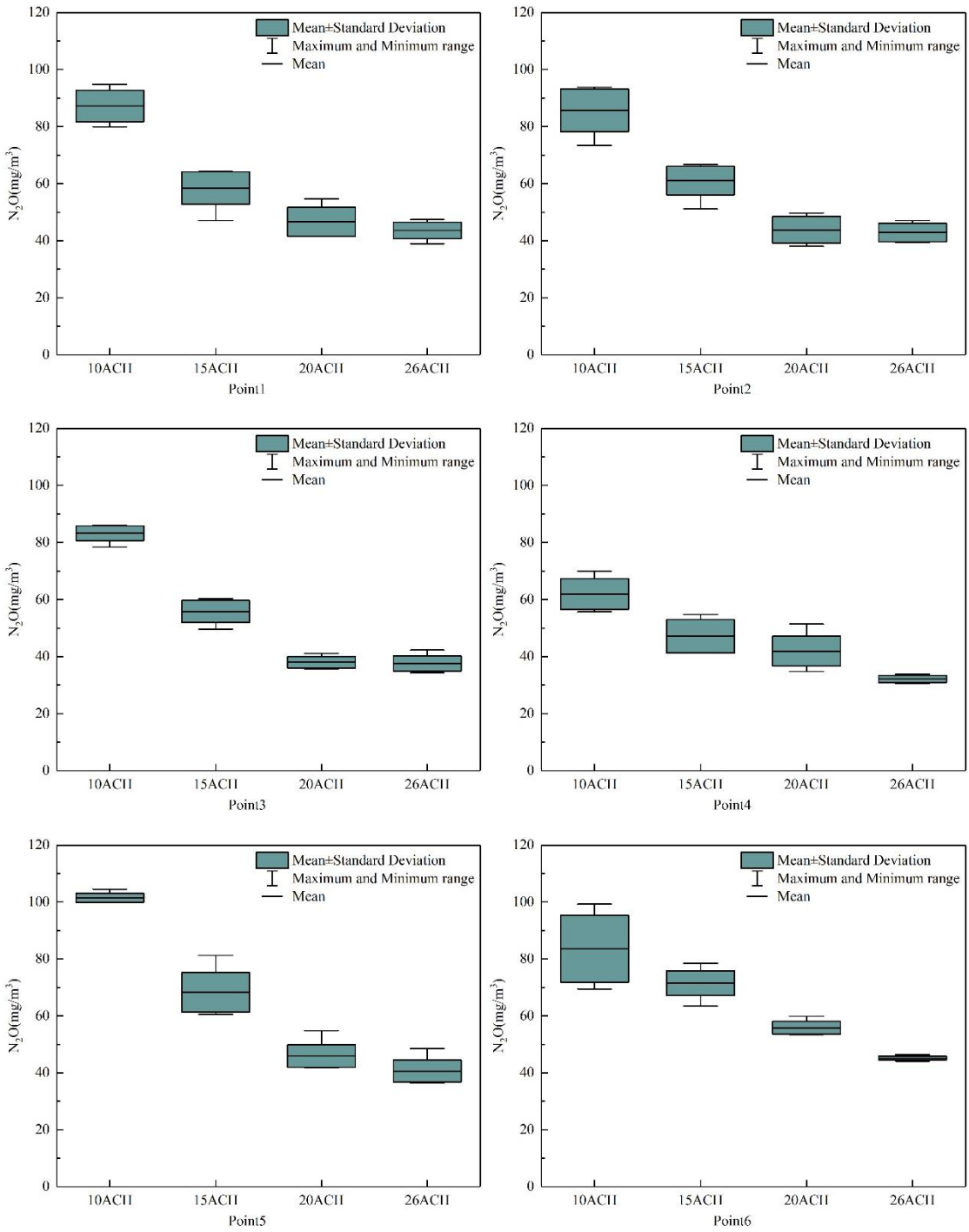

Figure 6. The mean, maximum, minimum and standard deviation values of N_2O concentration at Point 1–6 in Scenario 1

3.2 N_2O concentration of outlets

The N_2O concentration at the four points under different air change rates are plotted in Figure 7 and Figure 8. In Figure 7, the first observation is that the N_2O concentration at Point 7 and Point 8 at each case of air change rate are very close, no matter the difference in location and the difference of air exhaust ratio at the upper and lower outlets. The values are slightly smaller when the air change rate is larger. However, when compared to the N_2O reference concentration, the values at these two points are much lower. The variations of values at these two points in stable phase are small (less than 10 mg/m^3).

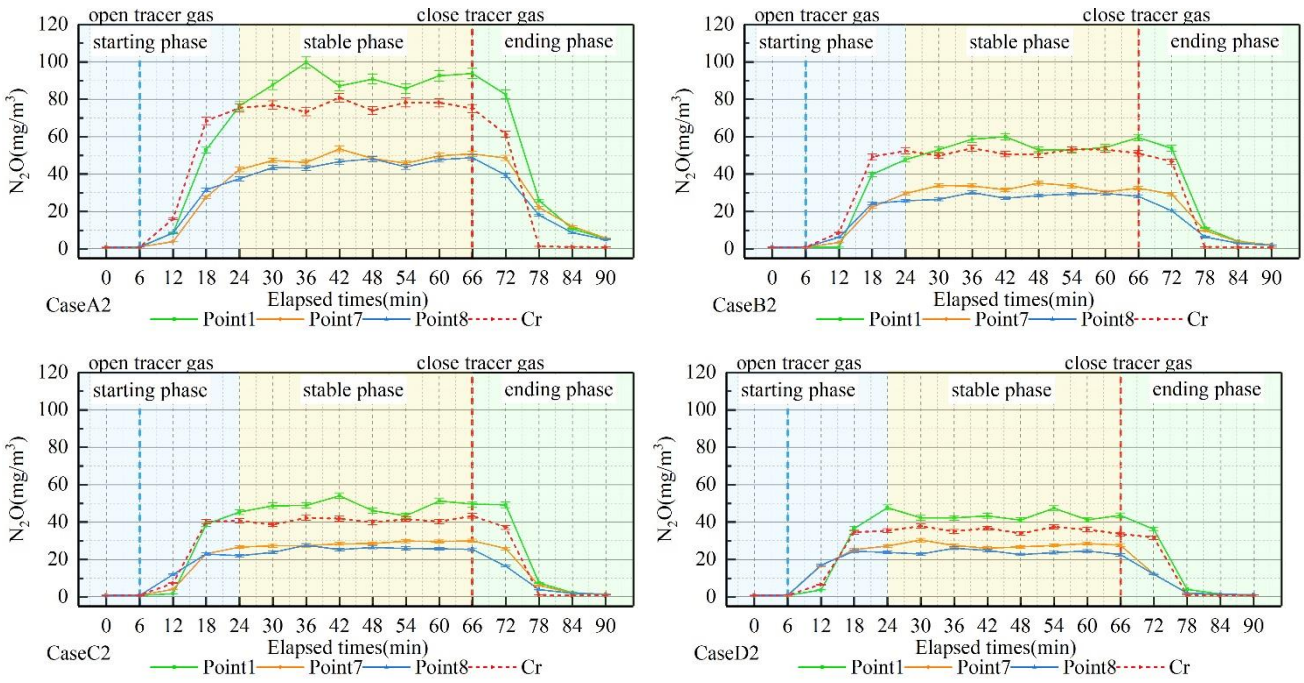

Figure 7. The N_2O concentration at Point 1, Point 7–8 in Scenario 2

In Figure 8, the N_2O concentration at Point 9 and Point 10 is similar when the air change rate is 10 ACH, with a slightly different variation at the stable phase. Regarding the air change rate at other three cases, the concentration at the upper outlet (Point 9) is larger than that of lower outlet (Point 10). The differences of N_2O concentration between the upper and lower outlets are larger as the air change rate is increased. As shown in Figure 3, Point 9 is close to the inlet which leading the N_2O concentration at this point is influenced by the turbulence of supply air. As a result, the variation at the upper outlet is larger than the variation at the lower outlet.

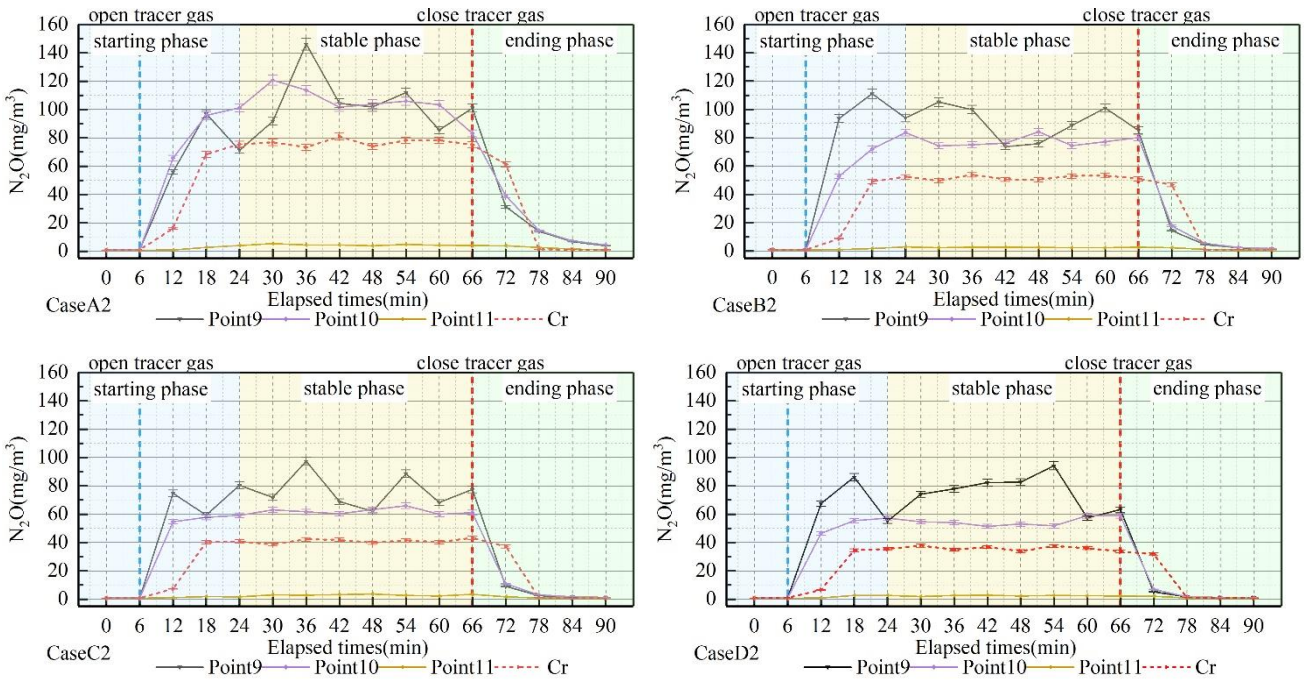

Figure 8. The N_2O concentration at Point 9–11 in Scenario 2

The statistics of Point 7–10 are shown in Figure 9. A similar conclusion as the measurement of Point 1–6 can be drawn for all these four points. The mean values of N_2O concentration decreases as the air change rate increases, while decrements of N_2O concentration are getting lower. Because Point 9 is influenced by the turbulence of supply air, the standard deviation values of N_2O concentration at this point is the largest among the four outlets. In addition, the fluctuation is much higher at the upper outlets under high air change rate (26 ACH) compared to the values at other points under the same air change rate.

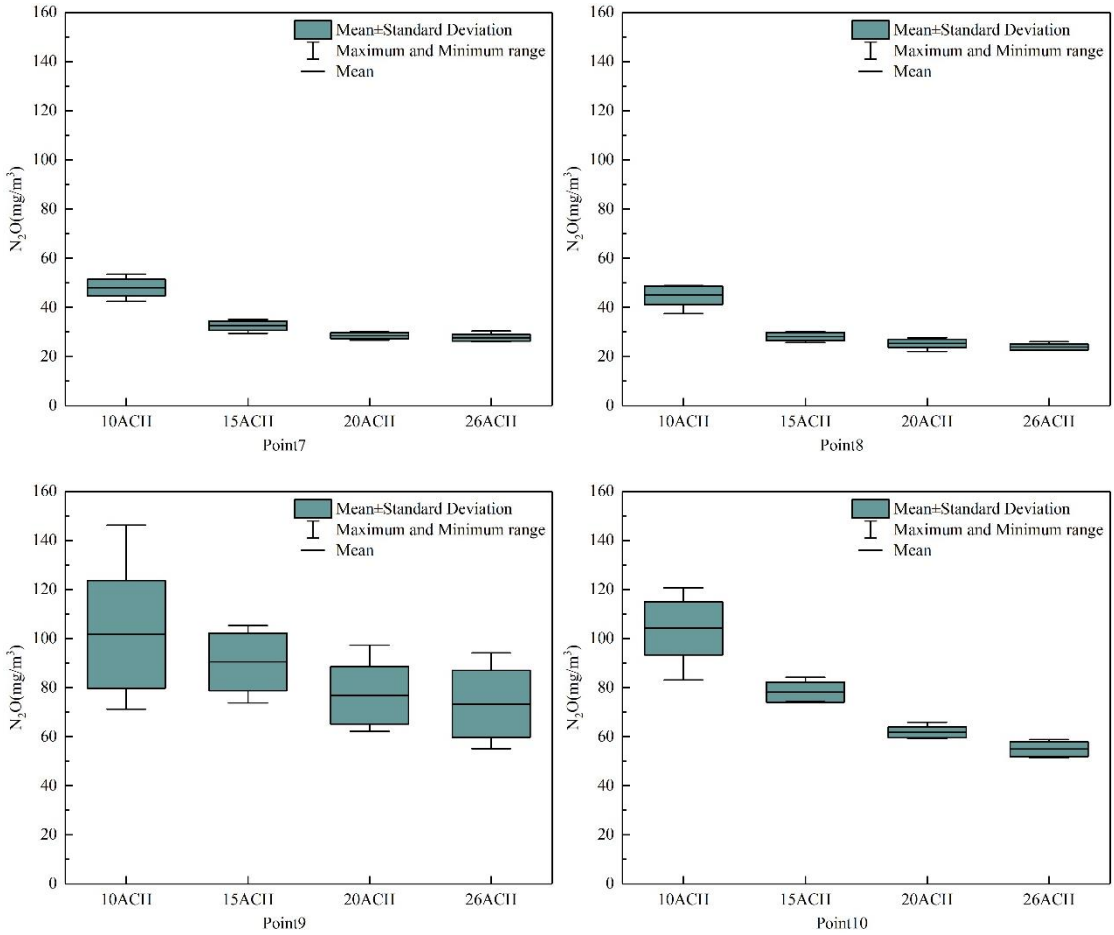

Figure 9. The mean, maximum, minimum and standard deviation values of N_2O concentration at Point 7–10 in Scenario 2

3.3 Local ventilation index

The calculated local ventilation index is shown in Figure 10. Among Point 1–6, all measurement points except Point 4 in the surgical microenvironment had local ventilation indexes larger than 1, which means N_2O wasn't diluted directly by the supply air. As the N_2O concentration in the surgical microenvironment appeared to generally be higher than the fully mixed concentration, it may suggest that risks are higher than expected simply from a mixing ventilation calculation. And the higher risks didn't appear with the increasing ACH. Point 7–10 were on the centre of four air-exhaust outlets. The local ventilation indexes of Point 7 and Point 8 were much lower than 1, indicating that there was an airflow recirculation zone near these two outlets, which was caused by blockages of airflow from medical equipment and convective flows. There were more contaminant sources closing to Point 9 and Point 10 than Point 7 and Point 8. Point 9 and Point 10 have local ventilation indexes much higher

than 1, which indicates that the contaminant sources may affect the efficiency of exhaust and the capacity of exhausting contaminant in these two outlets are heavier than designed. The efficiency of contaminant exhausting of outlets is affected by the air exhaust rate of the upper and lower outlets. Some standards suggest the air exhaust ratio to be 1/4 at the top and 3/4 at the base [29]. The Norwegian standard claims a good practice of the air exhaust ratio to be 1/3 at the top and 2/3 at the base. The clean and conditioned air is introduced into the OR through swirl or line diffusers with a high velocity for mixing ventilation. If air in the entire space is fully mixed, temperature variations are small and the contaminant concentration will be uniform. To evaluate which air exhaust ratio is preferable, one criterion is that the contaminant concentration at the upper outlet and lower outlet at the same corner should be approximately equal. The similar values at Point 7 and Point 8 indicate that the Norwegian practice seems to be working very well. However, we observe that the local ventilation index at Point 9 is higher than the local ventilation index at Point 10. It means that the outlet at Point 9 is less efficient than the outlet at Point 10 at absorbing airborne particles out of the room. Therefore, the air exhaust ratio of 1/2 might be too low, even though it is already higher than other standards.

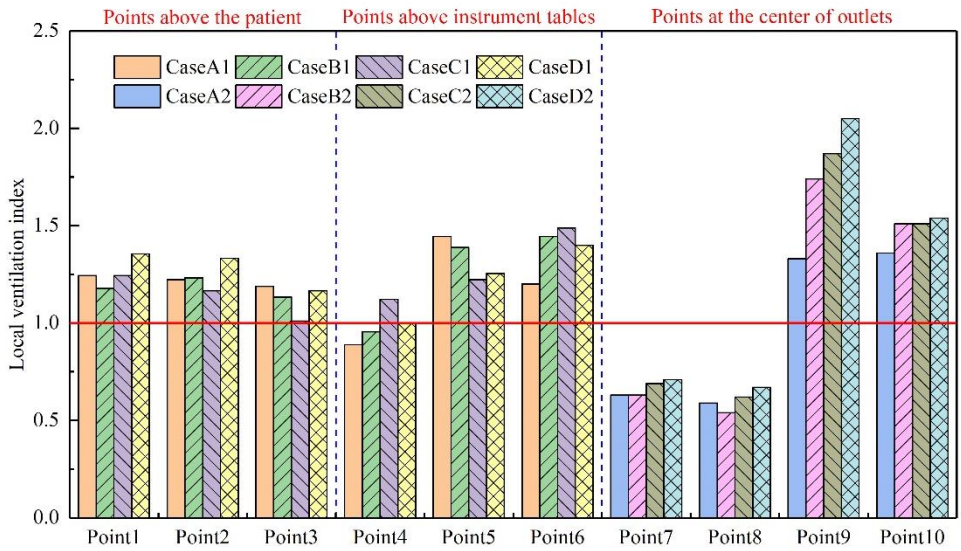

Figure 10. The local ventilation index of measurement points in two scenarios

3.4 Validity of experimental settings

It is intuitive that the concentration of contaminants in the air is less when the air change rate in the OR is higher. Air change rate is a direct factor determining the sweeping speed of air. However, on the one hand, an OR with high air change rate is required to decrease the concentration of contaminants. On the other hand, low air change rate is a preferred from the energy-saving perspective. Therefore, it is a trade-off to choose an appropriate air change rate. In addition, the air change rate determines the average air speed in the operation room in a perfect mixing situation. However, in most cases, many factors affect the local air speed. For example, local turbulence due to device obstacles, thermal heterogeneity, short circulars of air flow path due to outlet settings, etc., will all lead to localised air speed anomalies and consequently induce an abnormal contaminant concentration. Therefore, measurement from one isolated point may draw misleading conclusions. In our experiment, we distribute our measurement points among different zones with varying depth and horizontal locations. For all measurement points, we see consistent trends of decrease in contaminant concentration

associated with increasing air change rates. This is under the expectation and in other words, indicates that the experimental settings are appropriate for the study.

Because the standard minimum ACH in ORs installed with mixing ventilation in different countries varies from 12 ACH to 25 ACH [8-12], we only designed four air change rates (10 ACH, 15 ACH, 20 ACH, and 26 ACH), which is the limitation of our experiment. To better understand the behavior of a specific OR and propose a threshold value ACH, further works using more sophisticated techniques, such as CFD (Computational Fluid Dynamics) simulations, are needed. However, this limitation doesn't affect the conclusions.

Although this study is unique in its design and offers some scientific evidence to support the conclusions, there are some limitations of the measurement. Point 11 is measured for calculating the reference concentration under fully mixing ventilation. Ideally, we should measure the concentration of inlet for all cases in order to calculate case-dependent reference concentration curve. In practice, we only measured once for each case and for only one inlet. This is due to the limited numbers of sensors. However, we observed that the N_2O concentration at all inlets and in all cases is stable. Therefore, the lack of values at all inlets for all cases should not affect the conclusions.

Point 1 is 5 cm above the centre of the patient's wound, which is repeatedly measured to verify whether the OR Lab as a system is stable and linear for all cases. The relative differences of measurements at point 1 at four air change rates are listed in Table 2, where the differences of mean values between Cases A1–D1 and Cases A2–D2 are all less than 5%, and the differences of standard deviation relative to the mean values are less than 5% as well. A difference of 5% is treated as minor since the trace gases are released independently from Cases A to Cases B. Therefore, we infer that the OR Lab as a system is stable and linear, and values at all other points are reliable.

Table 2. The relative difference of mean and standard deviation of N_2O concentration

Case	Relative difference of mean of N_2O concentration	Relative difference of standard deviation of N_2O concentration
|(CaseA2-CaseA1)/CaseA1|	3.25%	0.18%
|(CaseB2-CaseB1)/CaseB1|	4.86%	4.31%
|(CaseC2-CaseC1)/CaseC1|	4.98%	4.18%
|(CaseD2-CaseD1)/CaseD1|	0.05%	0.71%

4 Conclusions

This paper aims to discover the effect of air change rate on the concentration of contaminants in an OR with mixing ventilation. The first conclusion that can be drawn from this study is that the air change rate is a direct factor determining the concentration of contaminants in ORs in both the surgical microenvironment and the outlets. The higher the air change rate is, the lower the contaminant concentration will be. The higher exposure risks of surgical incision in the surgical microenvironment may be mitigated with the increasing ACH.

Furthermore, we find that the decrease of contaminant concentration in the surgical microenvironment is not proportional to the increase in the air change rate. Among the four air change rates (10 ACH, 15 ACH, 20 ACH, and 26 ACH), the variation of N_2O mean concentration is the smallest from 20 ACH to 26 ACH at the point above the patient and instrument table. However, the little decreasing of contaminants concentration at these locations may be directly related to the incidence of SSI.

Therefore, the current most commonly recommended 20 ACH should be improved regarding the air quality of surgical microenvironment in a mixing ventilated OR.

Similarity in contaminant concentration is observed at certain distances above the wound. This supports the surgical staff in adjusting the height of the surgical site for comfort without sacrificing cleanliness around the wound. Significant difference of contaminant concentration among the air-exhaust outlets indicates the location of medical equipment and contaminant sources may affect the efficiency of exhaust.

As the N_2O concentration in the surgical microenvironment appeared to generally be higher than the fully mixed concentration, it may suggest that risks are higher than expected simply from a mixing ventilation calculation. And the higher concentration remained present even with the increasing ACH. Hence, it is very important to take other measures to reduce risks of the surgical microenvironment. The results of this study may be used to develop new guidelines for ventilation system design of ORs.

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References

[1] Tanner J, Khan D, Aplin C, Ball J, Thomas M, Bankart J, Post-discharge surveillance to identify colorectal surgical site infection rates and related costs, Journal of Hospital Infection. 72 (2009) 243-250.

[2] Badia J M, Casey A L, Petrosillo N, Hudson P M, Mitchell S A, Crosby C, Impact of surgical site infection on healthcare costs and patient outcomes: a systematic review in six European countries, Journal of Hospital Infection. 96 (2017) 1-15.

[3] Uçkay I, Harbarth S, Peter R, Lew D, Hoffmeyer P, Pittet D, Preventing surgical site infections, Expert review of anti-infective therapy. 8 (2010) 657-670.

[4] Turtiainen J, Hakala T, Hakkarainen T, Karhukorpi J, The impact of surgical wound bacterial colonization on the incidence of surgical site infection after lower limb vascular surgery: a prospective observational study. European Journal of Vascular and Endovascular Surgery. 47 (2014) 411-417.

[5] Wertheim H F L, Melles D C, Vos M C, Leeuwen W, Belkum A, Verbrugh H A, Nouwen J L, The role of nasal carriage in Staphylococcus aureus infections, The Lancet infectious diseases. 12 (2005) 751-762.

[6] Nouwen J, Schouten J, Schneebergen P, Snijders S, Maaskant J, Koolen M, Belkum A, Verbrugh H A, Staphylococcus aureus carriage patterns and the risk of infections associated with continuous peritoneal dialysis, Journal of clinical microbiology. 44 (2006) 2233-2236.

[7] Iudicello S, Fadda A, A road map to a comprehensive regulation on ventilation technology for operating rooms, Infection Control & Hospital Epidemiology. 34 (2013) 858-860.

[8] AIA Academy of Architecture for Health, Facilities Guidelines Institute. Guidelines for design and construction of hospital and health care facilities, Aia Press. (2001).

[9] Health care facilities, in: HVAC Applications Handbook, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA. (2003).

[10] ASHRAE A, Standard 170-2013, Ventilation of Health Care Facilities. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc, Atlanta. (2013).
[11] China Standard 2002, GB50333–2013, Architectural Code for Clean Operating Room in Hospital, Beijing, China. (2013).
[12] Standard HEAS-02-2004, Healthcare Engineering Association of Japan. (2004).
[13] Galson E, Hospital air conditioning and sepsis control, ASHRAE Journal. 10 (1968) 33-41.
[14] Goddard K R, Hospital ventilation system design, ASHRAE Journal. 8 (1966) 46-9.
[15] Balaras C A, Dascalaki E, Gaglia A, HVAC and indoor thermal conditions in hospital operating rooms. Energy and Buildings. 39 (2007) 454-470.
[16] Aganovic A, Cao G, Stenstad L I, Skogås J G, An experimental study on the effects of positioning medical equipment on contaminant exposure of a patient in an operating room with unidirectional downflow. Building and Environment. (2019).
[17] Bivolarova, M., Ondràček J., Melikov A., Ždímal V., A comparison between tracer gas and aerosol distribution indoors: the impact of ventilation rate, interaction of airflows, and presence of objects, Indoor Air Journal, 27 (2017), 1201-1212.
[18] Tang J W, Noakes C J, Nielsen P V, Eames I, Nicolle A, Li Y, Settles G S, Observing and quantifying airflows in the infection control of aerosol- and airborne-transmitted diseases: an overview of approaches, J Hosp Infect. 77 (2011) 213-222.
[19] Noakes C J, Fletcher L A, Sleigh P A, Booth W B, Beato-Arribas B, Tomlinson N, Comparison of tracer techniques for evaluating the behaviour of bioaerosols in hospital isolation rooms, Proceedings of healthy buildings. (2009) 13-17.
[20] Cao G, Storås M C A, Aganovic A, Stenstad L I, Skogås J G, Do surgeons and surgical facilities disturb the clean air distribution close to a surgical patient in an orthopedic operating room with laminar airflow? American journal of infection control. 46 (2018) 1115-1122.
[21] Chow T T, Yang X Y, Ventilation performance in the operating theatre against airborne infection: numerical study on an ultra-clean system, Journal of Hospital Infection. 59 (2005) 138-147.
[22] Chow T T, Lin Z, Bai W, The integrated effect of medical lamp position and diffuser discharge velocity on ultra-clean ventilation performance in an operating theatre, Indoor and built environment. 15 (2006) 315-331.
[23] Memarzadeh F, Manning A P, Comparison of operating room ventilation systems in the protection of the surgical site/Discussion, ASHRAE transactions. 108 (2002) 3.
[24] Chow T T, Wang J, Dynamic simulation on impact of surgeon bending movement on bacteria-carrying particles distribution in operating theatre, Building and environment. 57 (2012) 68-80.
[25] Cramer M N, Jay O, Biophysical aspects of human thermoregulation during heat stress, Autonomic Neuroscience. 196 (2016) 3-13.
[26] Levine J A, Schleusner S J, Jensen M D, Energy expenditure of nonexercise activity, The American journal of clinical nutrition. 72 (2000) 1451-1454.
[27] Zhu Y, Build Environmentology. Beijing: China Building Industry Press. (2009) 36-37.
[28] ISO/IEC Guide 98-3:2008 uncertainty of measurement part 3: guide to the expression of uncertainty in measurement (GUM:1995), Geneva: International Organization for Standardization. (2008).
[29] Balaras C A, Dascalaki E, Gaglia A, HVAC and indoor thermal conditions in hospital operating rooms. Energy and Buildings. 39 (2007) 454-470.