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Major Article

Laminar airflow and mixing ventilation: Which is better for operating room airflow distribution near an orthopedic surgical patient?

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Key Words:
Thermal plume
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Ventilation

Background: There has been little research on the performance of laminar airflow (LAF) and mixing ventilation (MV) systems regarding clean airflow distribution near a surgical patient in operating rooms (ORs). The objective of this study was to examine the performance of LAF and MV systems in ORs at St Olavs Hospital in Norway.

Methods: Experimental measurements were conducted in 2 ORs equipped with LAF and MV systems.

Results: Under real operating conditions, airflow distribution from the LAF system was disrupted, and airflow velocity became significantly lower than that of MV above the lying patient. Airflow pattern was observed as distributed vertically downward and horizontally with LAF and MV, respectively. Turbulence intensity of supply airflow from LAF was much lower than that of MV.

Conclusions: The airflow distribution by LAF system in close proximity to a patient is greatly affected by thermal plumes generated above incisions by both patients and surgical facilities. The effect of surgical facilities on airflow distribution by using MV is not significant compared to LAF ventilation. New guidelines are needed for the design of clean airflow distribution systems in the vicinity of surgical patients in ORs.

For a long time, surgeries were commonly performed in hospital wards, but this pattern changed in the 18th century, when operating theaters were opened to improve the teaching of surgery.[1] In the 1930s, the air in the operating theater gained renewed interest,[2] and in 1946, one of the first studies on wound infections and airborne bacteria was published.[1,3] In 1960, Blowers and Crew[4] published a study in which they investigated operating theaters across Britain and performed experiments in a dummy theater. In the theater, they investigated, among other things, different airflow distribution systems, the effects of pressurizing, and airflow patterns. Based on the results, they suggested design specifications for operating theaters to effectively remove contaminants and avoid cross-contamination. In the 1980s, the focus of operating theater design shifted toward ultraclean air ventilation systems because major studies found that these systems could significantly reduce the amount of airborne bacteria in an operating theater[5] and reduce the risk of developing deep sepsis[6] compared with conventionally ventilated theaters. However, recent studies have indicated that the basis for this focus may have been wrong. In 2017, Bischoff et al[7] concluded that ultraclean ventilation did not hold an advantage regarding surgical site infections (SSIs) compared to conventional ventilation. McHugh et al[8] stated that the supposed correlation between laminar airflow (LAF) ventilation and lower rates of SSIs was uncertain, and recent studies suggest a link between LAF ventilation and higher rates.

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Table 1
Comparison of LAF ventilation and MV

Aspects	MV	LAF ventilation
Position of the operating table and sterile operating team	Not important; designed to provide equal conditions to entire room	Very important; has specific borders between sterile zone and surroundings
Type and position of lamps	Less important; mixing airflow dilutes contamination concentration in entire operating room	Very important; Chow and Yang,[13] Brohus et al,[14] Sadrizadeh et al,[15] Aganovic et al,[11] and Cao et al[12] identified positioning of lamps as crucial to airflow distribution near patient
Operating staff clothing system	Very important (Tammelin et al[16]); determines staff source strength to great extent	Very important (Sadrizadeh et al[15]); determines staff source strength to great extent
Door discipline	Disputed; Alsved et al[17] reported no correlation between number of door openings and CFU concentration, whereas Scaltriti et al[18] found number of openings to be positively correlated with number of bacteria in OR	Disputed; Alsved et al[17] and Andersson et al[19] reported no significant effect, whereas Agodi et al[20] and Smith et al[21] state contamination rate increases with number of door openings

CFU, colony-forming unit; *LAF*, laminar airflow; *MV*, mixing ventilation; *OR*, operating room.

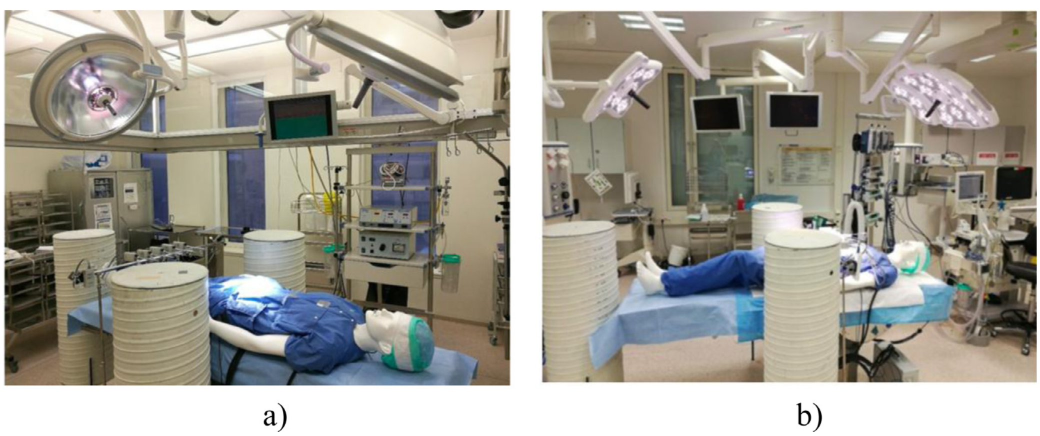

Fig 1. Experimental setup. (a) Photo of the operating room with LAF ventilation. (b) Photo of the operating room with MV. *LAF*, laminar airflow; *MV*, mixing ventilation.

The surgical environment design in operating rooms (ORs) is a great challenge because of the requirements of stabilized air temperature, relative humidity, air velocity, and air quality.[9] There are 2 main types of systems used for the ventilation of ORs: LAF and mixing systems. With mixing systems, one can dilute the concentration of airborne contaminants with a higher ventilation rate,[10] whereas laminar systems are supposed to directly deliver clean air to critical areas before it mixes with the contaminated surrounding air. The performance and efficiency of LAF and mixing systems in operating theaters are often investigated in terms of the number of bacteria-carrying particles in the room air or the number of particles that hits certain surfaces.[11,12] Multiple studies have investigated how different factors affect the efficiency of the 2 different ventilation systems, and Table 1 summarizes these findings.

In addition, movement in the periphery appears to be an important factor with LAF ventilation and can cause the transportation of bacteria to the sterile zone.[14] Another study shows that the posture of the operating team near the patient heavily affects the airflow and contamination rate with LAF ventilation[15,22,23] and may cause eddies to form and obstruct airflow. However, there is a debate as to the effect of the number of personnel in the OR. Rezapoor et al[24] and Sadrizadeh et al[23] found it to be significant, whereas Alsved et al[17] and Smith et al[21] did not.

The reason for these conflicting practices and recommendations is the lack of scientific understanding of dynamic airflow distribution in the operating microenvironment under operating conditions. ORs contain numerous transient phenomena (eg, opening of a door) that may cause significant changes to the time-resolved air distribution pattern. Notably, however, few studies have been conducted on airflow distribution in close proximity to a patient in ORs with LAF ventilation. The objective of this study was to characterize airflow distribution in close proximity to a patient in an OR with an LAF system at a tertiary teaching hospital.

METHODS

OR conditions

All measurements were conducted in 2 actual ORs at St Olavs Hospital, which has been in operation in Trondheim, Norway, since 2009. The OR with LAF ventilation has an area of 56 m^2 and an LAF zone of 11 m^2 and is surrounded by partial walls of 1.1 m in length (Fig 1). During the experimental measurements, the ventilation system operated with a full load, the temperature in the OR was controlled by temperature sensors in the exhaust ducts, and the temperature was commonly set to 22°C. Because of the electrical equipment and metabolic heat production of people in the OR, the supply air temperature was slightly lower than the set-point temperature. During the experiments, the supply air temperature was measured at 20°C ± 1°C. The relative humidity of the air in the OR was monitored on a display in the room and was 8%-29% during the experiment. The designed supply air in the orthopedic OR with LAF ventilation was 10,580 m^3/h and comprised 4,280 m^3/h of outdoor air and 6,300 m^3/h of recirculated air. A male thermal mannequin was used to simulate a patient in an OR. A detailed description of the thermal mannequin can be found in Cao et al.[12]

The OR with a mixing ventilation (MV) system was equipped with 4 ceiling-mounted diffusers. They were symmetrically positioned, with 1 in each quadrant of the ceiling. For the exhaust, there were 2 wall-mounted outlets and 1 outlet near the ceiling.

Table 2
Summary of measurement conditions for 4 cases and 2 scenarios

Scenario	Case	Ventilation mode	Operating lamps
S1	Case 1	LAF	Away from measurement zone
	Case 2	MV	Away from measurement zone
S2	Case 3	LAF	2 lamps 1.9 m from floor
	Case 4	MV	2 lamps 1.9 m from floor

LAF, laminar airflow; *MV*, mixing ventilation.

The OR had an area of 59.7 m^2 and a height of 2.90 m from the floor to the ceiling. It was connected to an adjacent corridor through a door, and the door remained closed during the recordings. Prior to the experiment, the OR was prepared as for an actual surgical procedure. The set-point temperature of the theater was 22.0°C in all scenarios. The supply airflow rate was 3,700 m^3/h, and the exhaust airflow was 3,600 m^3/h.

During measurement, an adjustable stand was used to carry the anemometers. Five anemometers were aligned on the stand with a separation of 10 cm. The stand was placed at 3 different positions above the operating table: pelvis, waist, and chest. At each cross-section, measurements were performed at 6 heights: 5, 10, 15, 20, 25, and 30 cm above the surface being studied. The heights of the measurement points were selected to represent relative distances from the human body, which does not have equal heights at each part of its surface.

Measurement conditions

In this study, 2 scenarios (Table 2), which included 4 different cases, were investigated to characterize airflow distribution in close proximity to a patient in 2 ORs with LAF ventilation and MV. Scenario 1 (cases 1 and 2) measured airflow distribution in ORs with a patient and 3 simulated surgical staff. Scenario 2 (cases 3 and 4) measured airflow distribution in ORs with a patient, 3 simulated surgical staff, and 2 surgical lamps.

Prior to the experiments, these 2 ORs were prepared as for an actual surgical procedure. The operating table was set in the middle of the sterile zone. The height of the table was set to 90 cm to represent a realistic working height during a procedure. The patient was mimicked using a thermal mannequin in each described scenario, and the mannequin wore clothing, including a protective head cover, a light short-sleeved shirt, and light pants.

Measurement instruments

The AirDistSys 5000 (Sensor Electronic, Gliwice, Poland) system with 5 omnidirectional anemometers was used to measure the velocity and temperature of the airflow near the operating table. The velocity range of the SensoAnemo 5100 LSF (Sensor Electronic) omnidirectional anemometers is 0.05-5.00 m/s, with an accuracy of ± 0.02 m/s ± 1.5% of readings. The recording time for each measurement row was set to 3 minutes. In addition, the system recorded the

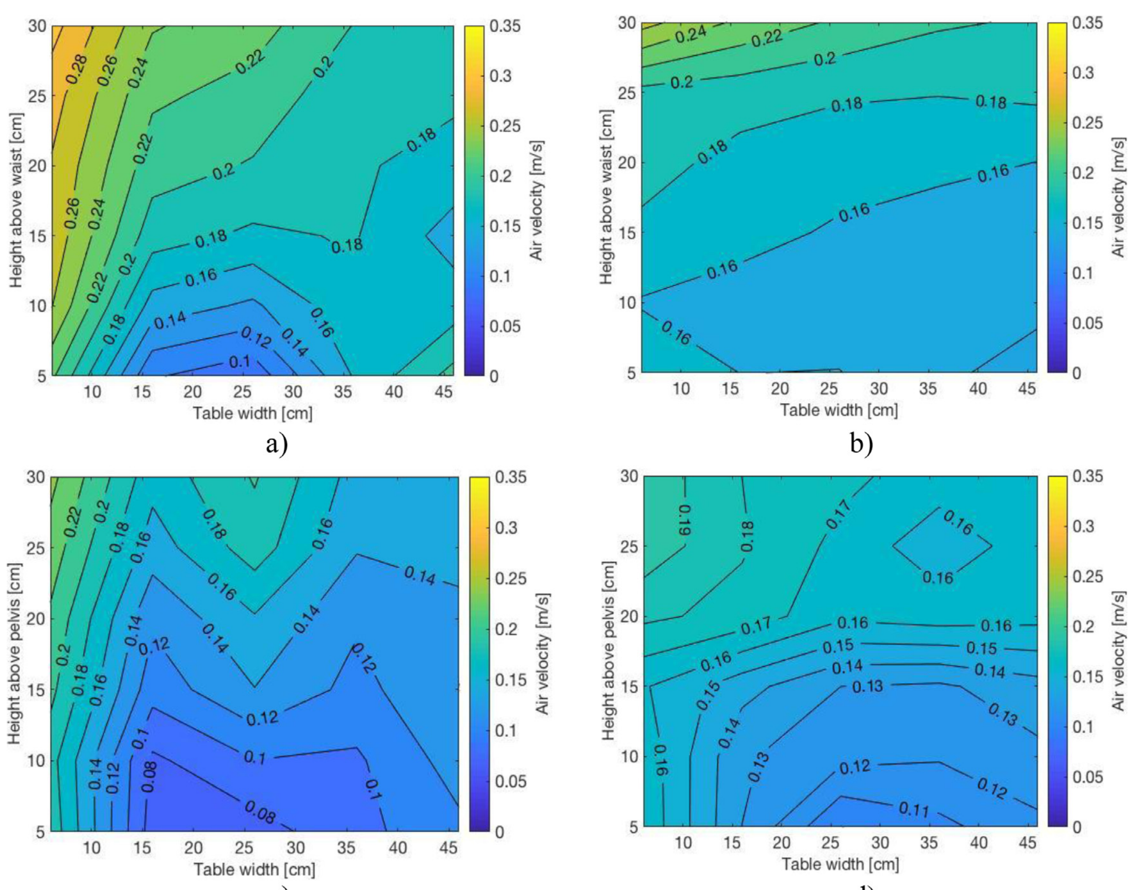

Fig 2. Velocity contours above a lying patient surrounded by 3 surgical staff (scenario 1), including cases 1 and 2. (a) Above-the-waist position with an LAF system, (b) above-the-waist position with an MV system, (c) above-the-pelvis position with an LAF system, and (d) above-the-pelvis position with an MV system. *LAF*, laminar airflow; *MV*, mixing ventilation.

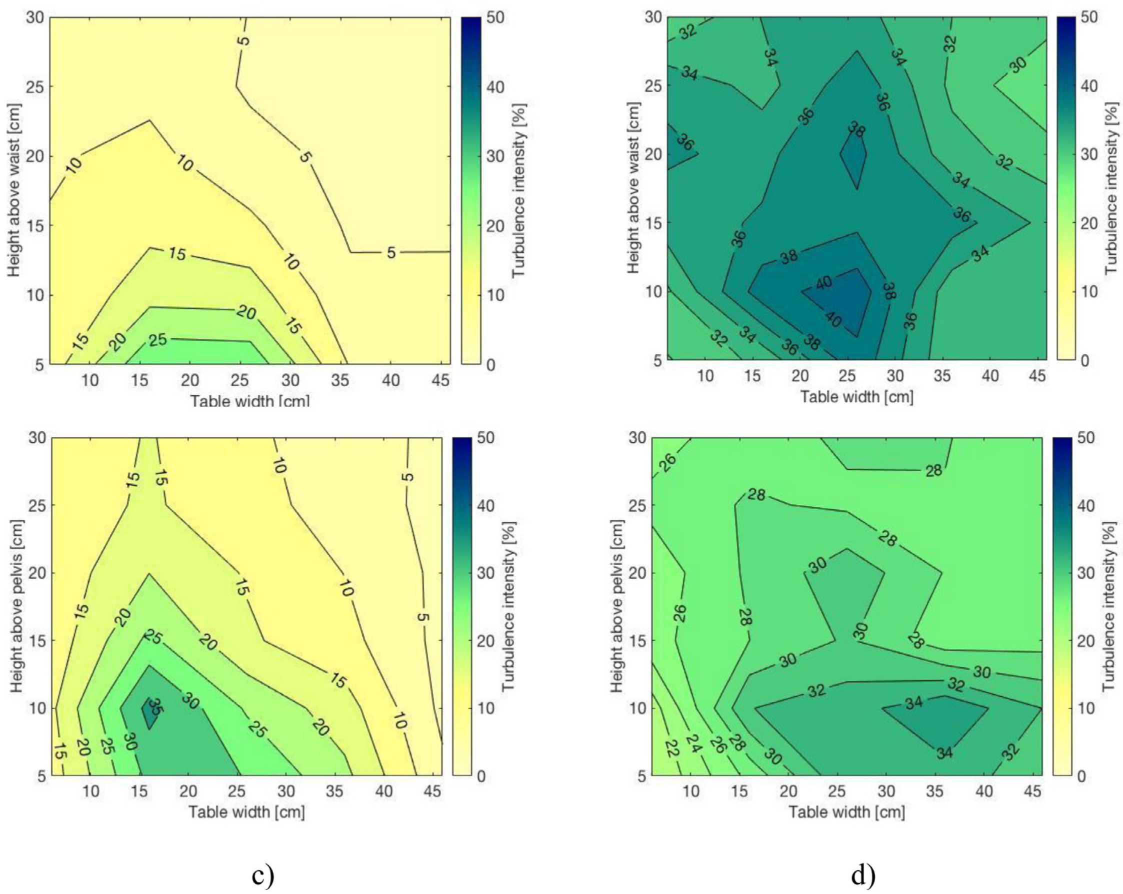

Fig 3. Air turbulence intensity contours above a lying patient surrounded by 3 surgical staff (scenario 1), including cases 1 and 2. (a) Above-the-waist position with an LAF system, (b) above-the-waist position with an MV system, (c) above-the-pelvis position with an LAF system, and (d) above-the-pelvis position with an MV system. *LAF*, laminar airflow; *MV*, mixing ventilation.

temperature, air velocity, turbulence intensity, and SD for each probe. The probes measured the magnitude of the velocity vector.

RESULTS

Measured airflow distribution in scenario 1

In scenario 1, measurements were conducted above the patient, who was surrounded by 3 simulated surgical staff (Fig 1) in these 2 ORs with LAF ventilation and MV. The measured values of air temperature were relatively stable and varied in the range of 22.1°C ± 0.1°C and 23.1°C ± 0.4°C within 30 cm of the body surface of the patient with LAF ventilation and MV, respectively.

Figure 2a shows a decreased air velocity of 0.1 m/s immediately above the patient's waist and an increased air velocity of 0.3 m/s at a height of 30 cm above the waist. Airflow distribution shows a clean effect of the rising thermal plume from the waist area of the patient. Figure 2b shows the well-mixed airflow distribution of the MV system above the patient's waist, where the airflow pattern is dominated by a large area with a velocity of 0.16 m/s. This result may indicate that the effect of surgical staff on the airflow distribution in the OR with MV is smaller than that in the OR with LAF ventilation. Figure 2c shows the airflow distribution above the patient's pelvis in the OR with LAF ventilation. The measured velocity is 0.08-0.24 m/s. Because 2 of the surgical staff stood near the patient's pelvis, the air velocity immediately above the pelvis was reduced compared with the air velocities above the chest and waist. Because the surgical staff released heat and generated thermal plumes, the air velocity above the middle part of the pelvis was lower than on the 2 sides. Figure 2d shows a lower air velocity distribution of 0.11-0.19 m/s with the MV system, whereas the air velocity immediately above the patient's pelvis remains higher than that in the OR with LAF ventilation.

Figures 3 a-d show the measured air turbulence intensity distributions in scenario 1. Figures 3a and 3c show the contours of air turbulence intensity above the simulated patient in the OR with LAF ventilation. The values ranged from 5%-20% at 15 cm above the body surface, whereas the highest values (25%-35%) were encountered within 10 cm of the body surface. Figures 3b and 3d show the measured contours of air turbulence intensity in the OR with MV, which vary from 30%-40% and from 26%-34% above the waist and pelvis, respectively, of the simulated patient. These results indicate that air turbulence intensity level of supply airflow from LAF ventilation is much lower than from MV because of the mixing process of supply air and ambient air in ORs. In addition, Figures 3 a-d illustrate the shapes of thermal plumes from lying patients because of the heating effect of a human body. The variation in turbulence intensity has a similar trend as the velocity variation inside thermal plumes. Figures 3 a-d show that the turbulence intensity of the center part of the thermal plume is higher than the outer layer of the plume. However, the air turbulence intensity level of supply airflow from MV does not change much when approaching the body surface, although the airflow turbulence intensity from LAF ventilation increases dramatically within 10 cm of the patient's waist and pelvis.

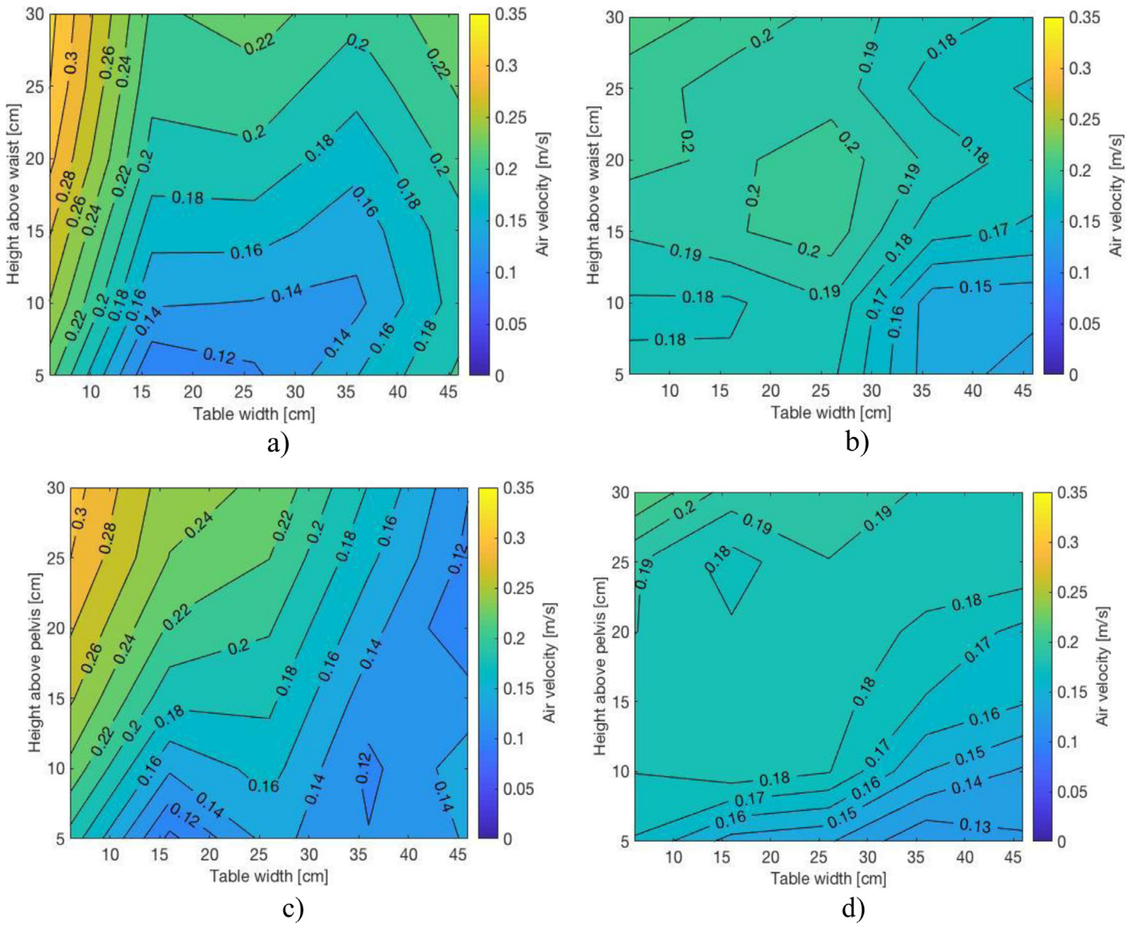

Fig 4. Velocity contours above a lying patient surrounded by 3 surgical staff and 2 surgical lamps (scenario 2), including cases 3 and 4. (a) Above-the-waist position with an LAF system, (b) above-the-waist position with an MV system, (c) above-the-pelvis position with an LAF system, and (d) above-the-pelvis position with an MV system. *LAF*, laminar airflow; *MV*, mixing ventilation.

Measured airflow distribution in scenario 2

Surgical lights were added in scenario 2. Figure 4a shows airflow distribution above the patient's waist of 0.12-0.32 m/s in the OR with LAF ventilation. This distribution is similar to that seen in scenario 1 without lamps. Figure 4b shows the airflow distribution above the patient's waist in the OR with MV. The airflow pattern presents a mixed structure of 0.15-0.21 m/s, with a peak area of 0.20 m/s in the center. The velocity contours in Figure 4b in this scenario are notably similar to that seen in scenario 1, but the surgical lights strengthen the effect of surgical staff on airflow distribution above the lying patient.

Figure 4b shows the measured airflow distribution above the patient's pelvis, with air velocities of 0.10-0.30 m/s, which is similar to the velocities seen in scenario 1 without the use of surgical lamps. Figure 4d shows the measured airflow distribution in the OR with MV. The airflow pattern shows a mixed structure, with air velocities of 0.13-0.21 m/s. The airflow distribution above the patient's pelvis is dominated by a large area of 0.19 m/s. With the MV system, the surgical lights significantly affect airflow distribution above the patient's pelvis, where the velocity distribution becomes steadier. The surgical lights have a strong effect on the velocity distribution above the patient and strengthen other influencing factors.

Figures 5 a-d show the distributions of measured air turbulence intensity in scenario 2. Figures 5a and 5c show the contours of air turbulence intensity above the simulated patient in the OR with LAF ventilation. The values range from 5%-15% within 15 cm of the body surface, whereas the highest values (20%-25%) are encountered above a height of 15 cm from the body surface. Figures 5b and 5d show the measured contours of air turbulence intensity in the OR with MV, which vary from 26%-36% and from 22%-32%, respectively, above the waist and pelvis of the simulated patient. These results indicate that the turbulence intensity level of supply airflow from LAF ventilation will be much lower than from MV because of the mixing process of supply air and ambient air in ORs. The air turbulence intensity level of supply airflow from MV does not change much when approaching the body surface, whereas it increases dramatically within 10 cm of a patient with LAF ventilation.

DISCUSSION

OR airflow distribution design

Airflow from a ventilation system should supply clean and controlled airflow to the operating microenvironment of the surgical site with sufficient velocity to sweep away undesired particles. There are different ventilation requirements for ORs regarding an airflow change of 15-25 changes per hour.[25,26] However, earlier studies show that the use of surgical lamps hinders the ability of ventilation system airflow to reach the operating table and surgical site even when the required supply airflow change rate is satisfied.[12,14,15] This study also shows the effect of simulated surgeons on airflow distribution in the surgical microenvironment with both LAF ventilation and MV.

For the minimum air velocity in the operating zone, the Health Technical Memorandum recommends a minimum air velocity of

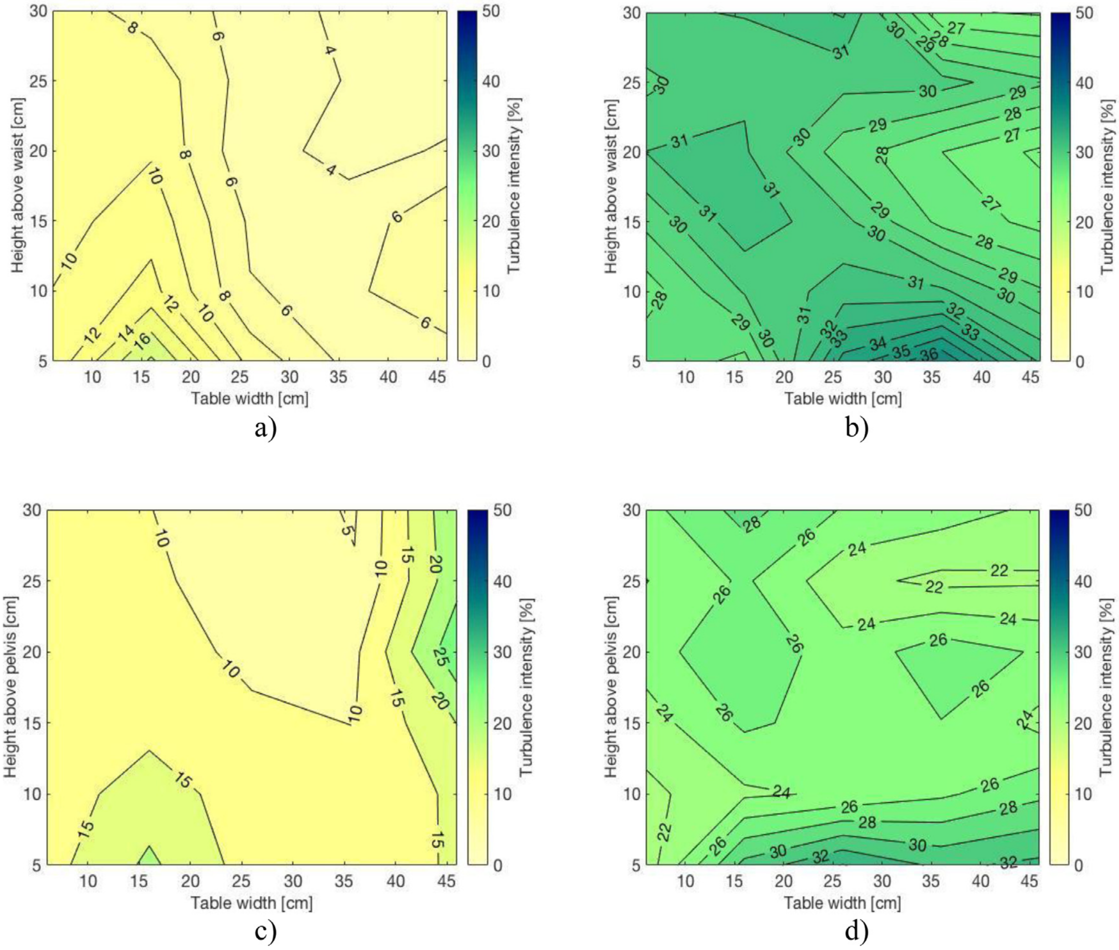

Fig 5. Air turbulence intensity contours above a lying patient surrounded by 3 surgical staff (scenario 2), including cases 3 and 4. (a) Above-the-waist position with an LAF system, (b) above-the-waist position with an MV system, (c) above-the-pelvis position with an LAF system, and (d) above-the-pelvis position with an MV system. *LAF*, laminar airflow; *MV*, mixing ventilation.

0.2 m/s above the operating table,[25] which is higher than the measured airflow velocity in this study at St Olavs Hospital. Another study showed that a desirable supply air velocity may be 0.3-0.4 m/s for pollutant control.[27] However, the Health Technical Memorandum has shown that decreasing the supply air velocity from 0.38-0.23 m/s may cause a higher bacterial count near a patient.[25]. Furthermore, the effect of various surgical facilities and the presence of the surgical staff and patient should be considered when assessing the performance of ventilation systems in ORs. Future research is required to explore how localized airflow patterns in the operating microenvironment affect deposition rates of bacterial cells and cell agglomerates on the surface of a mannequin.

Practical limitations

The experimental measurement results of this study are important for understanding the performance of downward LAF ventilation and mixing airflow distribution in close proximity to a lying patient in an OR. However, a few practical limitations of this study should be considered in further studies. The interaction between the thermal mannequin and the LAF ventilation was studied at only 1 discharge velocity from the LAF system and 1 mixing airflow rate. Different discharge velocities may be further investigated in a climate chamber to experimentally examine the discharge velocity needed to ventilate the total human plume. This study focused only on the velocity distribution in close proximity to a patient.

The anemometers could not measure the direction of the airflow but only the magnitude. Therefore, the results could not show the turning point of the interactive airflow of the thermal plumes and downward airflow. Because of the lack of information regarding airflow direction, it is challenging to quantitatively specify how the thermal mannequin and thermal dummies affect airflow even if it is evident that they affect air distribution above the table. However, for qualitative analysis, the mannequin and dummies provide an economical and practical method of characterizing the effect of thermal plumes on downward LAF ventilation. In addition, surgical lights influence the measurement of air temperature without a shielding device, which would significantly affect the airflow measurement. Advanced measurement instruments will be needed in the future to measure air temperature under surgical lights.

Air distribution in ORs may significantly change with different surgical facilities and various conditions, including surgical lamps, heat source, patient, surgical staff, and various monitors. This study provides evidence that the air velocity above a lying patient in an OR with an LAF system shows a wide range of values depending on scenario. In scenario 2, the air velocity immediately above the patient's pelvis was 0.06-0.1 m/s, which is much lower than that seen in the OR with MV (0.11-0.15 m/s). Thus, surgical staff and surgical lamps have a greater effect on airflow distribution in an OR with LAF ventilation than in an OR with MV. However, airflow distribution varies from pelvis to chest, where surgical staff slightly affect the local airflow distribution. A common feature of airflow pattern with both LAF ventilation and MV is that the velocity contours change drastically with each cross-section, which indicates the combined effect of several factors, including surgical lamps and the thermal plume of the patient. However, the thermal plume of the patient appears to have a greater effect on velocity in an LAF system than in an MV system. In principle, this phenomenon can be explained by the fact that the supply airflow in an LAF system and the thermal plume from the patient cause air movement in opposite directions, which decreases the total velocity. The decreased air velocity distribution may increase the exposure of the patient to various indoor airborne pollutants during orthopedic surgery.

All velocity contours of the MV system indicate that the changes in values and patterns from 1 scenario to another principally occur above the patient mannequin in both scenarios. This area also demonstrates large velocity differences, and the lowest velocities always occurred here. The velocity contours of the LAF system show a tendency identical to that of the corresponding contours of the MV system. Because no lamps were upstream of the waist or pelvis in the LAF system, where the direction of the supply airflow is known, the effect of the lamps is likely related to the heat generated by the lamps instead of the shape of the lamps. The effect of the surgical lamps on the velocity contours is observed in both LAF and MV systems. Compared with the corresponding contours for scenario 1, all contours for scenario 2 demonstrate increased velocities in general. For the velocity contours of the MV system, the airflow patterns change significantly from scenario 1 to scenario 2. This effect can be caused by the light from the lamps since the lamps were positioned above the head and foot of the operating table and focused on the pelvis area.

In this study, these measured results also indicate that the turbulence intensity level of supply airflow from LAF ventilation is much lower than from MV in the vicinity of a lying patient because of the mixing process of supply air and ambient air in ORs. The variation in turbulence intensity has a similar trend as the velocity variation inside thermal plumes. Unlike velocity profiles, the turbulence intensity of the center part of thermal plumes may be higher than the outer layer of the plumes. The air turbulence intensity level of supply airflow from MV may be relatively stable—in the range of $35\% \pm 5\%$—close to the body surface, whereas the airflow turbulence intensity from LAF ventilation increases dramatically within 10 cm of a patient's waist and pelvis (varying from 10%-35%). The mixing process of supply air and room air may mitigate the transmission of contaminants from sources to surgical site. This may indicate that the effect of various contaminant sources on the air quality around the surgical site may not be significant compared to LAF ventilation.

CONCLUSIONS

Compared to MV, the LAF system should be calibrated for all surgical facilities using simulated patients and surgical staff to ensure that air velocity fulfills operating zone requirements based on a comparison of measured air velocity in each case and the national standards. However, there is little information in current guidelines and standards regarding desired local temperature and turbulence intensity of airflow in the vicinity of lying patients. The results of this study may be used to develop guidelines for the design, commissioning, and inspection of the operating microenvironment with respect to air velocity, local air temperature, and air turbulence intensity in orthopedic ORs to prevent and control SSIs.

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