Airflow Path Matters

Patient Room HVAC

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Air is the primary carrier of heat, moisture, contaminants, and airborne contaminants in health-care facilities such as patient rooms, isolation rooms, and operating rooms. Therefore, the flow path of supply air plays an important role in determining the air velocities, air temperatures, concentration of contaminants, and flow path of airborne pathogens in these spaces. These factors, in turn, determine the thermal comfort of occupants, indoor air quality, distribution of surface contamination, and potential for transmission of airborne pathogens in a room.

The airflow patterns, temperature distribution, and concentration of contaminants including the flow path of airborne pathogens in a patient room can depend on several interrelated factors, including the location and type of supply diffusers, supply airflow rates (air change rates) and associated diffuser throws, supply air temperature, size and locations of room return, bathroom exhaust flow rates, locations and strengths of various heat sources in a room, arrangement of furniture and other obstructions to airflow, and importantly relative location of a patient in the room. In addition, orientation of the room can determine the solar sensible heat loads in the room. Several studies indicate that the design of a ventilation system and the resulting airflow patterns play a more important role in controlling the flow path of contaminants than just the supply airflow rate or air changes per hour (ach) alone.[1,2,3] A study of airflow patterns and resulting potential exposure of the healthcare worker to airborne pathogens in a patient room and in an isolation room indicates airborne aerosols released from the patient can flow towards the healthcare worker during the movement of the air from the supply diffuser to the room exhaust.[4] In another study, interactions of exhalation flows of the cough particles with the ventilation flow in a hospital suite indicated that low exhausts outperform other exhaust locations in terms of particle removal and particles remaining around the bed.[5]

This present study attempts to evaluate the impact of supply and return locations on the airflow patterns and temperature distribution along with the resulting thermal comfort of occupants, and probable flow path of airborne pathogens in a typical patient room using computational fluid dynamics (CFD) simulations.

Virtual Patient Room

A three-dimensional, steady-state CFD model of a patient room is developed for this analysis. The virtual patient room in *Figure 1* shows the location of the patient, healthcare provider, seating area, door to the corridor,

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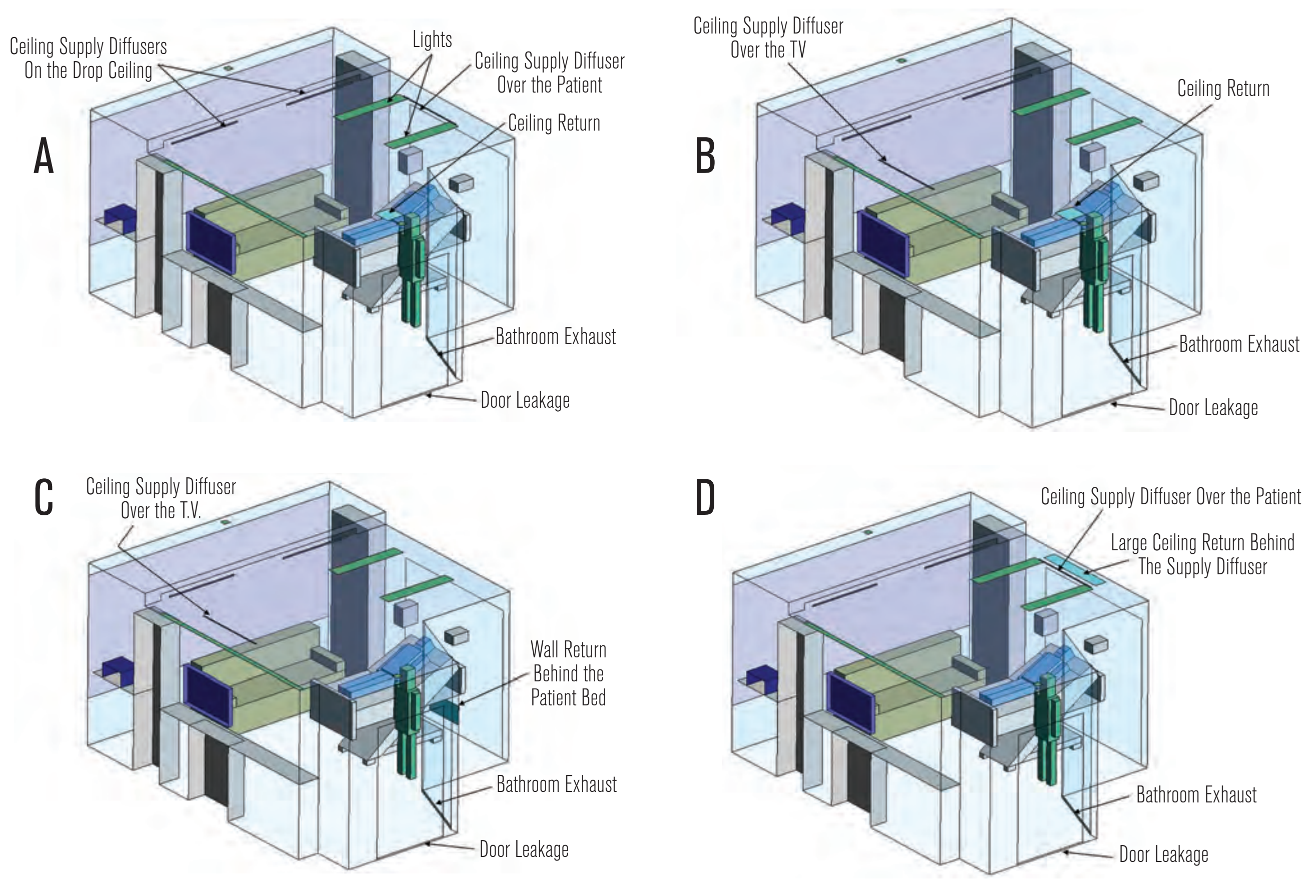

FIGURE 1 Schematic diagram of CFD models for the analysis of a patient room showing various HVAC configurations. A) Base Case; B) Case 1: Supply diffuser moved away from the patient; C) Case 2: Room return moved behind the patient; D) Case 3: Room return moved behind the supply diffuser.

door to the bathroom, and supply and return air locations for the various cases analyzed in this study. The room has about 200 ft^2 (18.9 m^2) floor area and 9 ft (2.74 m) ceiling height with a drop ceiling in part of the room. It contains several pieces of heat generating equipment including a monitor, infusion pump, a television, and a computer.

The total sensible heat load due to this equipment was assumed to be 2.2 Btu/h·ft^2 (6.84 W/m^2). The sensible heat load due to two occupants (patient and health-care person) was assumed 2.5 Btu/h·ft^2 (7.8 W/m^2) whereas the sensible heat load due to the lighting was assumed to be 2.3 Btu/h·ft^2 (7.3 W/m^2). The room has a south-facing window with a solar heat gain of 9 Btu/h·ft^2 (28.4 W/m^2). All other exterior walls of the room are assumed to be adiabatic. Thus, the total sensible heat load in the room is assumed to be 16 Btu/h·ft^2 (50 W/m^2). These analyses were carried out for partial load conditions which are more prevailing than the peak design load conditions.

The air is supplied through three, single-slot (1 in. [25 mm] wide) linear diffusers each 4 ft (1.2 m) long. The total supply airflow rate and the supply air temperature were specified at 227 cfm (107 L/s, 6 ach) and 58°F (14.4°C), respectively. The two linear diffusers placed on the drop ceiling are facing the window and designed to supply 70 cfm (33 L/s) each directly towards the window whereas the linear diffuser over the patient is designed to supply 87 cfm (41 L/s). All linear diffusers are assumed to supply the air at an angle of 15° to the ceiling, which is selected arbitrarily. The room was assumed to operate under negative pressure.

The return flow rate from the room was designed for 177 cfm (112 L/s), whereas the bathroom exhaust flow rate was designed 60 cfm (28 L/s). Thus, the total return flow rate was assumed to be 237 cfm (112 L/s) with a

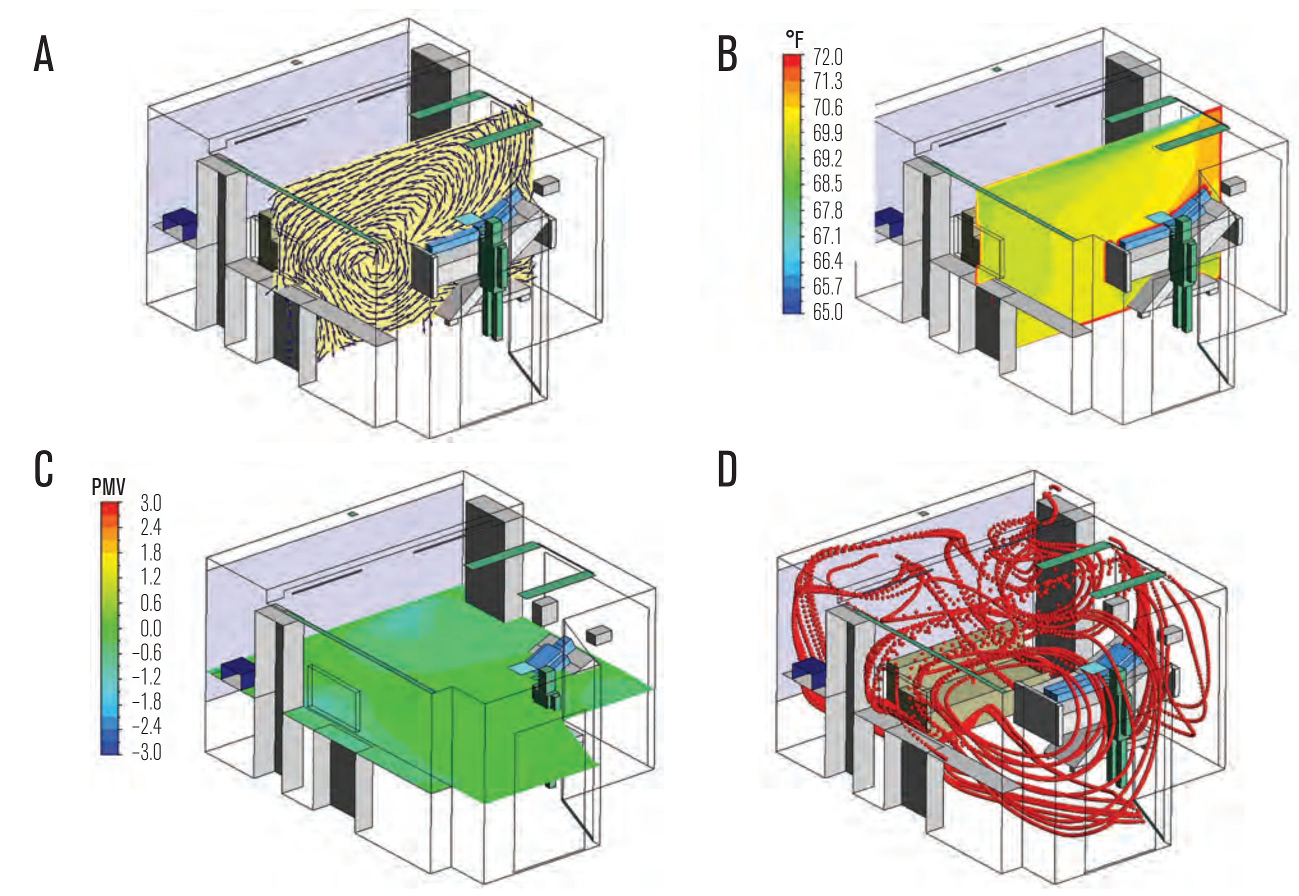

FIGURE 2 Results for the base case analysis showing A) airflow patterns; B) temperature distribution; C) PMV distribution at 4 ft (1.2 m) height; and D) resulting flow pathlines indicating probable trajectory of airborne particles released from the patient's face. This HVAC configuration entrains airborne particles back into the supply airstream, which eventually spreads into the entire room.

deficit of 10 cfm (4.7 L/s), which was supplied through the leakage under the main door from the corridor.

Thermal comfort of occupants was analyzed by employing predicted mean vote (PMV) index as described in the *2013 ASHRAE Handbook—Fundamentals*.[5] This index was computed assuming clo values of 0.5 and the metabolic heat production rate (met) of 1.2 representing the healthcare providers and other occupants. The probable flow paths of airborne pathogens are analyzed by tracking the airflow path streamlines released from the patient's face. This analysis focuses upon low-momentum pathogen releases (i.e., does not focus on high momentum releases such as full-volume coughing) and assumes most of the airborne pathogens released from the patient's face would follow the flow path of the air, neglecting any settling and deposition of these particles on the surfaces. This assumption is consistent for small particles as described in Reference 6. A total of four cases analyzed for various locations of supply and return diffusers are described below and in *Figure 1*.

- Base Case: Ceiling supply diffuser over patient's head and ceiling return near the entry door. This is a typical HVAC configuration for a patient room.
- Case 1: Ceiling supply diffuser over the patient's head moved over TV (away from the patient) and ceiling return kept near the entry door.
- Case 2: Ceiling supply diffuser over TV (away from the patient) and the ceiling return replaced by the low wall return placed behind the patient's head.
- Case 3: Ceiling supply diffuser over patient's head and the ceiling return near the door replaced by a large ceiling return over the patient's head.

Analysis and Insights

Base Case: Typical HVAC Configuration

Computational results for each case are presented in the form of color contour plots showing temperature

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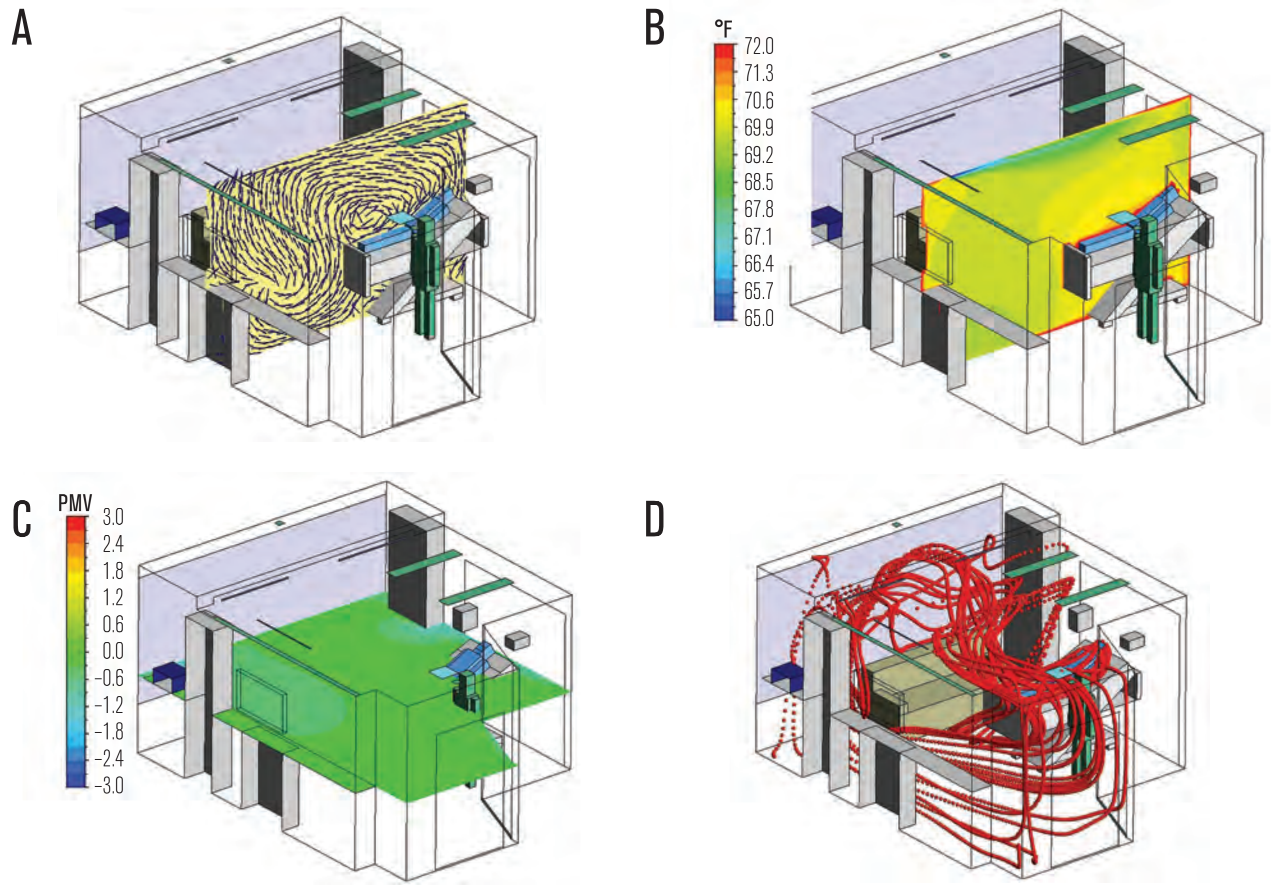

FIGURE 3 Results for Case 1. Supply diffuser moved away from the patient showing A) airflow patterns; B) temperature distribution; C) PMV distribution at 4 ft (1.2 m) height; and D) resulting flow pathlines indicating probable trajectory of airborne particles released from the patient's face. Moving the supply diffuser away from the patient reversed the flow path of airborne particles, which still get entrained into the supply airstream from the diffuser.

distribution, PMV distribution, vector plot showing the airflow distribution, and streamline plots showing probable path of airborne particles released from the patient's face. In the base case analysis, both the supply diffusers and the return grille are located at the ceiling with the linear supply diffuser placed directly above the patient's head (*Figure 1a*). The air exiting from the diffuser forms a strong recirculating pattern above the patient. Linear diffusers, which are also referred as "mixing diffusers," are known for their induction characteristics. The exiting air jet from the linear supply diffuser creates strong entrainment (induction) flow over the patient and behind the bed (*Figure 2a,* Page 18). As a result, the air flows upward over the patient and gets entrained back into the supply airstream. The airflow patterns shown in all of these cases are at one specific plane which passes through the center of the patient's body. However, the three-dimensional airflow patterns (not shown), resulting from various arrangements of the supply and return diffusers in the room are quite complex, which affects the airflow patterns in the plane which are shown in these figures.

The resulting air temperature distribution shows slightly higher air temperature near the patient's head, behind the bed, compared to the temperatures near the opposite wall (*Figure 2b*). This is partly due to the flow of the return (entrained) air passing through this region. *Figure 2c* shows the resulting distribution of the PMV, the thermal comfort index.

As shown in this figure at the 4 ft (1.2 m) height from the floor, occupant thermal comfort is almost at neutral level (PMV close to 0.0) indicating an acceptable thermal environment. The strong induction airflows cause the airborne particles released from the patient's face to move upward towards the supply diffuser and entrain back into the supply airstream that eventually can spread into the room. This illustrates that mixing airflows, which otherwise might be desirable for obtaining the uniform air temperature in the space, can adversely affect the goal of contamination control. This particular HVAC configuration introduces the airborne pathogens back into the supply airstream.

Case 1: Supply Diffuser Away from the Patient

In an attempt to avoid the strong air recirculation and entrainment airflows directly over the patient's face, the supply air diffuser was moved away from the patient and placed closer to the opposite wall over the TV (*Figure 1b*). As with the previous case, both the supply diffusers and the return grilles are now located at the ceiling. As shown in *Figure 3a,* moving the supply diffuser away from the patient reversed the airflow pattern. In this case the entrainment (induction) flow region moved near the TV. The supply air after exiting the diffuser falls near the patient's head and flows downward over the patient. Such a relocation of the diffuser slightly lowered the temperature near the patient's head and still maintained thermally comfortable conditions at 4 ft (1.2 m) height from the floor as indicated in *Figures 3b* and *3c*, respectively. However, the flow pathlines released from the patient's face indicate that airborne particles now move downward instead of upward from the patient's face and then move upward back towards the supply diffuser. Similar to the previous case, the airborne pathogens can still get entrained back into the supply airstream and can eventually spread into the entire room. Although relocation of the supply diffuser helped in reversing the flow path of airborne particles near the patient's head, it could not avoid the entrainment and the mixing with the supply airstream.

Case 2: Return Behind the Patient

In the next analysis (Case 2) as shown *Figure 1c* the location of the return grille is moved from the ceiling to the wall behind the patient at 0.5 ft (0.15 m) above the floor. The location of the supply diffusers still remained near the ceiling as in the previous case (Case 1). It was anticipated that such modification would cause the return air to move over the patient and down to the return and probably could avoid the spreading of airborne pathogens into the room.

However, as shown in *Figure 4,* the airflow patterns, the temperature distribution, the resulting thermal comfort, and the resulting flow pathlines are very similar to the previous analysis. It indicates the airborne particles released from the patient's face can still spread into the entire room before returning through the low wall return. High momentum (caused by the high air change rates) of the air exiting from the linear supply diffuser prevents the airborne particles from flowing downward directly towards the low wall return. Thus, the new location of the room return has little effect on the airflow distribution in the room.

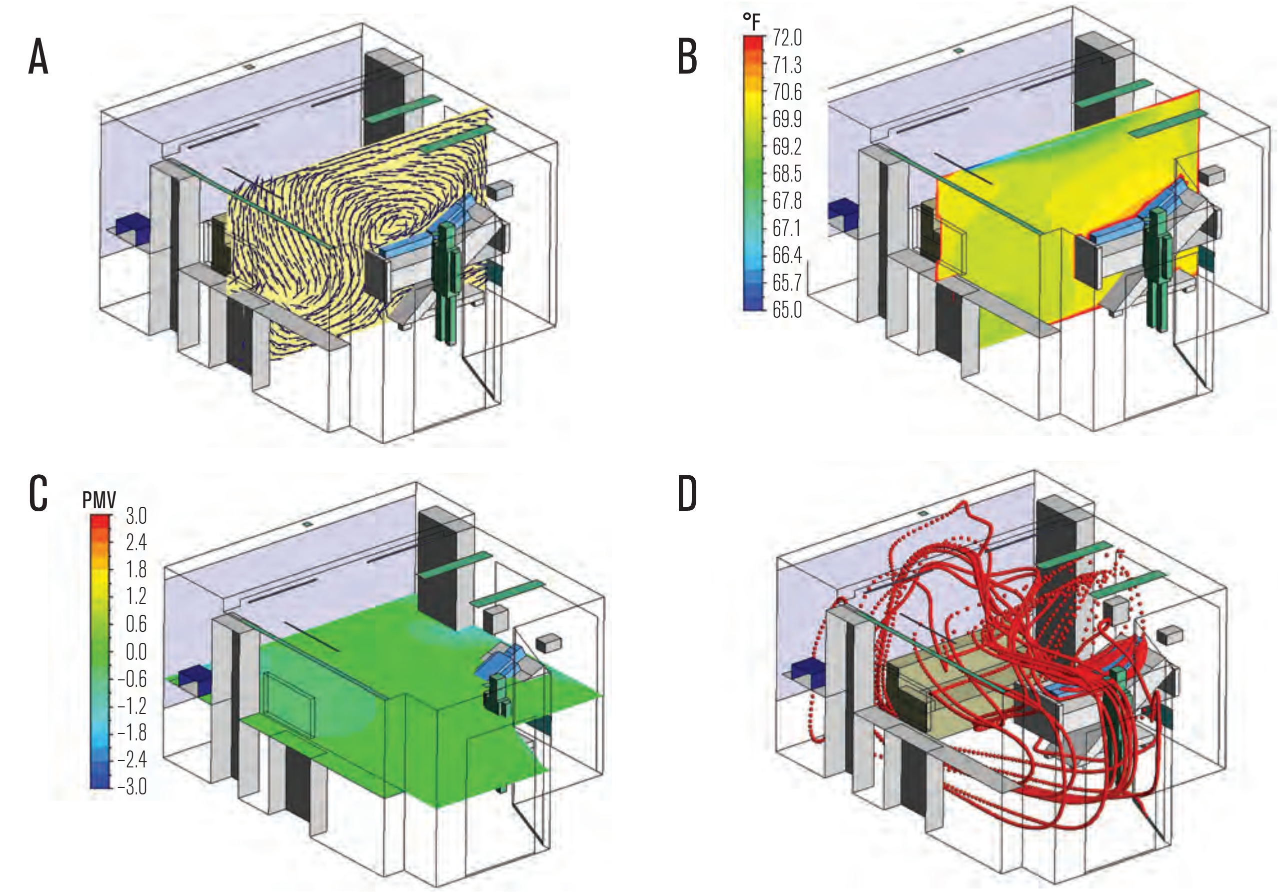

FIGURE 4 Results for Case 2. Room return moved behind the patient bed showing A) airflow patterns; B) temperature distribution; C) PMV distribution at 4 ft (1.2 m) height; and D) resulting flow pathlines indicating probable trajectory of airborne particles released from the patient's face. Placing the return low on the wall behind the patient does not provide ready exit for airborne particles. High momentum of the supply air prevents the airborne particles from flowing downward directly toward the low wall return.

Case 3: Return behind the Supply Diffuser

Ideally, the supply air after exiting the diffusers should pass over the patient and return back to the return grille through a single pass without entraining back into the supply airstream, which could avoid mixing with the room air. In the current analysis, the ceiling return is placed right behind the ceiling linear diffuser (with the discharge angle facing forward away from the ceiling return). This allows the entrainment airflow induced by the supply air discharge to work collaboratively with the ceiling return, allowing the return air to readily exit the room (*Figure 5a,* Page 24). The size of the return grille is also increased in this arrangement to facilitate easy passage of the return air.

Also as shown in *Figures 5b* and *5c* such modification does not significantly change the temperature distribution and resulting thermal comfort of occupants. However, it significantly modified the probable flow path of airborne particles as indicated by the flow pathlines released from the patient's face (*Figure 5d*).

It clearly shows such a configuration can potentially provide a single pass flow over the patient and can reduce the probability of entrainment of the airborne particles back into the supply stream. While a part of the return air may get entrained into the supply airstream, most of the airborne pathogens would follow a direct path into the return grille without any obstructions and recirculation. This arrangement can further reduce the possibility for deposition of airborne pathogens on the exposed surfaces in a patient room.

Summary

CFD models were developed to evaluate the impact of various HVAC design configurations on the airflow patterns, temperature distribution, and resulting thermal comfort of occupants, and on the probable flow path of airborne particles released from the patient's face. These analyses indicate the linear diffusers combined with high supply airflow rates (high air change rates)

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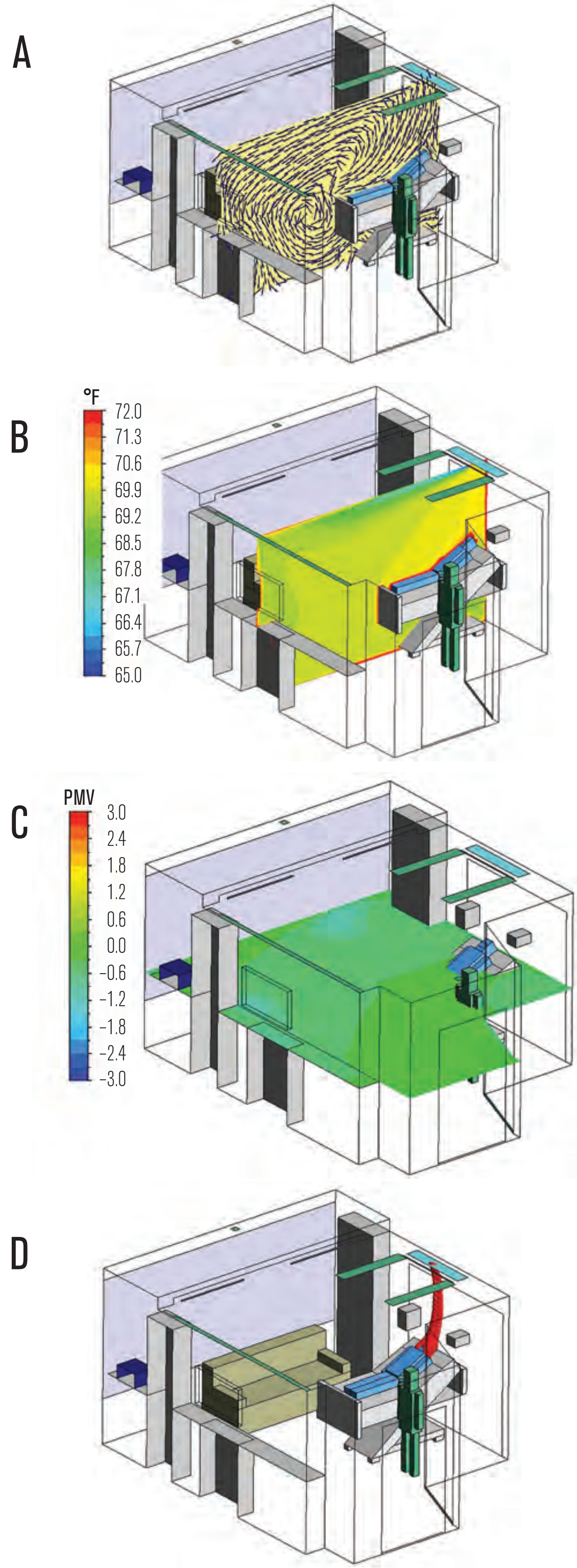

FIGURE 5 Results for Case 3. Room return moved to the ceiling and behind the supply diffuser showing A) airflow patterns; B) temperature distribution; C) PMV distribution at 4 ft (1.2 m) height; and D) resulting trajectory of airborne particles released from the patient's face. Placement of a return grille right behind the linear supply diffuser over the patient's head can potentially provide ready flow path to airborne particles to exit the room without significant recirculation and entrainment back into the supply stream.

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can cause strong recirculation and entrainment (induction) flows in the room. Depending on the location of the return grille, the airborne particles released from the patient's face can get entrained back into the supply airstream and can eventually spread into the entire room.

However, this study indicates placement of a return grille right behind the linear supply diffuser over the patient's head can potentially provide a ready flow path to airborne particles to exit the room without significant recirculation and entrainment back into the supply airstream.

A combination of locations and type of supply diffusers, locations of the room return and supply airflow rates can affect the airflow patterns in the patient room which are quite complex and specific to a particular design configuration. Therefore, it is difficult to reach any general conclusions about the optimized design configuration and placement of supply diffusers and return grilles in a patient room. This study demonstrates that the supply airflow paths, induced airflow paths, and exhaust grille placement can work collaboratively to establish protective and effective contaminant control. Thus, a careful evaluation of the HVAC configuration can help in gaining the insight and optimizing the flow path of air to obtain the desired combination of occupant thermal comfort and the best possible hygienic conditions in the patient rooms.

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