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Experimental measurements of surgical microenvironments in two operating rooms with laminar airflow and mixing ventilation systems

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A R T I C L E I N F O

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A B S T R A C T

At present, laminar airflow (LAF) systems and mixing ventilation (MV) systems are two commonly used ventilation solutions for operating rooms (ORs) to ensure the required indoor air quality. However, recent studies have shown that there is little difference in the prevalence of surgical site infection (SSI) for the LAF systems and MV systems. The objective of this study was to compare the performance of an LAF system with an MV system in ORs at St. Olavs hospital, Norway. In this study, all the experimental measurements were conducted in real ORs with LAF and MV systems. This study found that the air velocity above the surgical incision is approximately two times higher in the OR with LAF than that in the OR with MV. The use of surgical lamps and different airflow patterns may contribute to the different surgical microenvironment of ORs with LAF and MV.

1. Introduction

A surgical site infection (SSI) is an infection within 30 days post surgery. SSIs account for 36% of nosocomial infections and are the most common hospital-acquired infections for surgical patients in modern hospitals [1]. SSIs can be classified by their location, which indicates their severity. Superficial infections involve only the skin or subcutaneous tissue, while those involving deep soft tissues are referred to as deep incisional infections. The most severe infections involve organs or body spaces [2]. In Norway, the average SSI rate of hip surgery ranged from 3.3% to 3.6% between 2015 and 2018. However, more severe variations can be observed for St. Olav's Hospital over the same time period [3]. The general health and disease states of the patient, as well as proper technique and sound judgment being exercised by the surgical team, are the most critical factors in avoiding postoperative infections and are difficult to quantify. However, especially for procedures with low infection rates (<3%), the development of SSIs is related to airborne exogenous microorganisms [4].

A Spanish study including 18,910 patients investigated both environmental and patient variations in relation to SSIs [5]. A percentage of 6.7% experienced SSIs, but the definitions and procedures related to tracking SSIs vary, causing uncertainty when performing comparisons. Superficial SSIs were associated with environmental factors, such as temperature, humidity and surface contamination. Higher relative humidity was linked to a higher risk of SSIs. However, these were room characteristics and not directly linked to the surgical wound environment. Another study regarding humidity in operating rooms also found an increase in SSI rates with increased humidity, although the differences in the study were not statistically significant [6].

Thermal comfort is defined as that condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation [7]. An operating room is one of the most controlled work environments, and it is important that the environment is perceived as comfortable and healthy for both the surgical staff and the patient [8]. For the surgical staff, it is important to maintain thermal comfort so that they can perform their work. If the surgical staff experience thermal discomfort, they are either too cold or too warm in their working environment. The sensation of thermal discomfort can affect their well-being and lead to poor work efficiency, headache and dizziness. Thermal discomfort for the patient could mean that the thermoregulatory responses of the human body are suppressed, which can cause illness and, in some cases, death [9].

Thermal comfort depends on six parameters. They are divided into two groups: environmental parameters, which consist of the air temperature, mean radiant temperature, relative air velocity and relative humidity of the air, and personal parameters, which consist of the metabolic rate and clothing insulation [7]. According to ASHRAE [7], an acceptable thermal environment is an environment that 80% of occupants find thermally acceptable. The focus should be to achieve the environmen-

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Nomenclature

A	wound area (m^2)
B	temperature factor (K)
c_p	specific heat at constant pressure (J/kg•K)
h_c	convection heat transfer coefficient (W/m^2 •K)
h_r	radiation heat transfer coefficient (W/m^2 •K)
h_m	convection mass transfer coefficient (m/s)
h_{fg}	the latent heat of vaporization (J/kg)
k_{air}	conductivity of air (W/m•K)
L	characteristic length (m)
Le	Lewis number
M_w	molecular weight of water (kg/kmol)
n''_w	vapor transfer (kg/m^2•s)
$P_{w,i}$	water pressure at the temperature of the point above the incision (N/m^2)
$P_{w,sat}$	saturated water pressure at the temperature of the point above the incision (N/m^2)
q''_{conv}	convective heat transfer (W)
q''_{rad}	radiant heat transfer (W)
q	heat transfer (W)
R	gas constant (J/kg •K)
Ra_L	Rayleigh number by length scale.
Nu	Nusselt number
T	temperature (K)
T_i	air temperature above wound (K)
T_s	surface temperature (K)
T_{sur}	surrounding temperature (K)
ε	emissivity (0< ε <1)
σ	*Stefan–Boltzman constant* (5.67×10^{-8} W/m^2 •K^4)
ρ	density of fluid (kg/m^3)
$\rho_{w,s}$	density at the temperature of the surface (kg/m^3)
$\rho_{w,i}$	density at the temperature of the point above the incision (kg/m^3)

tal conditions where the highest possible percentage of the occupants feel thermally comfortable [10]. Standards and guidelines regarding the ventilation of operating rooms often provide ranges for environmental parameters rather than one specific value. This has to do with the different surgical procedures being performed at a hospital and each procedure's requirements for the indoor environment. When determining the requirements for one specific OR, the needs of the patient and the surgical team and the security aspects of infection control need to be considered [11]. Two ventilation strategies usually used in operating rooms are mixing ventilation (MV) and laminar airflow (LAF).

The working principle of MV is to supply air to a room with an air velocity high enough to create full mixing throughout the room [12]. The air velocity must be high enough so that the total air volume in the room is moved [13]. It is important to supply air at a velocity that can create full mixing in the room while considering that noise might be generated. The purpose of creating full mixing throughout the room is to mix the supply air with the existing air to dilute whatever the contaminants are present. To avoid draught in the zone of occupancy, the supply diffusers are usually located in the ceiling or on the wall.

LAF is normally used in cleanrooms such as operating rooms to prevent back swirling of polluted air. Cleanroom ventilation requires high airflow rates, which is why the ventilation is typically arranged by recirculating the air through a bank of high efficient particulate air filters (HEPA) [13]. In a hospital environment, the ventilation is a unidirectional airflow through the clean zone or room. This unidirectional airflow typically has a velocity between 0.3 and 0.5 m/s [13]. The airflow is highest at the center of the HEPA filter and decreases towards the periphery. The movement of the surgical staff is an important factor with LAF ventilation and can transport bacteria to a sterile zone [1]. Fig. 1 shows the working principle of both MV and LAF. As a matter as fact, using LAF has been recommended in several national guidelines and standards [14–17]. The great effort of previous studies have been made on the performance of various ventilation solutions regarding airborne contamination levels and the whole airflow pattern in the room [18–22]. However, very little studies have been done regarding the surgical microenvironment under various ventilation strategies [23]. The objective of this study was to investigate the effects of LAF systems and MV systems on the surgical microenvironments in ORs at St. Olavs Hospital. A surgical microenvironment is defined as the area close to the surgical incision, illustrated in Fig. 1.

2. Theoretical modeling

Room airflow distribution may affect the heat transfer from the surgical incision by convective heat transfer mechanisms. In addition, radiation from surfaces, including equipment and personnel, induce heat transfer. Wet surfaces can cause additional heat loss due to the evaporation of fluids [24].

The total heat transfer from the surgical wound can be denoted as shown in Eq. (1)

$$q = q''_{conv} + q''_{rad} \tag{1}$$

where A_s is the wound area, q''_{conv} is the convective heat transfer, q''_{rad} is the radiant heat transfer. The convective and radiant heat transfer rates are shown in Eqs. (2) and (3) [24]:

$$q''_{conv} = h_c\left(T_s - T_i\right) * A_s \tag{2}$$

$$q''_{rad} = h_r\left(T_s - T_{sur}\right) * A_s \tag{3}$$

$$h_r = \epsilon\sigma\left(T_s + T_{sur}\right)\left(T_s^2 + T_{sur}^2\right) \tag{4}$$

The radiation heat transfer coefficient, h_r, is determined from the surface temperature and surrounding temperature. The convective heat transfer is determined from the surface temperature and temperature directly above the wound, T_i.

Assuming the wound geometry is nearly a flat plate with very low velocities (<0.08 m/s), with the characteristic length $L = A_s/P$, the convective heat transfer coefficient, h_c, can be found from the following Nusselt number correlation in Eq. (5):

$$Nu_L = \frac{h_c L}{k_{air}} = 0.52 Ra_L^{\frac{1}{5}} \tag{5}$$

where k_{air} is the conductivity of air, and Ra_L is the Rayleigh number by length scale.

In this study, mass transfer is limited to moisture transportation. Water vapor transfer can be expressed in a manner similar to that of heat transfer by Eq. (6) [24]:

$$n''_w = h_m\left(\rho_{w,s} - \rho_{w,i}\right) \tag{6}$$

where ρ is the density at the temperature of the surface or the point above the incision. The heat and mass transfer relations for a particular geometry are interchangeable, resulting in the following relationship between the heat and mass transfer coefficients as shown in Eq. (7):

$$\frac{h}{h_m} = \rho * c_p * Le^{1-n} \tag{7}$$

Neglecting the net radiative heat transfer under steady-state conditions and treating the air as an ideal gas, the cooling effect of evaporation can be determined from Eq. (8)

$$\left(T_i - T_s\right) = \frac{M_w * h_{fg}}{R * \rho_{air} * c_p * Le^{\frac{2}{3}}} * \left[\frac{p_{w,sat(T_s)}}{T_s} - \frac{p_{water,i}}{T_i}\right] \tag{8}$$

Retrieved by the heat and mass transfer relation $\frac{h}{h_m} = \rho c_p Le^{1-n}$, n is assumed to be 1/3, where ρ, c_p and Le are all air properties. ρ is the

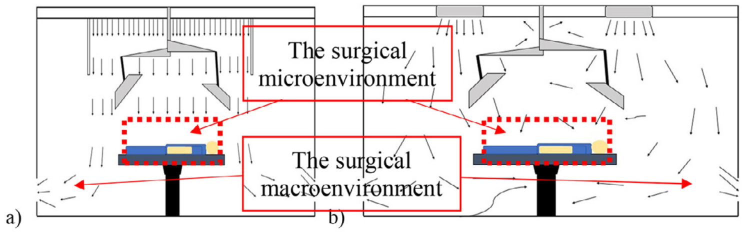


Fig. 1. Principle of ventilation systems in ORs: (a) a vertical LAF system and (b) a MV system [13].

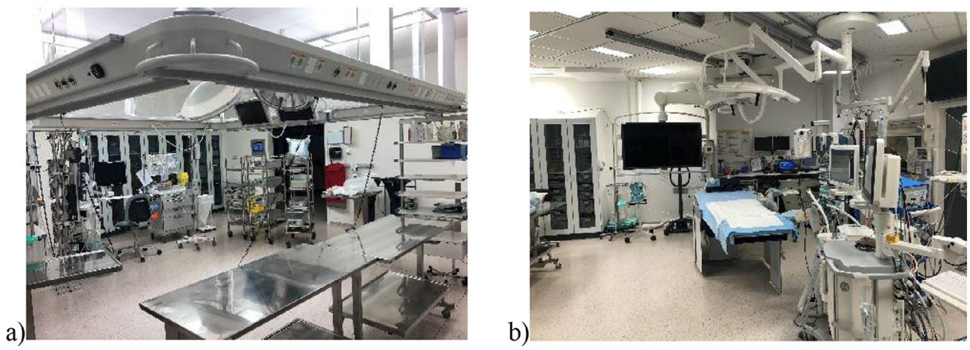


Fig. 2. Experimental setup with measurement points: (a) photo of the LAF OR; (b) photo of the MV OR.

density, c_p is the specific heat at constant pressure and Le denotes the Lewis number. M_w is the molecular weight of water, and h_{fg} is the latent heat of vaporization. All the properties are evaluated at T_i. In situations of very low humidity, $P_{w,\,i}$ can be neglected, and the surface temperature is calculated from Eq. (9):

$$T_s = \frac{T_i + \sqrt{T_i - 4B}}{2} \tag{9}$$

where

$$B = \frac{M_w h_{fg} P_{w,sat}}{R\rho c_p Le^{\frac{2}{3}}} \tag{10}$$

The evaporative heat loss can be shown in Eq. (11):

$$Q_{evap} = h_{fg} n'' A_s \tag{11}$$

3. Experimental setup

In this study, all the measurements were taken from two ORs at St. Olavs hospital in Trondheim, Norway. The OR with an LAF system had an area of 56 m^2 with a laminar airflow zone of 11 m^2 and was surrounded by 1.1 m long partial walls, as shown in Fig. 2. During the experimental measurements, the ventilation system was operated at the full load, and the room temperature was commonly set to 22.4 °C. During the experiments, the supply air temperature was measured as 20±1 °C. The designed supply air in the orthopedic LAF OR was 10,580 m^3/h, comprising 4280 m^3/h of outdoor air and 6300 m^3/h of recirculated air.

The OR with an MV system was equipped with four ceiling-mounted diffusers. For the exhaust, there were two wall-mounted exhaust outlets and one near the ceiling. The MV OR had an area of 59.7 m^2. The supply air temperature was set to 23.0 °C in all the scenarios. The supply airflow rate was 3700 m^3/h, and the exhaust airflow was 3600 m^3/h. During measurement, an adjustable stand was used to carry the anemometers.

In this study, three scenarios (see Table 1) that included six different cases were investigated. Scenario 1 (cases 1 and 2) investigated the thermal environment in the ORs. Scenario 2 (cases 3 and 4) measured the temperature and relative humidity in the ORs to calculate the heat and mass transfer. Scenario 3 (cases 5 and 6) measured the air velocity of surgical microenvironment in the ORs.

4. Measurement instruments

A variety of measuring devices were used to obtain valid results for temperature, relative humidity and velocity both in the macro- and microenvironments. To measure temperature and relative humidity close to the surgical incision, the humidity and temperature probe HMP9 (Vaisala, Finland) for rapidly changing environments was used, with a diameter of 5 mm, a measurement range of −40 to 120 °C and 0–100%RH, and measurement accuracies of ±0.8%RH and ± 0.1 °C at 23 °C. The manufacture calibration of HMP9 instrument was still valid.

A Bosch PTD 1 is a thermal detector based on infrared technology that detects the surface temperature of the surgical incision. The measuring range for surface temperatures is −20 to 200 °C for ambient temperatures between −10 and 40 °C. The accuracy at a measuring distance of 0.75–1.25 m, in an ambient environment of 22 °C, is ± 1 °C for surface temperatures between 10 and 30 °C and ± 3 °C for a temperature range of 30–90 °C. A Flir E60, displaying IR images in addition to the surface temperatures of the assigned spots, recorded thermal images and surface temperatures. Temperature measurements by the device have an accuracy of ± 2 °C for ambient temperatures between 10 and 35 °C Surface temperatures range from −20 to 120 °C, with a thermal sensitivity of 0.05 °C at 30 °C. The minimum focus distance is 0.4 m.

The TSI velocity meter was used to measure the velocity in a given direction, which was determined by the rotation of the telescoping probe. For air temperatures within −10 to 60 °C, the readings have an accuracy of 3% read value or 0.02 m/s, whichever is greater. TinyTag loggers were used to record the temperature and relative humidity room conditions in the real operating rooms at intervals of 5 min. A Pegasor Indoor Quality, with an operating temperature range of 0–40 °C, was used to measure the room conditions in cases 3 and 4. The device has an accuracy of ± 2 °C and ±1.5%RH.

The air velocity was measured at two points near the wound by using a Swema 03+ anemometer: The range of air velocity measured was 0.05–3 m/s at 15–30 °C. At 20–25 °C, the measurement uncertainty was ±0.03 m/s in the velocity range of 0.05–1 m/s or and ±3% read value in the velocity range of 1.0–3.0 m/s. At 15–30 °C, the measurement uncertainty was ±0.04 m/s at 0.05–1 m/s or ±4% read value at 1.0–3.0 m/s. The logging time for each point was 10 min, with a time interval of 1 s. The manufacture calibration was still valid.

Table 1
Scenarios of the experimental measurements.

Scenario	Case	Number of people	Ventilation mode	Remarks
S1 – real surgeries	Case 1	6	LAF	Thermal images were taken during:
	Case 2	10–12	MV	1 h 24 min (LAF), 3 h (MV)
S2 – simulated	Case 3	6	LAF	Parameters in surgical environment:
surgeries	Case 4	6	MV	relative humidity, air temperature
S3 – simulated	Case 5	6	LAF	Air velocity
surgeries	Case 6	6	MV	

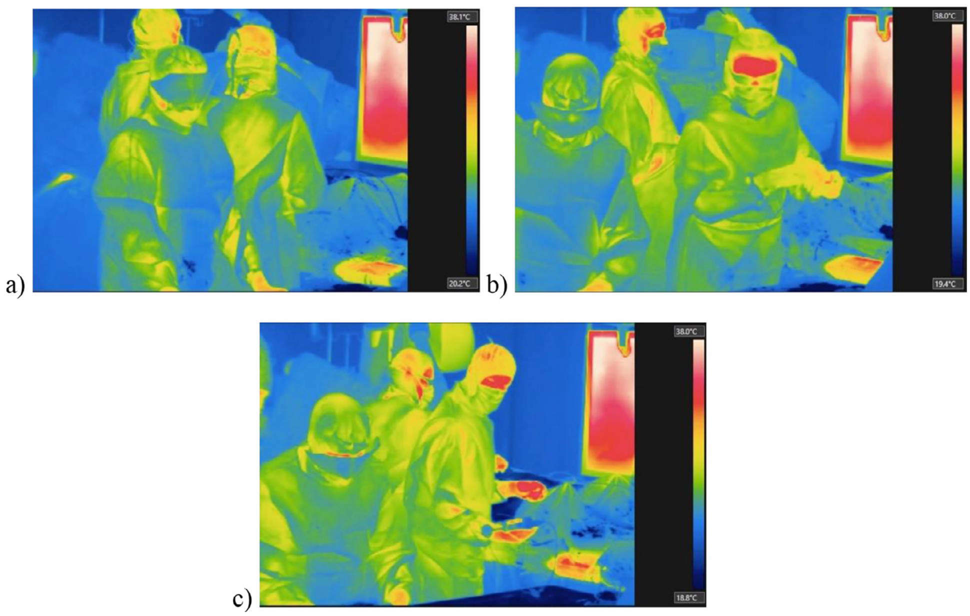


Fig. 3. Thermal images of the surgeon, assistant surgeon and sterile nurse in MV OR: (a) After 40 min; (b) After 1 h and 40 min; (c) After 2 h and 40 min.

5. Results and discussion

5.1. Thermal images of the surgical microenvironments in two operating rooms

The footage from the thermal camera is used to evaluate the surface temperature distributions in both operating rooms. Figs. 3–5 show the temperature distribution of the surgeon, assistant surgeon and sterile nurse in both operating rooms. The surgery in the MV OR was the insertion of a stent graft to prevent an aneurysm from growing. This surgery lasted for approximately 3 h. The surface temperatures of the surgeon and assistant surgeon are generally higher than the surface temperature of the sterile nurse (Fig. 3). This can be explained in two ways. The first is that the surgeons have a higher activity level than the sterile nurse, which leads to more sweating and heat released from the body. The second aspect is the fact that the surgeons are located closer to the surgical lamps and medical equipment. The equipment releases heat, which can be absorbed by the clothing of the surgeons, thus increasing the surface temperature. It can also be observed that the surface temperatures of all three members of the surgical staff is increase during the surgery, which is the expected result. The workload during the surgery, in addition to being in the same room with high air temperature and low relative humidity, leads to an increasing surface temperature throughout the surgery.

For the LAF OR, a knee replacement was conducted, which lasted for approximately 1.5 h. The tendencies observed (Figs. 4 and 5) are the same as those in the MV OR. Generally, the surface temperature of the surgeons is higher than that of the sterile nurse but not as clearly as Fig. 3 shows. Mainly the head and facial region has a higher surface temperature. This could be because of sweat from the forehead due to hard and tiresome work. One explanation for why the temperature difference between the surgeons and the sterile nurse is smaller under LAF could be the impact of the lamps. The field measurements show that the lamps in the MV OR emit more heat than the lamps in the LAF OR. Because of this, the surgeons in the LAF OR absorb less heat from the lamps. This could affect the surface temperature of the clothing and be a causative factor as to why the difference between the surgeons and sterile nurses is smaller. For the MV OR, the surface temperatures for all three individuals increase during the surgery, as expected.

5.2. Measured temperature and relative humidity

The surgical macroenvironment parameters, including air temperature and relative humidity (see in Fig. 2), were measured by a Pegasor Indoor Quality and were very stable throughout the experiments. The measured average room temperature in LAF OR is 21.2 ±0.47 °C, and the measured average relative humidity is 14.6 ± 0.73%. The measured average room temperature in MV OR is 24.6±0.17 °C, and the measured average relative humidity is 21.7±0.55%.

In the surgical microenvironment, the temperature and relative humidity were measured approximately 1–2 cm above the simulated surgical incision by a Vaisala HMP 9. Fig. 6(a) shows that the measured air temperature above the simulated incision in case 3 is stable, with an exception immediately after approximately 3000 s. A drop in the measured surface temperature and temperature directly above the incision can be observed simultaneously as the relative humidity increases. The surface temperature was recorded every minute by the Bosch PTD 1, while the Vaisala HMP 9 placed approximately 2 cm above the incision measured the relative humidity and temperature close to the incision.

Fig. 6(b) shows that the surface temperature is already below a realistic value and environmental temperature; nevertheless, it is decreasing steadily. Towards the end of the simulated surgery, the air temperature

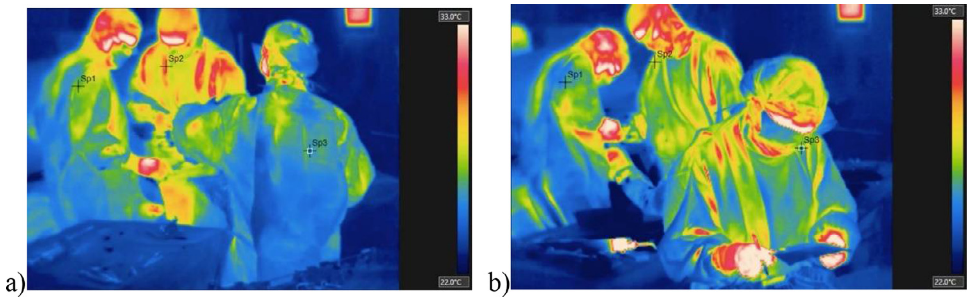


Fig. 4. Thermal images of surgeon and assistant surgeon in LAF OR: (a) After 20 min; (b) After 1 h and 20 min.

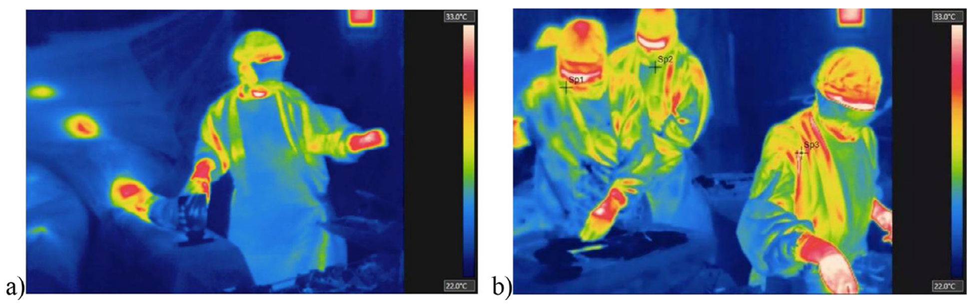


Fig. 5. Thermal images of sterile nurses in LAF OR: (a) After 1 min; (b) After 1 h.

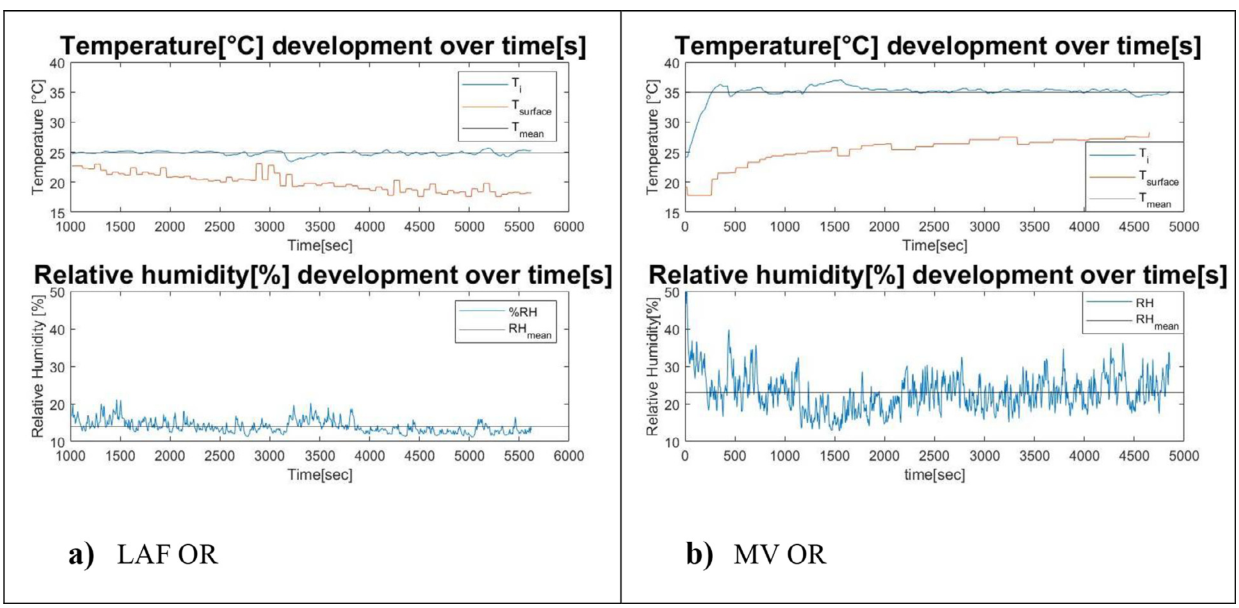


Fig. 6. Surface temperature of the incision, in addition to temperature and relative humidity measured close to the surgical wound during (a) case 3 in the OR with LAF (b) case 4 in the OR with MV.

is approximately 8 °C higher than the surface temperature. The higher air temperature in the surgical microenvironment may be caused by low air velocity comparing with the situation with LAF. Nevertheless, the surface temperature is still decreasing. The liquid always remaining at the surface suggests that the cooling effect of evaporation is larger than the heating from the higher room temperature under the given conditions.

Prior to the "start", surgical lamps are turned off in case 4. A slight decrease in the temperature above the incision can be observed at this stage. However, when the surgical lamps are turned on, a rapid change in the air temperature occurs. The surface temperature also increases, but naturally with a slower pace. The relative humidity levels follow an inverse pattern, resulting in a humidity peak at the lowest air and surface temperature measured. An explanation for the inverse pattern is the capability of warmer air to hold more moisture. This implies that for the same absolute humidity level, lower relative humidity is reached in warmer air. This justification suggests that the absolute humidity level does not increase enough to obtain the same relative humidity, even when evaporation from the incision occurs. After some time, the surface temperature converges towards a value of approximately 28–29 °C. Being able to have a significantly higher and more realistic surface temperature in the beginning would probably cause a more stable value throughout the surgery.

The correlation between the relative humidity and temperature suggests that low humidity levels appear for higher temperatures. Further investigation shows that almost one-third of all the measuring points are below the recommended RH value, as shown in Fig. 7. For higher temperatures, even lower RH values are measured. Near 37 °C, the lowest RH value is observed, slightly below 13%. The goal of the mixing airflow ventilation principle is a uniform air distribution. However, the mi-

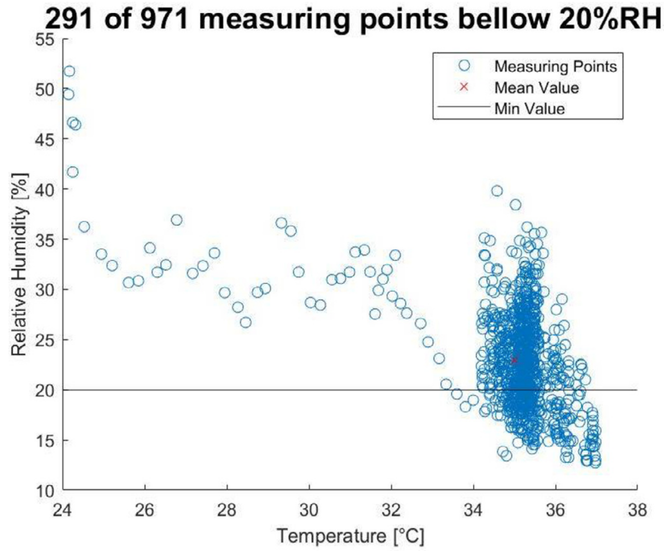


Fig. 7. Relative humidity plotted with the corresponding temperature.

croenvironment differs significantly from the overall room conditions. The results suggest that to obtain a certain relative humidity in the operating microenvironment, temperature is critical, which here is affected by the surgical lamps.

5.3. Calculated incision surface temperature

The theoretical modeling applied to case 3 suggests the introduction of a time-dependent variable for better approximation of the surface temperature. As almost a linear trend is observed for the surface temperature, a linear time parameter should be further investigated.

Applied to case 4, another trend can be observed. Going towards the steady surface temperature, the approximation is close. However, the inertia in surface heating, due to the thermal properties of the incision, is not sufficiently considered and should be studied in further work. Moreover, the dynamic process of evaporation of the surgical incision may not be accurately expressed and should be studied in further work.

Fig. 8 presents the results calculated by Eqs. (9) and (10), while all air and water properties are found in tables [24].

5.4. Measured airflow velocities

Fig. 9 shows that the air velocity fluctuates over time. Point 1 was above the wound, and Point 2 was above the knee at a height of 3.3 cm from the wound and knee. The point close to the wound experiences a higher air velocity than the point close to the knee. In the LAF OR, the vertical laminar airflow directly flows to the surgical microenvironment. In the MV OR, the supply air swirls into the room from four ceiling-mounted diffusers, and the airflow velocity is decreasing in the surgical microenvironment. Hence, the air velocity above the wound and knee is higher in the LAF OR than that in the MV OR. This may support one of the latest studies which found that in ORs with high-volume, unidirectional vertical airflow systems had lower risk of revision due to infection than in ORs with MV systems [25].

6. Conclusion

This study focused on the surgical microenvironment in two ORs with LAF and MV systems. By using a thermal camera, the thermal environment and comfort of the surgeon, assistant surgeon and sterile nurse were investigated. Based on the measurement results, conclusions regarding the surgical microenvironment can be drawn as follows:

(1) The surface temperatures of the surgeon and assistant surgeon are higher than that of the sterile nurse in both ORs.
(2) A higher surface temperature over time leads to the sensation of being warmer in the OR with MV than in the OR with LAF and thus causes thermal discomfort.
(3) The temperature of surgical incision microenvironment in the OR with MV becomes warmer than in the OR with LAF due to lower airflow velocity.
(4) The air velocity at a point of 3.3 cm from the surgical incision is approximately two times higher in the OR with LAF than that in the OR with MV.
(5) The use of surgical lamps and different airflow patterns may contribute to the different surgical microenvironment of ORs with LAF and MV.

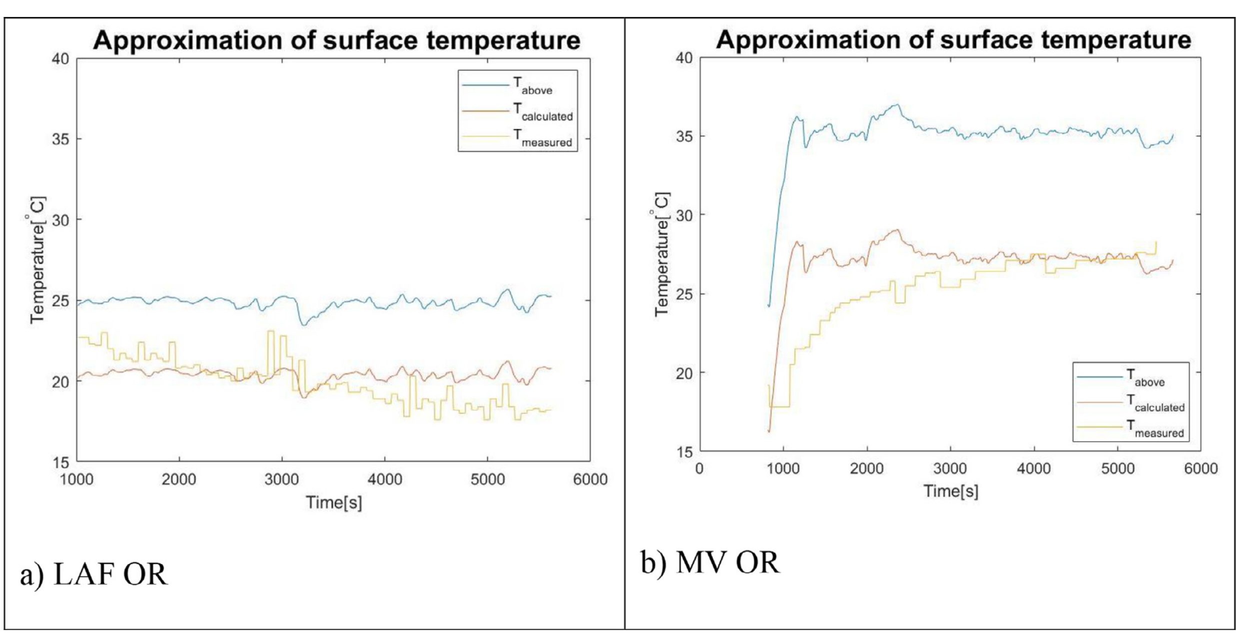
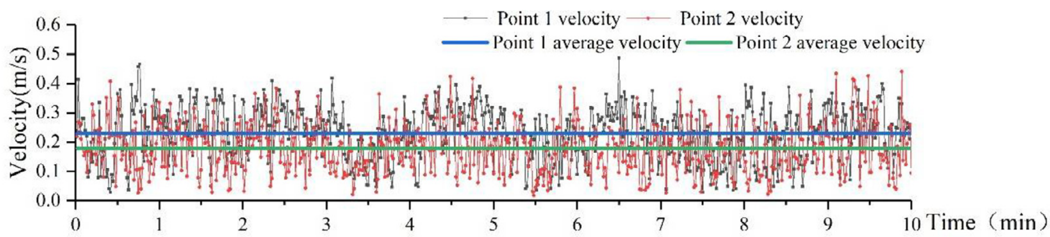
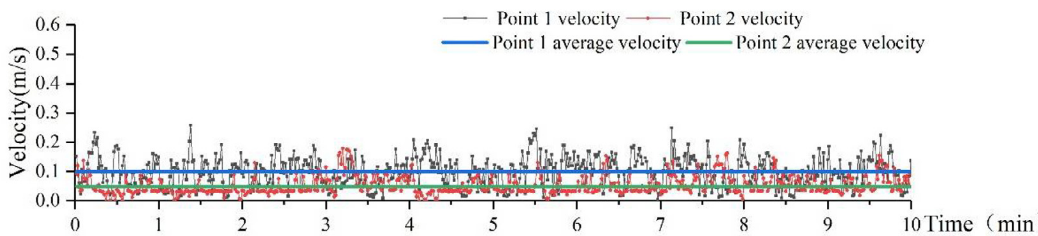


Fig. 8. Measured temperature approximately 2 cm above the incision, compared with calculated and measured surface temperatures for (a) case 3 (b) case 4.



a) LAF OR



b) MV OR

Fig. 9. The velocity measurements at two points close to the wound in two ORs for (a) case 5 (b) case 6.

The surface temperatures of the surgical staff differ because of differences in movement and location in relation to medical equipment. The fact that one OR experienced more heat emitted from the surgical lamps could have an impact on the results of thermal comfort and the surface temperature distribution obtained from observations with the thermal camera.

The results obtained from measurements in the surgical microenvironment are consistent with those of the thermal macroenvironment. In case 4, the emitted heat caused temperatures far above the recommended values, while the corresponding relative humidity values were below the recommendations. The goal of the mixing airflow ventilation principle is a uniform air distribution. However, the microenvironment differs significantly from the overall room conditions. The results suggest that to obtain a certain relative humidity in the operating microenvironment, one critical factor is local temperature, which will be affected by the surgical lamps.

In case 3, less heating from surgical lamps causes a slower evaporation of wound moisture. However, the evaporative cooling effect is suggested to be greater than the net heat gain due to radiation and convection from warmer, ambient environments. As the set values in the investigated operating room are below recommended values, further investigation is needed to evaluate the impact of these parameters. The presented equations provide a reasonable estimate of surface temperature in the surgical microenvironment. Nevertheless, further investigations and confirmation of these results are necessary. In particular, theoretical models related to moisture transfer need more validation.

Declaration of Competing Interest

None.

Acknowledgments

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