Experimental study on the thermal plume from a surgeon in an operating room with mixing ventilation during COVID-19 pandemic

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ABSTRACT

Following the outbreak of COVID-19 (SARS-CoV-2) in 2019, studies show positive results in protecting the surgical staff from patients infected by COVID-19 in operating rooms (ORs) with negative pressure. A negative pressure environment inside the operating room (OR) reduces the virus's circulation outside the OR (Chen et al., 2020). Nevertheless, it is unclear whether the surgeon's thermal plume can impact the transport of contaminants up to the breathing zone and thus cause infection in ORs with various pressure differences compared to adjacent rooms. The results show that a gap between the surgical manikin and the operating table greatly affects the development of the thermal plume from the head surgeon. A plate between the surgical manikin and the operating table may significantly influence the airflow distribution in front of the head surgeon more than the pressure difference inside the operating room.

INTRODUCTION

Outbreaks of viral infections have been shown to spread rapidly during the last years, first the SARS outbreak (SARS-CoV) in 2003 and then the COVID-19 (SARS-CoV-2) outbreak in 2019. It is crucial to ensure a safe OR environment for both patients and medical staff exposed to infectious contamination during a pandemic. Negative pressure operating rooms can reduce the circulation of the virus outside the OR (Chen et al., 2020). Typical operating rooms have positive pressure compared to adjacent areas and prevent contaminants from entering the OR. Negative pressure operating rooms are used to prevent contamination from leaving the OR. Operating rooms with negative pressure are crucial when virus outbreaks occur. Airflow distribution in an operating room causes the spread of contamination between the patient and the surgical staff. The air distribution is affected by the ventilation system, the thermal plumes, and the convective boundary layers from different heat sources in the room, such as equipment and persons. The convective boundary layer impacts particles' distribution to the breathing zone and affects the airflow around the human body (Cheng et al., 2020; Naseri et al., 2017).

It has been proven that the human thermal convection flow is essential for the spread of airborne diseases and also indoor air quality and thermal comfort (Licina et al., 2014). The convective thermal boundary layer is determined by the temperature difference between the human body and the surrounding air.

Liu, Liu, and Luo (2017) completed a numerical investigation of the boundary layer, velocity, and temperature, around a human upper body in a standard room environment with personalized ventilation. They found that the thickness of the boundary layer increased gradually from the lower part of the upper human body and further up along the body because of the constant heat exchange between the human body and the surrounding air. They also observed that the highest velocity was at chin height, which was slightly higher than at chest height. The velocity profile ranged from 0.075 m/s at hips height to 0.17 m/s at chin height.

Licina et al. (2014) investigated the human thermal plume in a quiescent indoor environment. For an ambient temperature of 20 °C, the highest mean velocity was generated at chest height, 3 cm from the body surface. From chest to chin height, the velocity was reduced before increasing after collision with the chin. At forehead height, the velocity was as high as it was at chest height.

Bolashikov et al. (2011) investigated the airflow at the breathing zone for a seated person with and without a plate between the abdomen and a table and personalized ventilation. The plate was used as a passive method to increase the quantity of clean air to the mouth region and block the rising convective flow from lower parts of the body. The free convective layer at the mouth region was reduced with the plate present. It was concluded that, inside the convective boundary layer, the absolute velocity at the mouth region decreased to 0.1 m/s when the plate was attached, compared to 0.19 m/s without the plate. It was also shown that the convective boundary layer at mouth height was more comprehensive without the plate compared to the case with the plate. The airborne pollutants from the leg region would not reach the breathing zone with the plate present. If there is a small gap between the table and the abdomen, the airborne pollutants may be entrained by the rising thermal plume and reach the breathing zone.

The aim of this study is to quantify the thermal plume in front of the head surgeon in an operating room with mixing ventilation under different pressures and scenarios.

THEORETICAL MODELLING

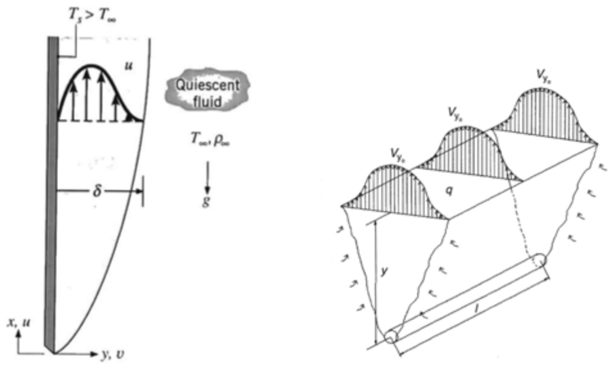
To achieve thermal comfort in a specific indoor environment, the core temperature must be relatively stable. This is obtained when there is a balance between the metabolic heat rate production and the heat loss to the surroundings. The temperature difference between the surrounding air and the body surface leads to a heat transfer, convective and radiative, between the body and the surrounding environment (Craven and Settles, 2006). In this study, only convective heat transfer will be taken into account. The convective heat transfer equation is shown in Equation 1 below (Incropera et al., 2017).

$$\dot{Q}_k = h_c * A_c * (T_s - T_0) \tag{1}$$

Where $\dot{Q}_k$ is the convective heat output [W], h_c is the convection coefficient [W/m^{2}K], A_c is the convective surface area [m^2], T_s is the surface temperature [K] and T_0 is the surrounding air temperature [K].

A body surface temperature higher than the surrounding air temperature separates the human skin from the ambient atmosphere by a boundary layer of convective air (Lewis et al., 1969). This convective boundary layer will develop into a plume due to the buoyancy effect caused by the density differences, dependent on the temperature change. The more significant the temperature difference between the body surface and the surrounding air temperature, the stronger the thermal plume. Heat sources with a higher temperature than the surrounding air will create upward flow at these sources, and convective heat transfer will occur (Incropera et al., 2017).

In a rising plume, the initial velocity is low but increases with height due to buoyancy. A hot vertical plate, seen in Fig. 1a, can be assumed as a standing person. In Fig. 1a, the surface temperature, T_s, is greater than the ambient temperature, T_∞. This means that the fluid closest to the heat source has less density and will rise vertically, simultaneously pushing the quiescent fluid further away (Incropera et al., 2017). Fig. 1b shows the thermal plume from a line source. A line source can be associated with the thermal plume from a person in a supine position (Awbi, 2004).



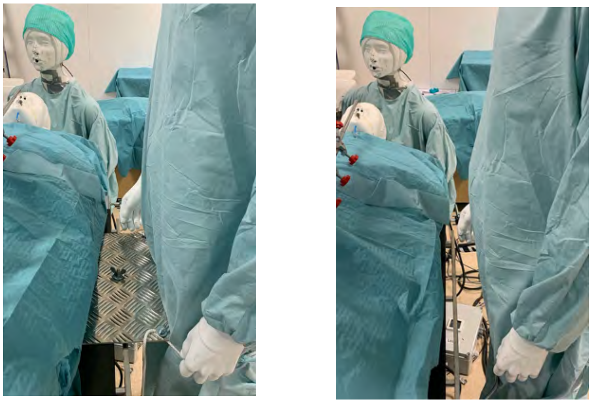
(a) (b)

Figure 1: (a) Velocity boundary layer generation on a vertical heat source (Incropera et al., 2017). (b) Thermal plume from a line heat source (Awbi, 2004).

METHODOLOGY

All experimental measurements were done in the same OR lab located at Gløshaugen, NTNU Trondheim. The OR lab's internal area is 61.55 m^2, the length is 8.73 m, and the width is 7.05 m. The internal volume of the lab is 200 m^3.

Four cases of measurements were performed to investigate if a gap between the head surgical manikin and the OR table influences the thermal plume in front of the head surgeon. The setup with and without a gap can be seen in Fig. 2.



(a) (b)

Figure 2: (a) Metal plate between the surgical manikin and the operating table. (b) No metal plate between the surgical manikin and the operating table.

Velocity measurements were conducted to investigate the thermal plume in front of the head surgical manikin in an operating room for different pressures. The same measurements were done for four different cases, each case containing two scenarios. The cases are presented in Table 1:

Table 1. Overview of the four different cases.

	Pressure difference between the OR lab and adjacent rooms	With or without plate between the surgical manikin and the operating table
Case 1	10 Pa	With a plate
Case 2	-5 Pa	With a plate
Case 3	10 Pa	Without a plate
Case 4	-5 Pa	Without a plate

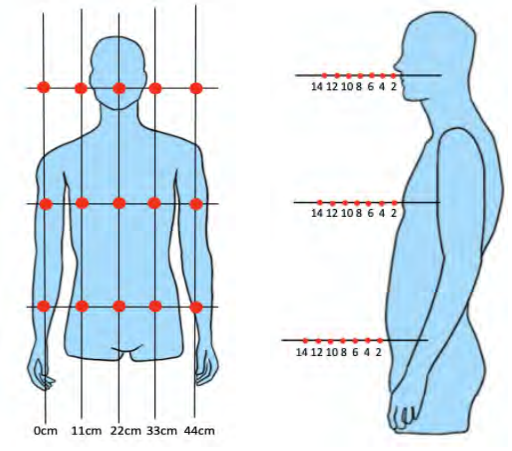
In scenario 1, only heat gain from the head surgical manikin is provided. In scenario 2, heat gain from the head surgeon, the assistant surgeon, two nurses, one anaesthesiologist and the patient, represented by manikins. An overview of the manikins and the OR lab can be seen in Fig. 3.

Figure 3: Picture of the OR lab.

After watching two recordings of actual surgeries performed at St. Olavs Hospital in Trondheim, Norway, it was clear that the OR lab at NTNU is similar to the actual operating room at St. Olavs when it comes to the placement of equipment and surgical staff. During the actual surgery, the surgeons were placed on opposite sides of the operating table, and they did not move around during the surgery. Significantly, the head surgeon was placed very close to the table, alternating between leaning over the wound area and standing upright. There were two nurses, one standing by an equipment table at the end of the operating table and the other placed a little further away by another equipment table.

Measurement points

The measurement points are shown in Fig. 4.



(a) (b)

Figure 4: Measurement points: (a) From the front. (b) From the side.

Five anemometers were aligned on a movable stand. The center of the manikin was the reference point, and the middle anemometer was placed in line with this point, as shown in Fig. 4a. The measurements were taken at seven different distances from the manikin, as can be seen in Fig. 4b. At 14 cm from the surgical manikin, the anemometers were placed right over the patient's arm. This can affect the results in scenario 2. The measurements were taken at three different heights starting at 118 cm above floor level, and this is by the head surgeon's hips. The following measurements were taken at the head surgeon's chest, 148 cm above floor level. The last measurements were placed by the head surgeon's mouth, 176 cm above floor level. Hence, 105 measurements were used for both scenarios in all four cases. The distance between the surgical manikin and the table was approximately 11 cm.

OR and measurement equipment

The OR lab is equipped with two different air handling units (AHU). The supply temperature of one of the AHU cannot be determined, making it hard to regulate the temperature of the air supplied to the OR lab. Depending on which day the measurements were conducted, the room air temperature varied between 19 °C to 22.5 °C, and the relative humidity ranged between 33 % and 40 %. Measurements of the airflow velocity were performed by the AirDistSyst 5000, delivered by Sensor Electronic. The logging of the measurement lasted for three minutes, and values were recorded every two seconds. The AirDistSyst 5000 measures the magnitude of the speed and not the direction of the speed. Even so, the results are presented as velocity plots since this is the usual representation within this field.

Thermal manikin

The thermal manikins used can generate heat. The surgical manikin's surface temperature was measured regularly through all the experiments and varied between 31 and 34 degrees. Throughout scenario 2, the patient's surface temperature was measured regularly, and a surface temperature of around 30 °C was maintained. The four other manikins used in scenario 2 also had a surface temperature of about 31-34 °C.

RESULTS

All measured air velocities are presented as velocity plots using the contourf function in MATLAB. The top plot in all Figures represents the mouth, followed by the chest-plot and hips-plot. The color bar on the right-hand side of the plots describes the velocity. All velocity plots are between 0.06 and 0.2 m/s. Case 1 is represented in Fig. 5. It can be seen that the velocity profiles vary for each height and scenario, which means that the velocity varies with height above floor level and also the interruption from other heat sources. Fig. 5a and Fig. 5b at hips height show the variation in velocity at hips height, and it appears that the plate is blocking the thermal plume from the surgical manikins' legs. This is an indication that the convective boundary layer has not started to develop at this point.

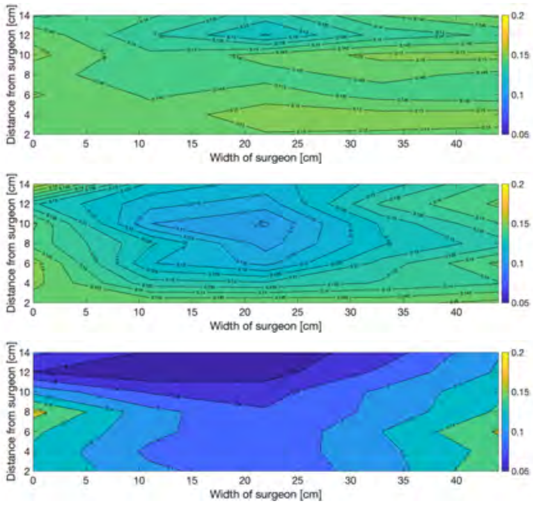


Figure 5a: Case 1 – scenario 1. Mouth, chest, hips.

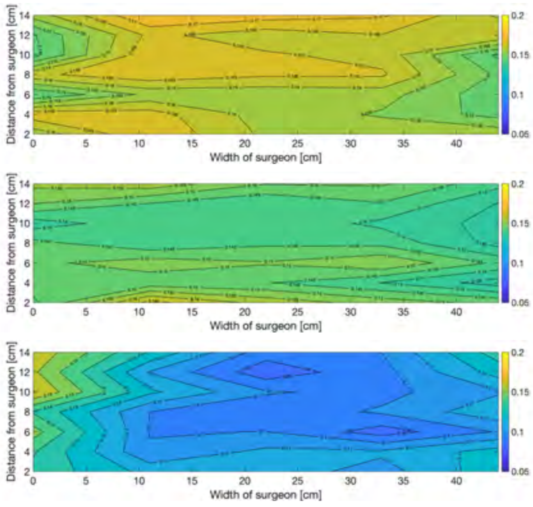


Figure 5b: Case 1 – scenario 2. Mouth, chest, hips.

The velocity profiles are similar for cases 1 and 2, where the plate was attached between the surgical manikin and the OR table and ranges between 0.06 m/s and 0.165 m/s. Case 2 can be seen in Fig. 6. The lowest velocities are observed at hips height. In contrast, the highest velocities are observed at mouth height, which is only a few centimeters above the chin. This applies to cases 1 and 2 for scenario 1, which can be seen in Fig. 5a and Fig. 6a, and is in resemblance to the study by Liu, Liu, and Luo (2017). They investigated the boundary layer around a human upper body and found that the velocity profile ranged from 0.075 m/s at hips height to 0.17 m/s at chin height.

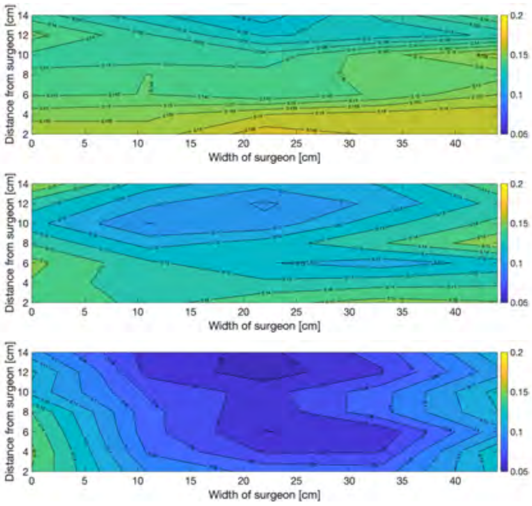


Figure 6a: Case 2 – scenario 1. Mouth, chest, hips.

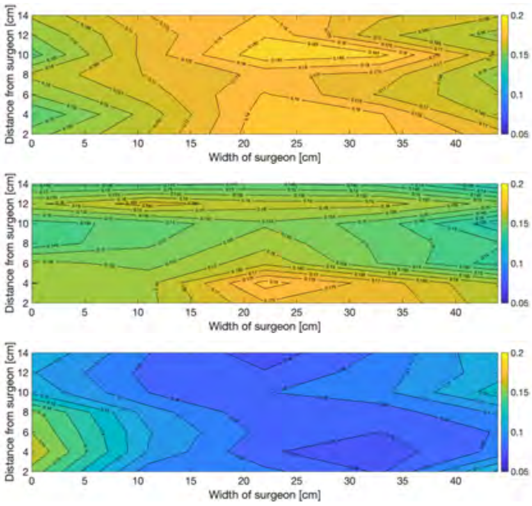


Figure 6b: Case 2 – scenario 2. Mouth, chest, hips.

A higher velocity is observed at mouth height without the plate attached (cases 3 and 4) between the surgical manikin and the OR table than in cases 1 and 2. Cases 3 and 4 can be seen in Fig. 7 and Fig. 8. This can be compared to the study conducted by Bolashikov et al. (2011) where the airflow at the breathing zone for a seated person with and without a plate between the abdomen and a table was investigated. It was found that the absolute velocity at the mouth region decreased to 0.1 m/s when the plate was attached, compared to 0.19 m/s without the plate. This study was done on a seated person but can be compared to the results in this study.

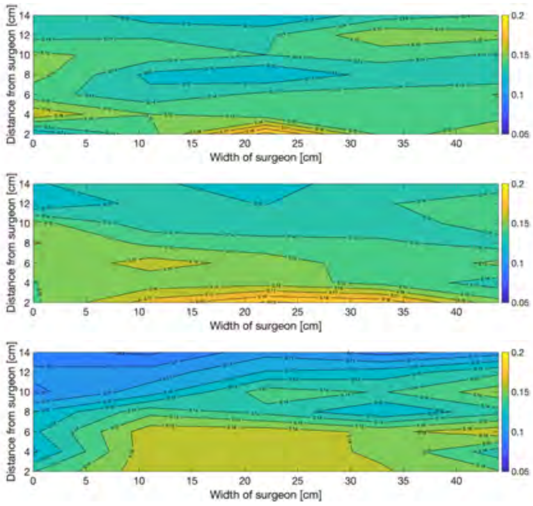


Figure 7a: Case 3 – scenario 1. Mouth, chest, hips.

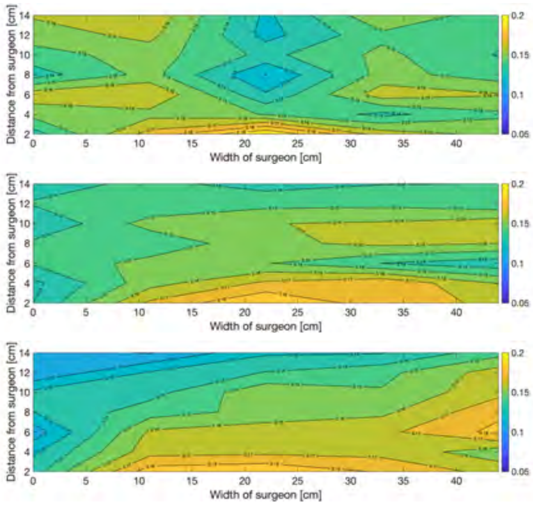


Figure 7b: Case 3 – scenario 2. Mouth, chest, hips.

Cases 1, 2, 3, and 4 for scenario 2 have a slightly higher velocity than for scenario 1. This increase in velocity from scenario 1 to scenario 2 may be due to the heat gain from the patient and the other surgical staff influencing the velocity of the thermal plume. Also, in scenario 2, the overall velocities are higher in cases 3 and 4, where the plate is removed, than in cases 1 and 2. For scenario 2, cases 1 and 2 have a velocity range between 0.08 m/s and 0.185 m/s, the velocity range for cases 3 and 4 is 0.12 m/s to 0.2 m/s for scenario 2. In cases 3 and 4, there is a small tendency for a higher velocity at a broader range in scenario 2 compared to scenario 1. However, in cases 3 and 4 for scenario 2, the influence of the heat gain from the patient and other surgical staff does not impact the velocity profile furthest away from the surgical manikin. This is in contrast to what is observed in cases 1 and 2 for scenario 2.

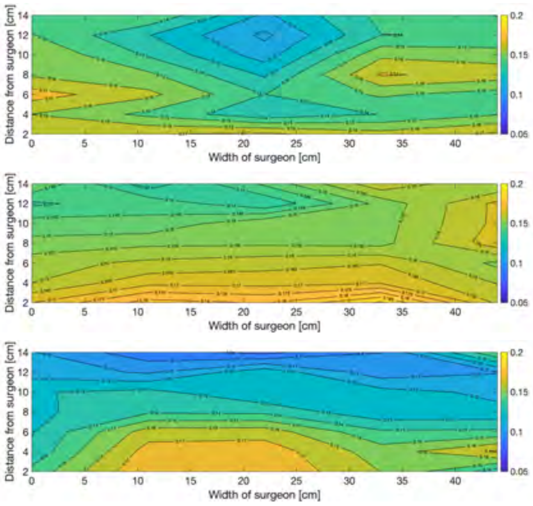


Figure 8a: Case 4 – scenario 1. Mouth, chest, hips.

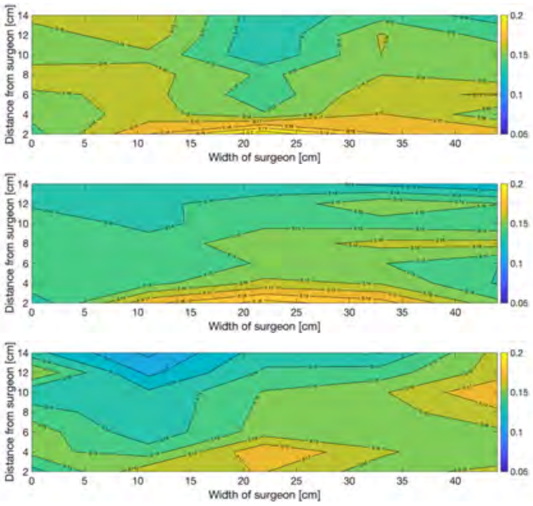


Figure 8b: Case 4 – scenario 2. Mouth, chest, hips.

In cases 1 and 2, a typical boundary layer is not recognized at hips height due to the plate blocking the heat gain from the surgical manikin's legs. This applies to both scenarios. The measurement points at hips height are placed 118 cm above floor level, which is about 30 cm above the metal plate. The characteristic convective boundary layer flow will not affect the measurements due to the small distance between the metal plate and the measurement points. Therefore, the classic thermal plume flow is not recognizable at hips height for cases 1 and 2. This is also in relation to theory, where it is described that the initial velocity of the boundary layer is low and increases with height due to buoyancy.

DISCUSSION

In all cases, for both scenarios, the highest velocities are found to be closest to the surgical manikin. Fig. 1a clarifies that the velocity within a convective boundary layer increases rapidly from the heat source to a small distance from the source. This suggests that the heat generated by the surgical manikin increases the velocity close to the body surface. This corresponds to the study by Licina et al. (2014), who found that the highest velocity was generated close to the body surface.

In scenario 2, for cases 1, 2, 3, and 4, the highest velocities are found at mouth height. This is slightly higher than the velocity at chest height. This corresponds to the study completed by Liu, Liu, and Luo (2017), where it was found that the velocity increased with increasing height above floor level. For cases 1 and 2 in scenario 2, it is evident that a higher velocity is located close to the body surface of the surgical manikin but also farthest from the surgical manikin. This is especially noticeable at mouth and chest height. This can be compared to the width of the patient's thermal plume, which increases with increasing height above the patient. This corresponds to Fig. 1b.

In cases 1 and 2 for both scenarios, the thickest/widest part of high velocity is found at mouth level. This corresponds to Fig. 1, where it is observed that the thickness of the boundary layer increases with height. It also corresponds to the study by Licina et al. (2014) and Liu, Liu, and Luo (2017), where it was concluded that the convective boundary layer's thickness increases with increasing height above the floor. For case 3, the thickness of the convective boundary layer is greatest at hips height, compared to chest and mouth height. This is in contrast with the investigation completed by Licina et al. (2014). Case 4 illustrates an increase in the convective boundary layer's thickness from hips to chest height before the thickness decreased at mouth height. This can be seen in Fig. 4 and shows a broader connection to the study done by Licina et al. (2014).

Particles and pollution are transported around the human body depending on the convective boundary layer's design (Nilsson, 2003). The convective boundary layer can transport particles with a diameter of up to 80 μm (Clark and Calcina-Goff, 2009). A thicker and faster boundary layer will transport more particles through it. Cases 3 and 4 for scenario 1 show a thicker and faster boundary layer in front of the surgical manikin. This type of convective boundary layer indicates that more particles will be transported up along the human body in these two cases than in cases 1 and 2. Bolashikov et al. (2011) used a plate between the abdomen and a table to increase the clean air quality to the mouth. The plate's absence in cases 3 and 4 will lead to more particles dispersing from the floor. This particle transportation from the floor will not occur to a great extent in cases 1 and 2, where the plate will prevent most of the particles dispersing from the floor from being transported to the upper body. The relative humidity inside the OR lab varied between 33 % and 40 %. This can also affect the dilution and dispersion of particles. The particle size and weight will decrease at lower RH, which will cause the convective boundary layer to transport the particles further up along the heated surface.

The OR lab used for this experiment is similar to an actual operating room at St. Olavs Hospital in case of placement of equipment and surgical staff. From observation of a proper surgery, it is clear that the head surgeon is alternating between leaning over the wound area and standing upright, always being close to the operating table. A plate, to block the particle transportation from the floor, must therefore be adapted to the surgeon and the movements to and from the operating table.

There are some uncertainties associated with the experiments that will affect the results of this study. A thorough analysis of the results was challenging to perform because the AirDistSyst 5000 could not determine the velocity direction. A method to know the direction of the velocity should therefore be implemented to get more accurate results. Nevertheless, some interesting results have emerged from this study on how the airflow in front of the head surgeon is affected by different heat sources and different pressures.

CONCLUSION

Surgeries performed on infectious patients should be done in a negative pressure operating room to avoid viruses' transportation to adjacent areas. The thermal plume in front of the head surgeon is investigated under different pressure conditions and scenarios inside an OR lab with mixing ventilation.

The results from the velocity measurements show a slight increase in velocity from scenarios 1 to 2 in all cases and imply that the thermal plumes from the patient and the surgical staff influence the airflow in front of the surgical manikin. This study confirms that the gap between a surgeon and an operating table may affect the thermal plume of the surgeon. In this study, the plate is blocking the thermal plume in cases 1 and 2. Therefore there is an overall lower velocity and thinner velocity profile in these two cases compared to cases 3 and 4. A thicker and faster boundary layer in cases 3 and 4 may imply that more airborne contamination at a lower level of the OR room may be transported to the surgeon's mouth in these cases with a gap between the surgeon and the operating table. Therefore, to avoid airborne contamination being transported from the OR floor up to the head surgeon's mouth, a plate or any objects between the head surgeon and the OR table is recommended.

The comparison of the different cases implies that the plate between the surgical manikin and the OR table has a more significant influence on the airflow distribution in front of the head surgical manikin than the pressure difference inside the OR lab. It is clear that the airflow distribution in front of the surgical manikin does not vary significantly in a negative pressure operating room compared to a traditional operating room with positive pressure. This is important to know as the thermal plume in front of the head surgeon in a negative pressure operating room has not been adequately tested before. Further investigation will be needed to find more practical solutions to reduce the exposure of infectious contamination from infected patients to the surgical staff.

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