TECHNICAL FEATURE

Computational Fluid Dynamics (CFD) Analysis of

Hospital Operating Room Ventilation Systems

Part II: Analyses of HVAC Configurations

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The primary objective of the hospital operating room (OR) ventilation system is to minimize surgical site infection due to airborne bacteria and to provide a comfortable environment for surgeons and other staff in the room. The key factor in reducing surgical site infection is to minimize the entrainment of airborne particulates from the non-sterile zone into the sterile zone.

Part I of this study[1] analyzed the impact of air change rates on the airflow patterns, temperature distribution, and resulting flow path of airborne particulates. The study indicated that high air change rates (ACH) potentially provide better thermal environment and minimize the mixing and recirculation of airborne particulates in the non-sterile section of the OR; however, higher ACH cannot substantially alter the airflow patterns and the resulting flow path of airborne particulates that may entrain into the sterile zone from the non-sterile zone. This present study evaluates whether the HVAC layout, including the location and number of supply and exhaust grilles in the OR can influence the airflow patterns and alter the flow path of contaminants.

As mentioned in the previous article,[1] air is the primary carrier of heat, moisture, contaminants, and airborne particulates in operating rooms. Therefore, the distribution of supply air determines the resulting air velocities, temperature, concentration of contaminants, and the flow path of airborne particulates in the room. These factors subsequently determine thermal comfort, air quality, and the potential for transmission of airborne particulates. In the operating room, ASHRAE/ASHE Standard 170-2017[2] recommends a supply of unidirectional downward airflow passing over the operating table and surgical staff, which sufficiently covers the entire sterile zone. Furthermore, Standard 170-2017 requires an exhaust through at least two low sidewall grilles placed on opposite walls of the OR.

Previous studies indicate that the HVAC configuration, including the location and type of supply diffusers, and exhaust grilles can affect the airflow

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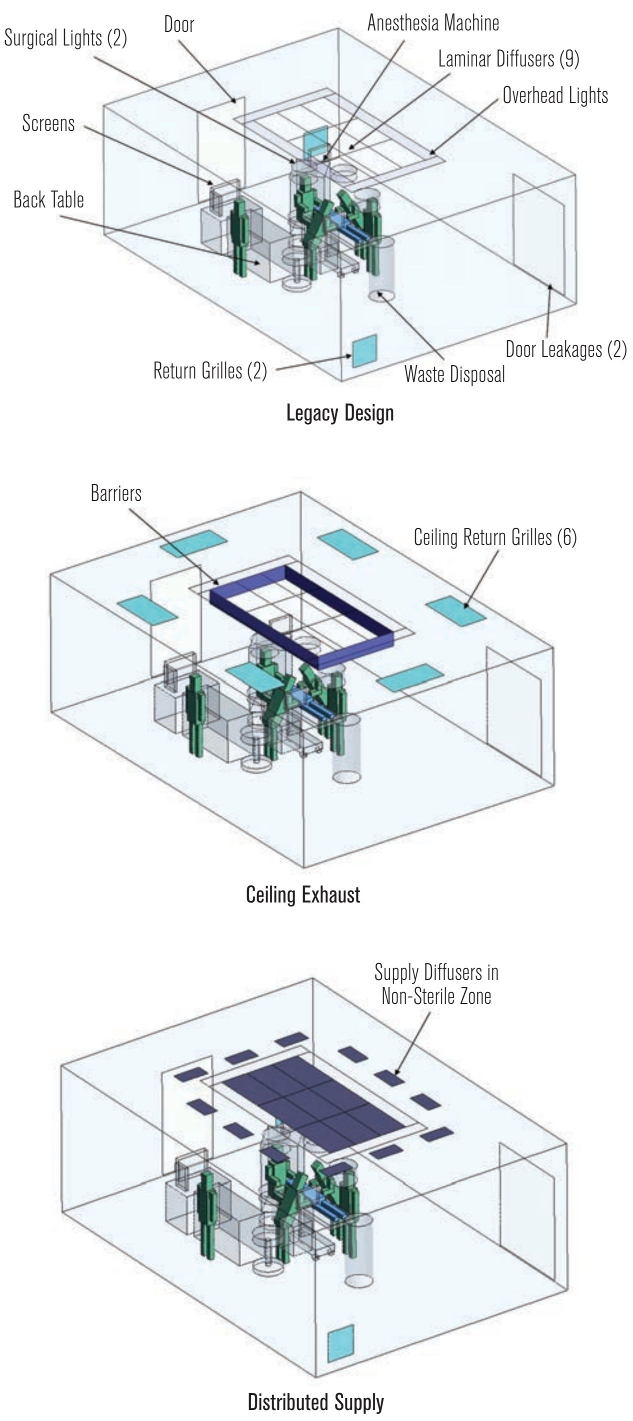
patterns, which in turn can affect the flow path of contaminants.[3,4,5] Analysis of several commonly used supply diffusers for a wide range of ACH showed that ventilation systems that provide laminar (unidirectional) flow conditions with adequate coverage of the sterile zone can yield better contamination control.[4]

Another study indicated a single continuous array of supply diffusers without gaps can be more effective in promoting the airflow that sweeps particles away from the operating table.[5] Yet another intuitive approach is to create a barrier by providing an air curtain surrounding the array of laminar diffusers.[6] However, the performance of these systems depends on the proper design and operation of the air curtains, which includes the length and location of air curtain, airflow split between the core supply through laminar diffuser and through the air curtain; and the relative ratio of the discharge velocities.[6,7]

A recent CFD study of a patient room ventilation systems showed that simply relocating the return over the patient's bed can significantly alter the flow path of contaminants and can reduce recirculation and mixing of the contaminants in the room.[3] However, previous studies did not examine different HVAC configuration to potentially improve upon the legacy design to effectively reduce entrainment of air from the non-sterile zone back into the sterile zone.

The current CFD study analyzes the impact of three different HVAC configurations on the entrainment of the surrounding air into the sterile zone and on the resulting flow path of airborne particulates. A total of three HVAC configurations are evaluated, including the legacy configuration which was studied previously, and two additional conceptual modifications of the legacy design. The overall airflow patterns, temperature distribution, and the probable flow path of airborne particulates are compared. Also the impact of these configurations on the acceleration of centerline velocity of the supply air jet from the laminar diffusers is evaluated.

FIGURE 1 Schematic diagram of three HVAC configurations of a hospital operating room ventilation system.



Virtual Setup of the Operating Room

A three-dimensional, steady-state, non-isothermal CFD model of a hospital OR was developed for this study. The room has about 560 ft^2 (52 m^2) floor area (28 × 20 ft, 8.5 × 6.1 m) with 10 ft (3 m) ceiling height. *Figure 1* shows three different HVAC configurations for the OR. These virtual ORs have an operating table with a patient, two surgeons, two nurses, anesthesiologist, surgical lights, overhead lights, and other equipment and furniture. Most of these entities are located within the sterile zone (under the array of laminar diffusers) except the scrub nurse and a table at the back of the room. In all three

TABLE 1 Minimum requirements for OR ventilation according to Standard 170-2017.[2]

MINIMUM REQUIREMENT	LEGACY	CEILING EXHAUST	DISTRIBUTED SUPPLY
Total Air Change Rate (ACH): 20	23	23	23
Pressure Relationship to Adjacent Areas: Positive	Positive	Positive	Positive
Design Temperature: 68 to 75°F (20 to 24°C)	70°F (21°C)	70°F (21°C)	70°F (21°C)
Airflow: Unidirectional, Downward	Unidirectional, Downward	Unidirectional, Downward	Unidirectional, Downward
Airflow: Average Discharge Velocity 25 to 35 cfm/ft^2 (127 to 178 L/s·m^2)	30 cfm/ft^2 (153 L/s·m^2)	30 cfm/ft^2 (153 L/s·m^2)	22.5 cfm/ft^2 (114 L/s·m^2)
The Room Shall be Provided With at Least Two Low Sidewall Return or Exhaust Grilles Spaced at Opposite Corners or as Far Apart as Possible*	Two Low Sidewall Returns	Six Ceiling Returns*	Two Low Sidewall Returns

*In addition to the required low return (or exhaust) air grilles, such grilles may be placed high on the walls.

cases the air in the sterile zone is supplied through an array of nine laminar flow diffusers located at the center of the room ceiling. In the legacy design, the room air is exhausted through two exhaust grilles located on opposite walls and through the leakage openings located under the two doors. The supply airflow rate of 23 ACH, which corresponds to a discharge velocity of 30 fpm (0.15 m/s), was kept constant for all three HVAC configurations analyzed in this study. The exhaust flow rate through the two door openings was maintained at 350 cfm (165 L/s) and the remaining air was exhausted through the exhaust grilles by keeping the room at positive pressure. These values of supply airflow rate and discharge velocity and the room layout of the legacy design are consistent with Standard 170-2017.[2] *Table 1* shows how these three HVAC configurations comply with the space ventilation requirements according to the specifications in this standard.

Two additional OR configurations are analyzed in this study. In the first ("ceiling exhaust") configuration (shown in *Figure 1*), the sidewall exhaust grilles of the legacy design are replaced by six ceiling exhaust grilles that are distributed in the non-sterile section of the room. Additionally, a curtain barrier of 1 ft (0.3 m) deep is placed near the ceiling along the perimeter of the laminar diffuser array surrounding the sterile zone. While the large ceiling exhaust grilles would provide an easy path for the air to exit the OR without significant recirculation, it is anticipated that the barrier would prevent any entrainment of the air from the non-sterile zone back into the sterile zone.

In the second ("distributed supply") case (shown in *Figure 1*), an additional 12 laminar supply diffusers are placed in the non-sterile zone while keeping the low sidewall exhaust grilles, as in the case of legacy design. Thus, an annular ring of supply diffusers is formed around the main array of the laminar diffusers in the sterile zone. The total supply airflow rate of 23 ACH is split between the main and annular array of diffusers in the proportion 3:1, whereas the discharge areas of these two diffuser arrays are also split in the same proportion. As a result the discharge velocity from all the diffusers in the sterile and non-sterile zone is maintained at 22.5 fpm (0.11 m/s) that is reduced from 30 fpm (0.15 m/s) of the legacy design. It is anticipated that the supply air from the annular diffusers would bathe the non-sterile zone in clean air, preventing entrainment of air from the non-sterile zone into the sterile zone.

The sensible heat loads due to the occupants and the overhead lights were assumed to be 1,500 Btu/h (440 W) and 2,457 Btu/h (720 W), respectively. The total sensible heat load due to the other equipment including the anesthesia machine, screens, surgical lights, and monitors was assumed to be 3,583 Btu/h (1050 W). Thus, the total sensible heat load in the room was assumed to be 7,540 Btu/h (2210 W). The supply air temperature was kept constant at 67°F (19.4°C) for all three cases.

The standard k-epsilon (k-ε) turbulence model was employed to compute the turbulent viscosity of the air. The probable flow paths of airborne particulates are analyzed by tracking the airflow path streamlines released from the occupant's faces. The particulates are assumed to be skin squames. This analysis assumes most of the airborne particles released from the occupant's faces would follow the flow path of the air. This analysis does not explicitly consider any settling and deposition of these particulates on the surfaces.

Results and Discussion

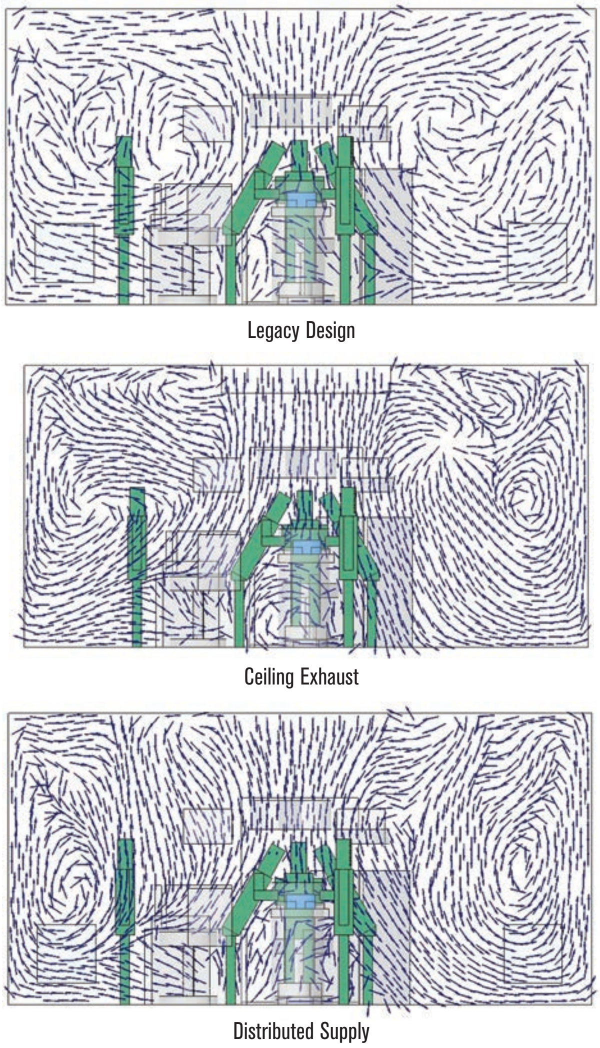
Airflow Patterns

In the case of legacy design, the air near the floor moves away from the sterile zone toward the exhaust grilles, while the air in the middle and upper sections of the room moves from the non-sterile zone toward the sterile zone (*Figure 2*). High velocity non-isothermal air jet exiting from the laminar diffusers leads to the entrainment of the surrounding non-sterile air into the sterile zone. The air exiting from the sterile zone moves in a recirculation pattern in the non-sterile zone before exiting the OR, which can promote entrainment. The air velocity contour map shows increase in the velocity of the discharge air from the laminar diffusers as it approaches the operating table (*Figure 3*). It also shows contraction in the middle section of the supply air jet as the discharge air moves downward.

In the case of "ceiling exhaust," with the barrier surrounding the diffuser array, the discharge air from the sterile zone moves along the floor toward the exterior walls and then moves upward toward the ceiling exhaust grilles. A small air-recirculation zone is formed in the middle section of the non-sterile zone, which is prominent in the gap between the adjacent exhaust grilles (not shown in *Figure 2*). However, unlike the legacy configuration, the acceleration of the discharge air, and the contraction of the discharge jet show significant reduction (*Figure 3*), which indicates reduced entrainment of the air from the non-sterile zone into the sterile zone. The barrier surrounding the laminar diffusers near the ceiling perhaps helps to maintain a downward flow of the discharge air jet and reduces entrainment near the ceiling.

In the case of "distributed supply," the air from the additional annular supply diffusers in the non-sterile zone drifts toward the sterile zone due to the accelerating discharge jet in the core region. This results in a similar airflow patterns as seen in the legacy design. However, unlike the legacy configuration, in this HVAC configuration it is fresh, sterile supply air, rather than contaminated air, that entrains into the sterile zone. The discharge air jets in the non-sterile zone act like an "air curtain" between the main sterile zone and the exterior walls forming a "semi-sterile" zone in between the sterile zone and non-sterile zone, effectively reducing the non-sterile zone to a space between the exterior walls and annular array of laminar diffusers.

FIGURE 2 Airflow patterns at a central plane in the operating room for three HVAC configurations.



Temperature Distribution

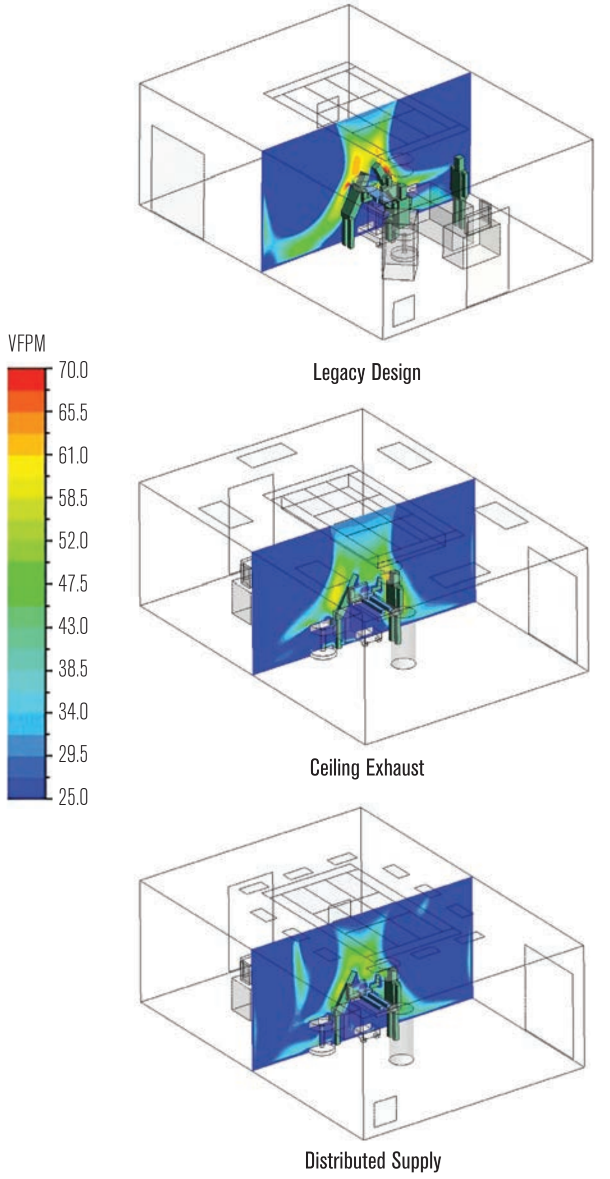
Legacy HVAC configuration shows significant thermal stratification near the ceiling, shown in red (*Figure 4*). The air recirculation patterns in the middle section of the non-sterile zone causes hot air to accumulate near the ceiling surrounding the sterile zone while keeping the cooler air near the floor. It further shows a large thermal gradient between the supply air jet and the surrounding region that can contribute to the entrainment of the surrounding hot air into the core region. The contraction of the central core is an indication of such entrainment.

Further, the higher air temperature in the non-sterile zone can cause thermal discomfort to occupants, which according to many facility managers is a common complaint from the surgeons.

The temperature distribution in the "ceiling exhaust" case shows a complete contrast. Unlike in the legacy design, the relatively cold air from the sterile zone moves upward in the non-sterile zone along the exterior walls toward the ceiling exhaust grilles. This causes mixing of the cold air from the floor with the warm air near the ceiling and helps in reducing the thermal gradient between the central core and the surrounding air, which in turn helps in reducing the entrainment. As a result, the central core maintains the cooler temperature throughout the entire sterile zone without any significant contraction. Lower temperatures in the non-sterile zone can also help in improving thermal comfort of the occupants.

In the case of "distributed supply," the air jets exiting from the annular array of the laminar diffusers drift toward the central core region, which led to the contraction of the central jet. However, unlike the legacy design, it is the cold supply air that gets entrained into the main core in the sterile zone, which helps in lowering the temperatures surrounding the central core. Therefore, the temperatures in this region are lower than those in the legacy design (*Figure 4*). Further optimization of the 3:1 airflow split between sterile and non-sterile zones would be required in the "distributed supply" configuration. Higher air velocities in the non-sterile zone could help to minimize the drifting of air toward the sterile zone. Nevertheless, due to relatively lower temperatures in the non-sterile zone, the thermal environment for the "distributed supply" design would be more comfortable than the legacy design.

FIGURE 3 Contours of air velocity at a central plane in the operating room for three HVAC configurations showing reduced acceleration in the discharge velocity in the cases of ceiling exhaust. Note the discharge velocity in the case of distributed supply is lower than the other two cases.

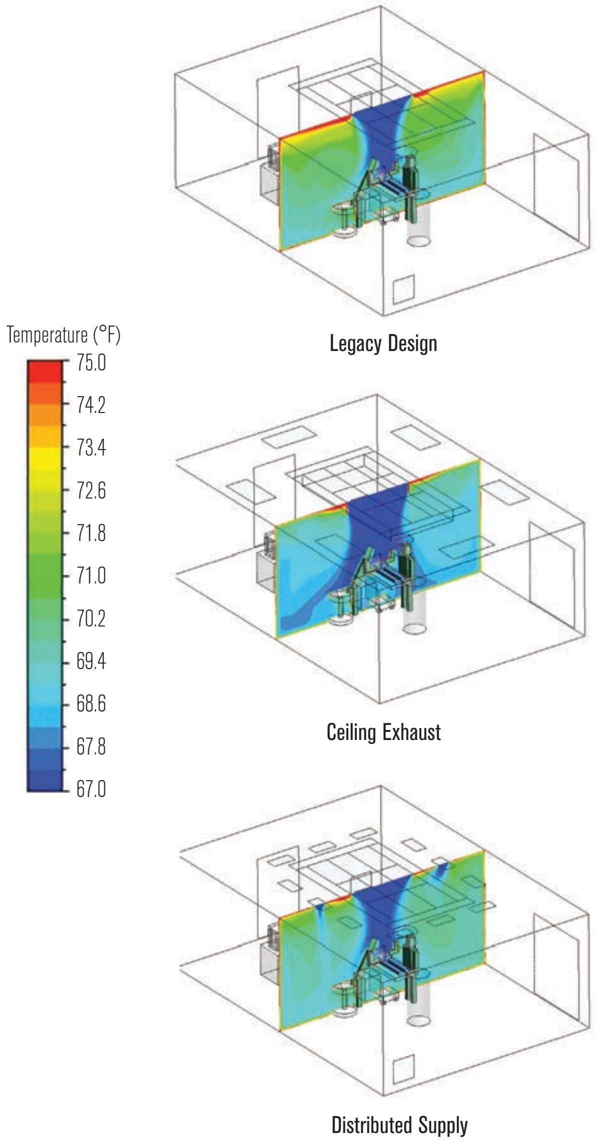


Flow Path of Contaminants

The flow paths of particulates released from the faces of two surgeons and the nurse who are located inside the sterile zone are shown in *Figure 5*. The flow path in the case of legacy design shows these particulates travel low toward the exterior walls and then drift into the non-sterile zone in search of the exit. Whereas in the case of "ceiling exhaust," the particulates initially follow the same flow path as in the legacy design; however, once they reach the wall they travel upward toward the ceiling exhaust. In the case of "distributed supply" the particulates also follow similar initial flow path as in the previous case of "ceiling exhaust;" however, they get entrained into the supply air streams in the non-sterile zone. To find the exhaust grilles near the floor, these particulates recirculate in the non-sterile zone before exiting the OR via the exhaust grilles located near the floor. In spite of such recirculation, the analysis does not indicate any entrainment of these particles back into the sterile zone.

The probable flow paths of the airborne particulates released from the face of an anesthesiologist who is

FIGURE 4 Contours of air temperature at a central plane in the operating room for three HVAC configurations shows in the case of ceiling exhaust the overall temperature in the OR would be lower than the other two cases, which could create thermally comfortable environment for the occupants.

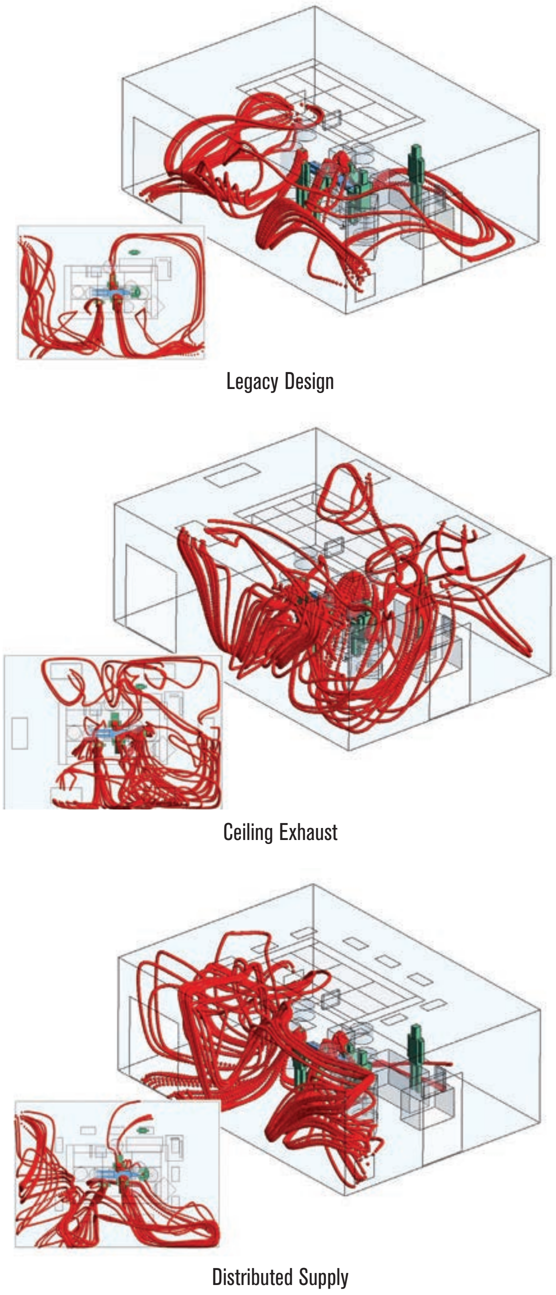


Legacy Design

Ceiling Exhaust

Distributed Supply

FIGURE 5 Flow path of airborne particulates originating from the OR occupants inside the sterile zone in three different configurations. The results show particulates being swept away from the sterile zone in all cases, however, they are forced upward in the "ceiling exhaust" and "distributed supply" configurations.



Legacy Design

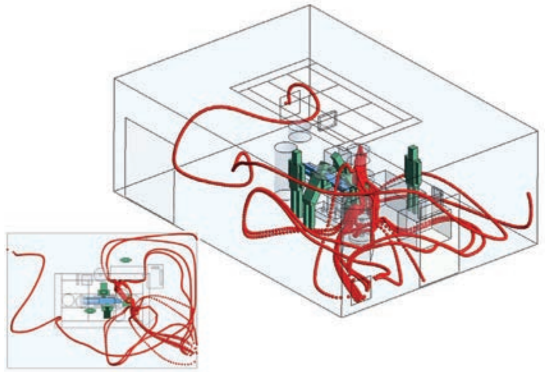
Ceiling Exhaust

Distributed Supply

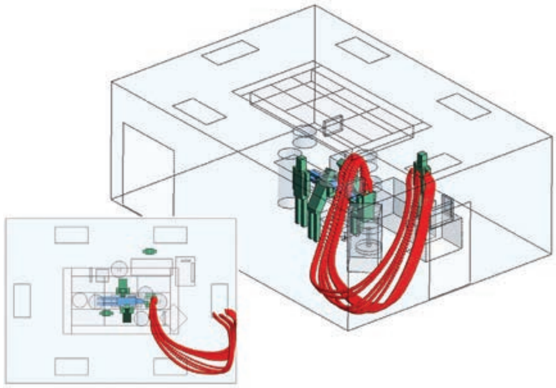
located at the border of the sterile zone away from the operating table are shown in *Figure 6*. In the legacy design and "distributed supply" configurations, these particulates are swept away from the sterile zone although with significant recirculation in the non-sterile zone before exiting the OR. In both the legacy design and "distributed supply" cases in which the exhaust grilles are located near the floor on the sidewalls, the particulates tend to move toward the back table, increasing the potential risk of contamination of any instruments located there. On the contrary, in the "ceiling exhaust" configuration, these particulates are initially forced upward toward the ceiling where they readily exit the OR. In all three cases the particulates released from the anesthesiologist do not indicate any entrainment into the sterile zone.

In another scenario, the probable flow paths of airborne particulates are released from the face of a scrub

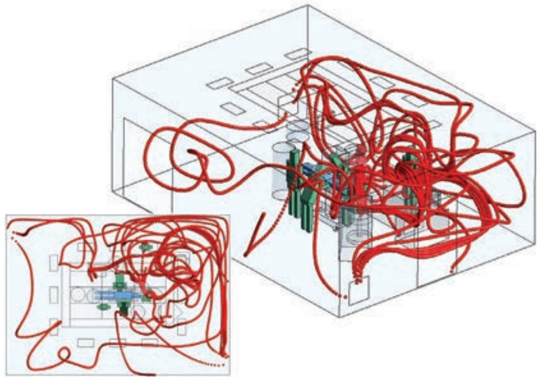
FIGURE 6 Flow path of airborne particulates originating from the anesthesiologist located on the edge of the sterile zone. Results show particulates readily exiting the OR when the exhaust grilles are placed in the ceiling.



Legacy Design

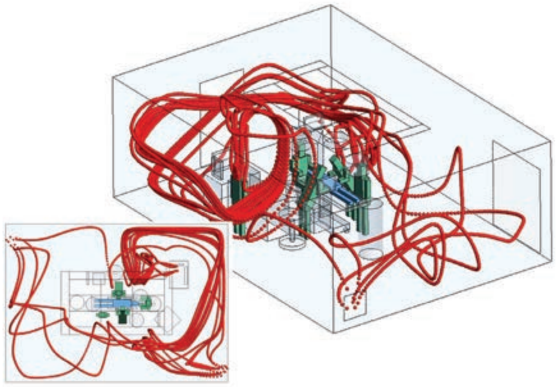


Ceiling Exhaust

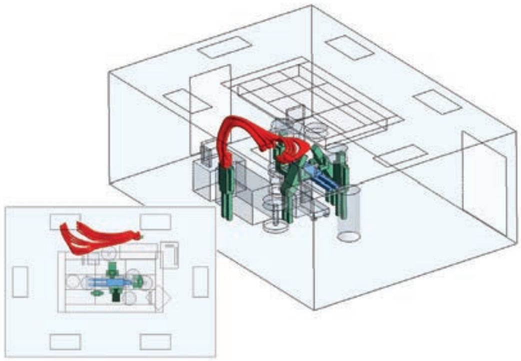


Distributed Supply

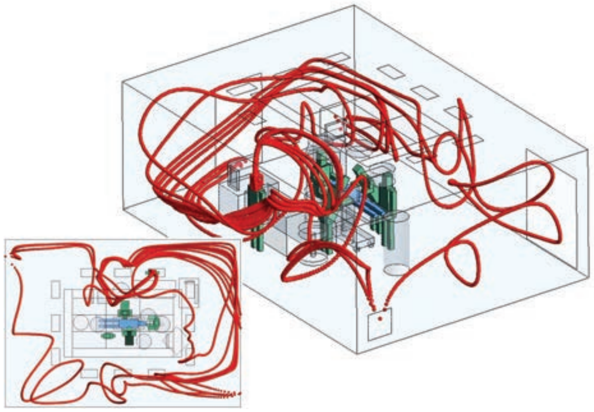
FIGURE 7 Flow path of airborne particulates originating from the scrubbing nurse outside the sterile zone showing the "ceiling exhaust" configuration as the most efficient option for removing particulates from the OR without significant recirculation and entrainment into the sterile zone.



Legacy Design



Ceiling Exhaust



Distributed Supply

nurse located outside the sterile zone. These analyses are shown in *Figure 7.* In the cases where the exhaust grilles are located low on the opposite walls (legacy design and "distributed supply"), these particulates are initially forced upward toward the ceiling, and then get entrained back into the sterile zone. The downward air velocity from the "distributed supply" diffusers in the non-sterile zone is likely not high enough to force these particulates downward toward the exhaust grille to overcome the pull from the discharge air jet in the sterile zone. Contrary to the other designs, in the case of "ceiling exhaust," the particles exhibit a single pass flow path without any signs of re-entrainment back into the non-sterile zone. In this case the particulates are lifted upward, similar to the other two cases. However in the "ceiling exhaust" configuration, they exit the OR through a single pass through the ceiling exhaust grilles. These analyses suggest that the "ceiling exhaust" design may provide the most efficient flow path for particulate removal (generated outside the sterile one) without significant entrainment from the non-sterile zone into the sterile zone.

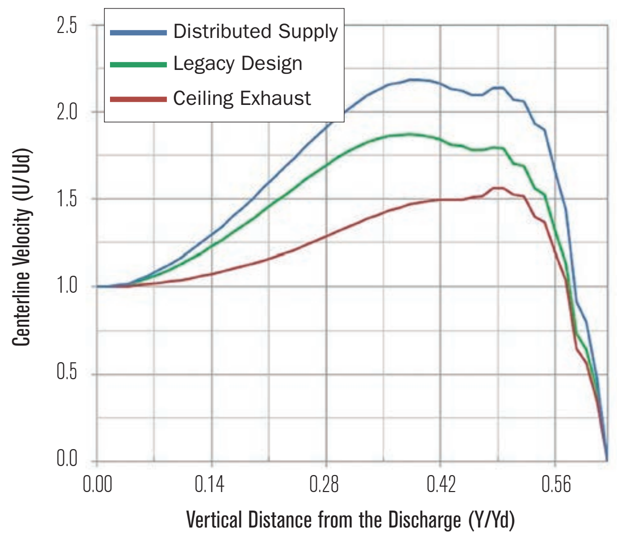
Analysis of Centerline Velocity

As described before, the temperature gradients between the sterile and non-sterile zone can cause acceleration of the supply air jet from the laminar diffusers, which in turn, can promote entrainment of the contaminated air from the non-sterile zone into the sterile zone. Due to the recirculation pattern of the entrained air in and out of the sterile zone, it is difficult to quantify the flow rate of entrained air. The extent of acceleration in the velocity of the supply air along the vertical centerline from the ceiling to the floor can provide an indirect estimate of such entrainment.

The variation of non-dimensional velocity—a ratio of centerline velocity at a specific distance along the vertical centerline to the discharge velocity at the exit of the laminar diffuser—is shown in *Figure 8*. This variation is plotted against the non-dimensional vertical distance—a ratio of the height at a specific vertical location to height of the laminar diffuser from the ceiling. At a non-dimensional height of 0.0 at the laminar diffuser, the non-dimensional centerline velocity is 1.0. This analysis indicates for all three cases the centerline velocity increases as the air jet moves downward toward the operating table. However, in the "ceiling exhaust" case, the results indicate the lowest acceleration of the centerline velocity, which is an indication of low possibility for entrainment into the sterile zone. Note in this case the thermal gradient across the sterile and non-sterile zone was minimum.

The case of "distributed supply" shows the highest increase in the centerline velocity indicating a high level of potential entrainment. As mentioned before, the air jets from the annular diffusers in the non-sterile zone get directly entrained into the air jets from the sterile zones. In all of these cases the centerline velocity starts accelerating at about 38% of the vertical distance from the ceiling where it reaches about 1.9, 1.6, and 2.2 times of their respective discharge velocities for the legacy design, ceiling exhaust, and distributed supply.

FIGURE 8 Variation of non-dimensional centerline velocity along the normalized distance from the laminar diffuser shows relative acceleration in the discharge velocity as it approaches the operating table. Since the supply air in the non-sterile zone gets directly entrained into the sterile zone the "distributed supply" configuration shows the highest acceleration.



Summary and Conclusions

Previous computational fluid dynamics (CFD) studies of a legacy HVAC design for a hospital operating room indicate that when airborne particulates originate in the non-sterile zone (i.e., from the face of a scrubbing nurse), these particles can get entrained back into the sterile zone, irrespective of the supply airflow rate or ACH. This study evaluates whether modifications in the legacy HVAC configuration could alter the flow path of these contaminants and mitigate the issue of particulate entrainment. During this study CFD analyses of two conceptual modifications in the legacy HVAC design of a hospital operating room are performed to compare the airflow patterns, temperature distribution, and resulting flow path of airborne particulates. Additionally, the acceleration of centerline velocity of the supply air jet is also evaluated to understand the extent of entrainment for the three HVAC configurations analyzed.

These analyses indicate HVAC configuration, including the number and locations of supply diffusers and exhaust grilles, influences the HVAC performance of the ventilation systems of OR. Unlike the legacy design with low wall exhaust, when the exhaust grilles are placed in the ceiling with a small barrier around the sterile zone (“ceiling exhaust”), the entrainment of particulates from the non-sterile zone into the sterile zone are significantly reduced compared to the legacy design. Furthermore, in the “ceiling exhaust” configuration, mixing of the cold exiting air from the sterile zone with the warm air in the non-sterile zone reduced thermal gradients across the sterile zone. This may help in creating a more comfortable thermal environment for the occupants in the OR, reduce the possibility for contaminated air entrainment into the sterile zone, and reduce the acceleration of discharge air jet from the laminar diffusers.

In the second design modification, additional laminar diffusers are placed in the non-sterile zone surrounding the array of laminar diffusers in the sterile zone (“distributed supply”). The total supply airflow and the discharge area of the diffusers between the sterile and non-sterile zone were split in the proportion of 3:1, keeping the same discharge velocity from all the diffusers. This analysis showed the discharge air jets in the non-sterile zone get drifted toward the air jet in the sterile zone, which can effectively increase the air entrainment. This was evident from the highest acceleration in the centerline velocity of the discharge air jet in the sterile zone. Thus, the particle movement from the non-sterile zone to the sterile zone did not show any significant improvement over the legacy design. However, unlike the legacy design, entrainment of the cold supply air from the non-sterile zone into the sterile zone results in lowering the temperatures surrounding the central core. For the discharge air jets in the non-sterile zone to sweep the occupants and prevent entrainment of the airborne particulates into the sterile zone, the flow split and the discharge velocities between the sterile and non-sterile zones may require careful balancing and adjustment. The modifications in HVAC configuration presented in this study are only conceptual and not necessarily the “optimized” designs.

These studies indicate that HVAC configuration, rather than ACH, has a larger influence on the airflow patterns, temperature distribution, and hence, the resulting flow path of contaminants and thermal comfort of occupants. Therefore, to improve the effectiveness of OR ventilation systems high ACH should not be considered as the only potential solution. Rather, analysis and modification of the legacy HVAC configuration at a low ACH should be considered first before considering increasing ACH.

Acknowledgments

Author is thankful to Dr. Nikhil Khankari, cancer epidemiologist, for reviewing the manuscript and making valuable suggestions.

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