CFD Analysis of Ventilation Performance of the Hospital Post Anesthesia Care Unit (PACU)

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ABSTRACT

Healthcare workers in post-anesthesia care units (PACU) are at risk of exposure to waste anesthetic gases (WAGs) released by patients in the recovery stage. The airflow patterns in the PACU play a crucial role in determining the spread and concentration of WAGs in the breathing zone of the occupants. A Computational Fluid Dynamics (CFD) study was conducted to evaluate the impact of various combinations of supply and return air locations on ventilation performance in the PACU. The CFD analyses indicate that traditional HVAC layouts with 4-way supply diffusers and ceiling returns create mixing airflow patterns that distribute WAGs throughout the entire PACU, thereby increasing the risk of healthcare workers' exposure. Proposed HVAC layouts with ceiling laminar diffusers and headwall returns can induce a horizontal movement of contaminated air towards the headwall returns, significantly reducing the concentration of WAGs in the breathing zone and limiting their spread in the PACU. These analyses further indicate that the PACU with an optimized HVAC layout can operate at a reduced dilution airflow rate without significantly affecting ventilation.

INTRODUCTION

The immediate postoperative patient in the hospital is brought into a Post Anesthesia Care Unit (PACU) for recovery after surgery. These patients are sources of waste anesthetic gases (WAGs) in the PACU. These gases include nitrous oxide (N_2O) and halogenated agents (vapors) such as halothane, sevoflurane, enflurane, isoflurane, and desflurane. Exposure to waste anesthetic gases can potentially cause nausea, dizziness, headaches, fatigue, and irritability, as well as sterility, miscarriages, birth defects, cancer, and liver and kidney disease (McGlothlin et.al. 2014, 2021). The perianesthesia nurses and other care providers who primarily work in the PACU can be exposed to hazardous WAGs. The National Institute for Occupational Safety and Health (NIOSH) recommends that workers should not be exposed to halogenated agent concentrations of more than 2 ppm when used alone or more than 0.5 ppm when used in combination with N_2O over a sampling period of less than 1 hour (NIOSH, 2016). Currently NIOSH does not have specific recommended exposure limits (RELs) for the three most used anesthetics (isoflurane, desflurane, and sevoflurane) (Garcia, 2022).

The primary objective of the PACU ventilation system is to reduce the concentration of WAGs in the breathing zone of occupants, and thereby, minimize the workers' exposure to hazardous gases. Airflow patterns and the resulting flow path of WAG can affect its distribution and spread in PACU. Several factors related to the design and operation of the ventilation system can affect the occupant exposure levels. These factors include the number, location, and type of supply diffusers; supply airflow volume or air changes per hour (ach) and associated diffuser throw; supply air temperature; number, size, and locations of return/exhaust grilles; the location and strengths of various heat sources; arrangement of furniture and other obstructions to airflow; and the layout of patient beds in PACU. Physical testing of all these parameters under controlled conditions for various operating conditions is time and labor-intensive, if not impossible. Computational Fluid Dynamics (CFD) analysis provides a feasible alternative

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for systematic evaluation of these parameters (Khankari, 2016 and 2018b).

This study with the help of steady-state, non-isothermal computational fluid dynamics (CFD) simulations evaluates the impact of various HVAC layouts including supply and return locations on the airflow patterns, temperature distribution, and the concentration of sevoflurane in the breathing zone of occupants. In addition, the impact of the supply airflow rate is also evaluated. A newly developed metric of the Spread Index is employed to compare the spread of sevoflurane under different HVAC layouts and supply airflow rates.

DESCRIPTION OF THE CFD MODEL

A three-dimensional, steady-state, non-isothermal CFD model of a PACU was developed for this study. The total floor area of the model PACU space is 3026 sq. ft. (281 m^2) (68 x 44.5 feet, 20.7 x 13.6 m) with 9 feet (2.7 m) ceiling height. As shown in Figure 1 the PACU model has a total of ten patient beds and three caretakers. The patient beds are located at three perimeter walls and the caretakers are positioned at three arbitrary locations. The PACU has a total of four doors. The nurse station is located close to the two entry doors. The three perimeter walls are equipped with headwall systems to accommodate medical gas and electrical functions. As shown in Figure 1, an equipment cart and a computer are placed alongside each patient's bed.

The analysis includes two types of supply diffusers and four locations of returns, as presented in Table 1 and Figure 1. Case 1 represents a traditional overhead mixing HVAC layout, which features 4-way supply diffusers and ceiling returns. This layout is commonly observed in PACUs during field studies (Garcia, 2022). Cases 2 to 5, on the other hand, involve laminar diffusers placed over each patient bed and two laminar diffusers located above the nurse station, along with three different return locations. In Case 2, 13 returns are placed on the wall at a low level between the patient beds. In Case 3, 10 returns are placed in the ceiling close to the back wall, adjacent to the laminar diffusers. As for Case 4 and Case 5, 10 returns are placed over the headwall behind each patient bed.

Table 1: Description of HVAC layouts analyzed.

Case	HVAC Configurations Analyzed
1	4-way supply diffusers close to the patient beds and returns in the core region - 6 ach
2	Laminar supply diffusers over each bed and low wall returns in the headwall - 6 ach
3	Laminar supply diffusers over each bed and ceiling returns adjacent to the laminar diffuser - 6 ach
4	Laminar supply diffusers over each bed and headwall returns behind the bed - 6 ach
5	Laminar supply diffusers over each bed and headwall returns behind the bed - 4 ach

The non-isothermal CFD analysis was performed for a total cooling load of 11877 BTU/h (3.5kW) which includes the heat rejected from 13 persons (3250 BTU/h, 0.95 kW), 10 computers (3850 BTU/h, 1.13 kW), and 14 lights (4777 BTU/h, 1.4 kW). The supply airflow rate was set at 2723 cfm (1285 L/s) which corresponds to 6 ach (1/h). The PACU was assumed to be at positive pressure, and thus, an offset airflow of 200 cfm (94.4 L/s) was allowed to exit through the undercuts of the four doors. To meet the set point temperature of 72 F (22.2 C) in the space, the supply air temperature was set to 68 F (20 C). In addition, Case 5 with the headwall returns was analyzed for 4 ach (1/h) for the supply airflow rate of 1800 cfm (850 L/s). The sevoflurane was used as a surrogate for WAGs and released from the mouth of a patient at 2000 ppmv concentration at the temperature of 90 F (32.2 C). The breathing rate of patients is assumed to be 0.18 cfm (5 L/min) (Hiller et.al. 2015).

Spread Index (SI) $_{TC:}$ is a CFD-based metric developed to analyze and quantify the spread of contaminants in indoor spaces. It is the ratio of the volume of the space occupied by the contaminants above a certain target concentration (TC) to the total volume of the space. Ideally, the ventilation for indoor spaces should reduce the contaminant concentrations below the acceptable levels everywhere in the space and limit the spread of contaminants. Spread Index (SI) $_{TC}$ is a ventilation effectiveness metric for analyzing and quantifying the extent of the spread of contaminants above a certain threshold level in a three-dimensional space. The Spread Index provides three-dimensional visualization in identifying the contaminated zones at or above certain target concentrations. (Khankari, 2021)

Assuming the target concentration is a safe exposure limit then the WAG concentration levels should remain below the target value at all times and everywhere in the space. It means the $(SI)_{TC}$ should be always close to zero in the entire PACU space. It should be noted that the safe level of concentrations can depend on several risk factors including the type and quantities of WAGs released in the PACU. High values of $(SI)_{TC}$ can indicate the spread and build-up of contaminants above the target levels of concentration. The design of a ventilation system and the resulting airflow patterns play an important role in determining the $(SI)_{TC}$ levels in the space[6]. For this study, the target concentration of sevoflurane is assumed to be 2 ppmv. Additionally, the Spread Index values for various target concentrations are also presented

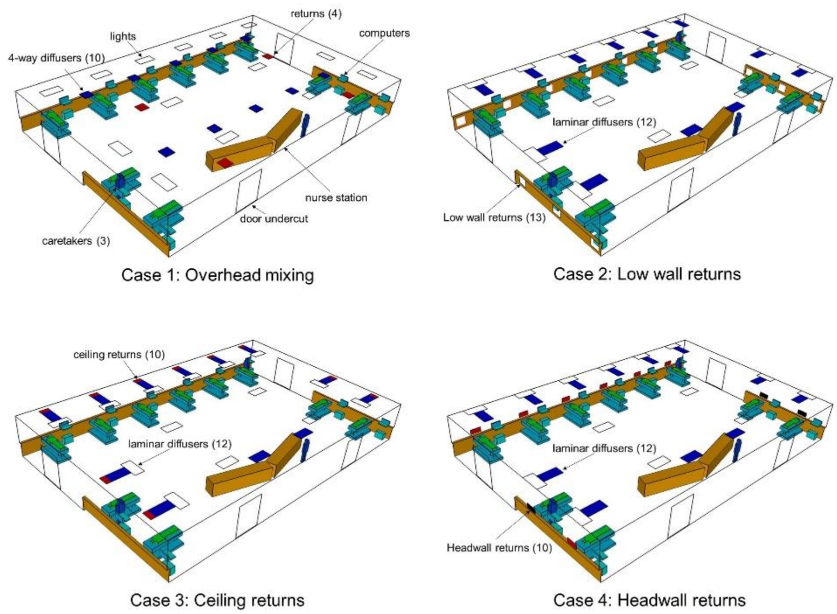


Figure 1: Schematic diagram of CFD models for four different HVAC layouts.

RESULTS AND DISCUSSION

Airflow Patterns

Figure 2 shows airflow patterns in PACU for various HVAC layouts. The flow path lines are colored by the sevoflurane concentration. This CFD analysis confirms that the traditional overhead mixing layout (Case 1) with 4-way supply diffusers and ceiling returns forms mixing airflow patterns. Once the supply air is released from the 4-way diffusers it moves along the ceiling and then flows downward after encountering another supply air stream or a wall. Such flow patterns in turn create several air recirculation zones which promote the entrainment of WAG plumes into the supply air streams. The mixing airflow patterns spread and accumulate the contaminated air in the PACU and form zones of high concentration before exiting through the returns in the ceiling.

In other cases (Cases 2 to 5), downward flow patterns are formed once the supply air is released from the laminar diffusers. Such high-velocity downward flow also entrains the surrounding air into the supply stream. However, the locations of returns play a crucial role in determining the flow path of the contaminated plumes. In the case of low wall returns (Case 2), the exhaled plume from the patient's face gets entrained into the adjacent recirculation zone formed by the downward air streams. The contaminated plume moves towards the back wall, gets lifted upward, and then mixes with the downward flow. Due to the high downward momentum of the supply air, only part of this contaminated air can exit through the low wall returns while the rest spreads into the PACU that eventually exits through other returns.

In Case 3 a part of the clean air supplied through the laminar diffusers escapes through the adjacent ceiling return without reaching the PACU space. Such a short-circuiting is not desirable. In this case, the airflow exhibits similar flow patterns as in the previous case. However, unlike the previous case, the exhaled plume from the patient's face moves sideward along the wall, gets lifted upward toward the ceiling returns where it exits the space. It should be noted that in this case also the supply air streams get contaminated due to the entrainment of the exhaled plumes.

The airflow patterns for the headwall return layout (Case 4) are similar to the low wall return layout (Case 2). However, as the exhaled plume containing sevoflurane moves toward the back wall and gets readily captured by the headwall return which is located right behind the patient's bed. Such capture of the exhaled plume close to the source (patient's face) avoids contamination of the supply air and the eventual spread into the PACU space. In contrast to the other cases, the lower concentration of sevoflurane in Case 4 as depicted by the blue color of flow path lines indicates that the supply air streams are not contaminated by the exhaled plumes from the exhaled plume.

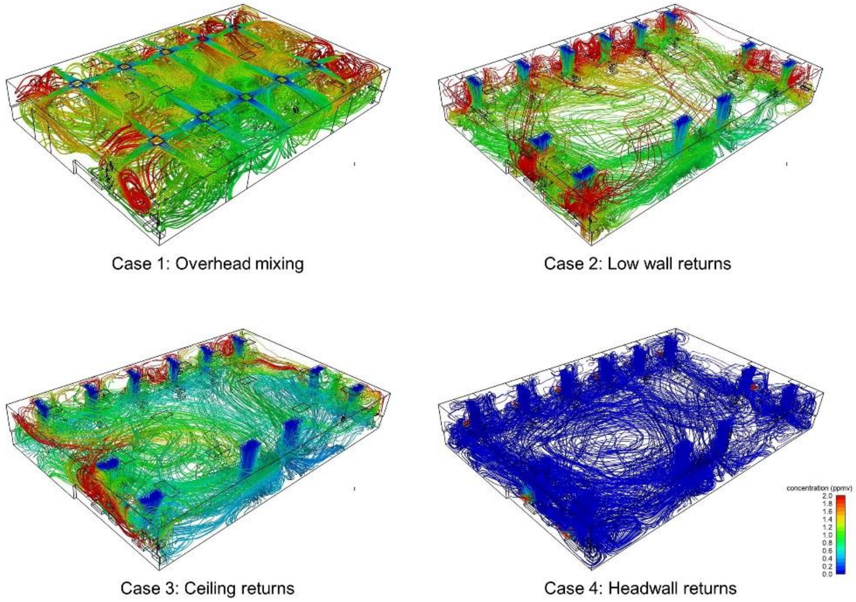


Figure 2: Airflow patterns in the PACU for four different HVAC layouts.

Distribution of Sevoflurane Concentration

Figure 3 shows the distribution of sevoflurane concentration in a horizontal plane in the breathing zone of occupants at a 4-foot (1.2 m) elevation. These figures indicate that the layout of Case 4 with the laminar diffusers and headwall return shows the most promise in reducing the WAG concentration in the breathing zone. Whereas Case 2 layout with the laminar diffusers and low wall returns shows poor ventilation performance with the highest concentration in the breathing plane. Case 1 traditional layout and Case 3 layout with the laminar diffusers and ceiling returns show similar performance in controlling the concentration of sevoflurane in the breathing zone. However, the placement of laminar diffusers over the nurse station helps in reducing the sevoflurane concentration in the vicinity. In all the cases the highest concentration of sevoflurane is shown to be around the patients' heads indicating that the highest exposure will occur when the health workers are close to the patient's face whereas those at the nurse station will experience significantly lower exposure. Placing the return behind the patient's head can be the most desirable layout for significantly lowering the WAG exposure everywhere in the PACU.

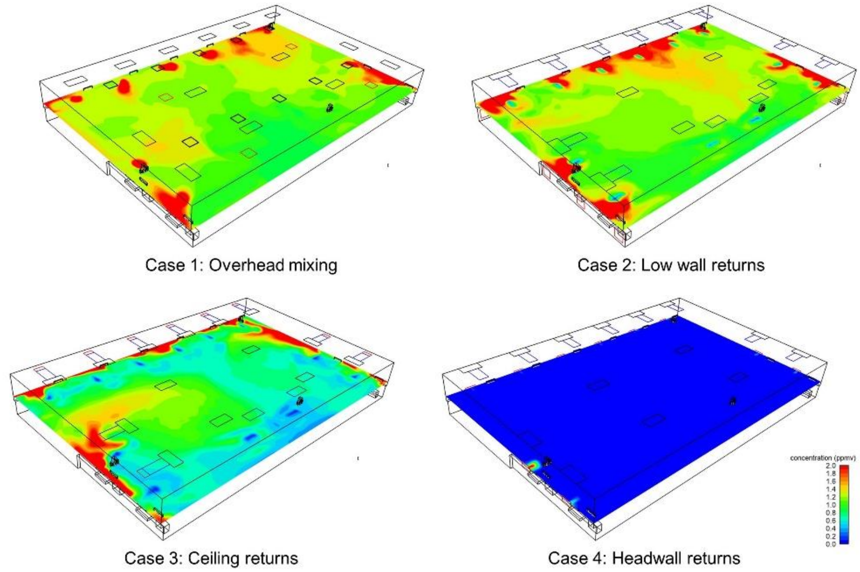


Figure 3: Distribution of sevoflurane concentration in the breathing plane at a 4-foot (1.2 m) elevation.

Analysis of Spread Index

Figure 4 shows the Spread Index $(SI)_{2ppmv}$ plots for all four HVAC layouts for the target concentration of 2 ppmv. The Spread Index values show the percentage of the PACU volume occupied by the sevoflurane concentration at or above 2 ppmv. Unlike the contour plots in Figure 3, the Spread Index plots depict a three-dimensional spread of the sevoflurane in the PACU.

As per the figure, the HVAC layout with laminar diffusers and headwall returns (Case 4) has a Spread Index value of 0.07 percent. This indicates that such a layout can significantly limit the spread of WAGs by keeping the zone of high WAG concentration close to the patient's face. Such a high concentration zone forms below the breathing zone of caretakers which is below 4- to 6-foot (1.2 to 1.8 m) elevation.

On the other hand, Case 2 HVAC layout with the laminar diffusers and low wall returns shows the highest values of the Spread Index of 17.3 percent. Case 1 with overhead mixing and Case 3 with laminar diffusers and ceiling returns layouts show similar values of $(SI)_{2ppmv}$ of about 4 percent. As explained before the vertical movement of the sevoflurane plume as in Cases 1 to 3 can potentially increase the caretakers' exposure in the breathing zone. Whereas in Case 4 layout, the horizontal movement of a sevoflurane plume below the breathing zone of occupants combined with an immediate exit through the headwall returns can significantly limit the spread of WAGs and keep the exposure levels low.

Table 2 displays the Spread Index values for various target concentrations ranging from 1 to 5 ppmv. These values confirm that among all the cases the Case 2 layout shows the relatively higher spread of sevoflurane for all target concentrations. In the cases of Case 1 and Case 2, the Spread Index values range from 85 to 88 percent for the target concentration of 1 ppmv indicating potentially widespread of WAGs in PACU. Whereas in Case 3 with ceiling returns it reduces to 22 percent. Consistent with the previous results, the Case 4 HVAC layout shows the lowest values of the Spread Index for all target concentrations.

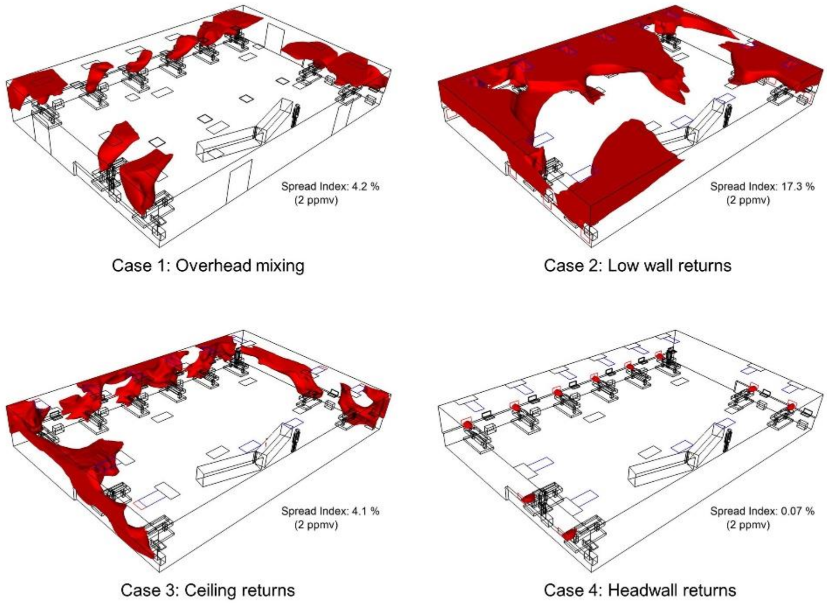


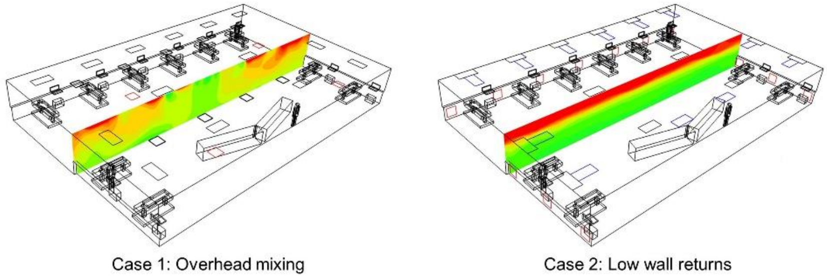
Figure 4: Spread Index plots showing zones of high concentration in the PACU.

Table 2: Spread Index values (percent) for various target concentrations.

Target Concentration (ppmv)	Case 1	Case 2	Case 3	Case 4	Case 5
1	87.6	84.8	21.9	0.11	0.15
2	4.2	17.3	4.1	0.07	0.11
3	0.6	4.2	1.6	0.06	0.08
5	0.1	1.1	0.4	0.04	0.05

Temperature Distribution

Figure 5 shows the temperature distribution on a vertical plane passing through the center of the PACU space. The figures show that thermal stratification occurs in all HVAC layouts. In cases with the laminar supply diffusers this stratification is particularly notable. As explained before, the downward supply of cold air reaches the floor first and then rises due to the circulating flow patterns. However, as the air moves upward, it becomes warmer as it passes around and through the heat sources. The hot air then rises toward the ceiling and moves along it. This is similar to the displacement ventilation systems where cold air is introduced at the floor level, creating a temperature stratification. The high-concentration zones near the ceiling, as indicated by the Spread Index plots (Figure 4), can be partly attributed to this thermal stratification.



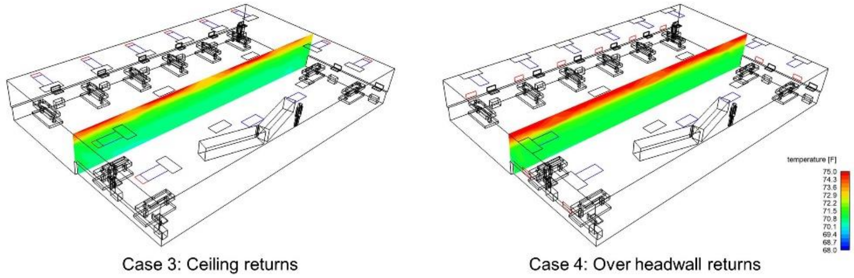


Figure 5: Distribution of temperature at central plane in the PACU.

Impact of Supply Airflow Rates

Figure 6 displays the distribution of sevoflurane concentration in the breathing plane while Figure 7 shows the Spread Index $(SI)_{2ppmv}$ plots for 6 and 4 ach corresponding to the supply airflow rates of 2723 cfm (1285 L/s) and 1800 cfm (850 L/s), respectively. Both analyses were performed for the same HVAC layout with laminar diffusers and headwall returns. This analysis indicates that a reduction in the supply airflow rate from 6 to 4 ach does not significantly affect the ventilation performance of the PACU. In both cases, the high concentration zones are limited only in the vicinity of the sevoflurane source. Table 2 shows a slight increase in the Spread Index values for the reduced airflow rate (Case 5) for various target concentrations. This can be attributed to the reduced dilution than the airflow patterns. As demonstrated in the previous studies the airflow patterns depend only on the space HVAC layout and not on the supply airflow rate (Khankari 2016 and 2018a). Therefore, these analyses show that optimized airflow patterns with proper locations for air supply and return can reduce the supply airflow rate, leading to a reduction in energy consumption, first costs, and operating costs of HVAC equipment.

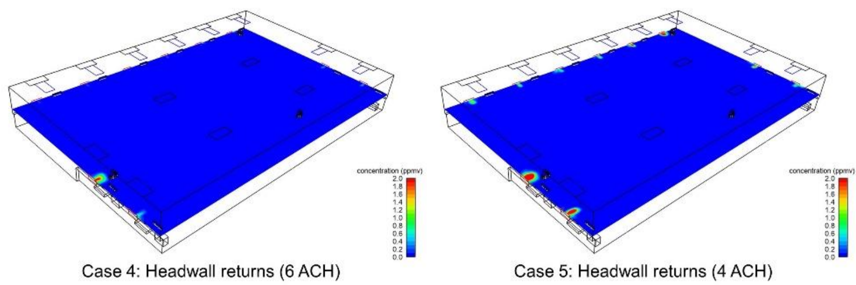


Figure 6: A comparison of sevoflurane concentration the breathing plane for 6 and 4 ach (1/h).

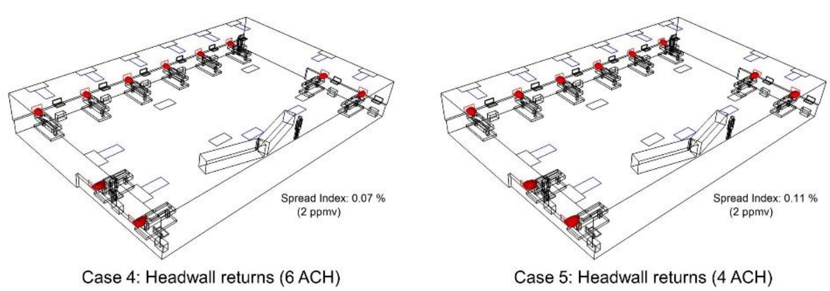


Figure 7: A comparison of Spread Index $(SI)_{2ppmv}$ for 6 and 4 ach (1/h).

SUMMARY AND CONCLUSIONS

The postoperative patients in the Post Anesthesia Care Unit (PACU) of a hospital are the sources of waste anesthetic gases (WAGs). The healthcare workers in the PACU can potentially be exposed to hazardous WAGs. To protect these workers, it's important to design a ventilation system that effectively removes these gases and reduces exposure. By improving airflow patterns, the concentration of WAGs in the breathing zone of occupants can be reduced. To evaluate the impact of various HVAC layouts on the ventilation performance of the PACU, a study was conducted using non-isothermal computational fluid dynamics (CFD) simulations. The study employed a Spread Index metric to compare the spread of sevoflurane, a commonly used anesthetic gas, for various HVAC layouts.

The traditional HVAC layout with four-way supply diffusers and ceiling returns was found to create mixing airflow patterns. These patterns can potentially distribute WAGs throughout the entire PACU, increasing the risk of exposure for healthcare workers. Similarly, the low wall and ceiling returns layouts with ceiling laminar diffusers also create recirculating airflow patterns, which can bring sevoflurane plumes from the patient's face into the breathing zone of occupants.

The HVAC layout with laminar diffusers and headwall returns showed the most promise in reducing the concentration of WAGs in the breathing zone. This layout utilizes horizontal movement of a sevoflurane plume below the breathing zone of occupants combined with immediate exit of the contaminated air through the headwall returns. This significantly reduces the concentration of sevoflurane in the breathing zone and limits the spread of WAGs in the PACU.

The study also indicates that the PACU with such an optimized HVAC layout can be operated at reduced dilution airflow rates without significantly affecting the ventilation performance. This confirms that it's not the air change rates but the airflow patterns that play a crucial role in improving ventilation effectiveness. By using CFD to analyze and optimize airflow patterns in indoor spaces, it's possible to limit the spread of contaminants and reduce the exposure of occupants. Such optimized ventilation designs can further reduce energy consumption, first costs, and the operating costs of the HVAC system.

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