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Effectiveness of a Local Ventilation/Filtration Intervention for Health-Care Worker Exposure Reduction to Airborne Infection in a Hospital Room

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ABSTRACT

This study numerically examines the effectiveness of an expedient intervention to provide surge airborne-isolation capacity and health-care worker (HCW) protection during epidemics such as pandemic flu. The intervention pairs a portable ventilated headboard with a High Efficiency Particulate Air (HEPA) filter/fan system. Airborne droplet nuclei were theoretically generated via a patient cough in a traditional hospital patient room. Room airflow patterns were modeled by solving the Reynolds-Averaged Navier-Stokes equations along with the continuity and energy equations. The Lagrangian discrete-phase model in the finite-volume solver ANSYS Fluent 14 was used to track the dispersal of an "infectious aerosol" originating from the patient cough. The study examined five different test configurations, and tracked the aerosol for 35 seconds following the cough. Without the intervention in the room, the HCW was exposed to the cough aerosol which also approached the HVAC exhaust and room door within 35 seconds. The ventilated headboard, in the operating position with its canopy extended and the HEPA system activated, was very effective, eliminating 99% of the patient-source aerosol within 20 seconds, and not allowing aerosol to escape the canopy or expose the HCW, thereby providing excellent HCW and patient-room protection. With the canopy retracted, the ventilated headboard lost its local control of the aerosol as the retracted canopy obstructed half of the headboard's inlet area, and failed to prevent exposures to the HCW or to the vicinity of the room-entry door; however, the overall patient room would continue to benefit from the dilution filtration air cleaning provided by the HEPA system.

INTRODUCTION

Influenza is a common infectious disease whose transmission is predominantly attributed to contact and droplet (to include short-range airborne) modes of transmission. Thus, confined spaces where flu-ridden persons are located (e.g., hospital rooms) are high-risk locations for disease transmission. According to Ref. 1, there is a strong association between ventilation and airflow directions inside buildings, and the transmission and spread of infectious diseases such as measles, TB, chickenpox, influenza, smallpox, and severe acute respiratory syndrome (SARS). Hence, the use of negatively pressurized isolation rooms may be recommended for hospital patients with these diseases. Hospital shortages of isolation facilities were highlighted during the 2003 SARS pandemic. As the nature and scale of future pandemics is unknown, the construction of sufficient isolation rooms is not realistic, and alternate isolation techniques need to be considered (Ref. 2).

The present study examines the effectiveness of a local airborne infection isolation technique used in a traditional patient room. The study expands on the work of Ref. 3 in which a health-care worker (HCW), working with a patient, was exposed to cough aerosol in both a regular patient room and an Airborne Infection Isolation room (AIIR). To reduce the HCW's airborne exposures, the use of a ventilated headboard intervention coupled with a high efficiency particulate air (HEPA) filter/fan system could be effective by reducing the amount of patient-source aerosol in the vicinity of the HCW's breathing zone. The ventilated headboard intervention consists of a filtered headboard mounted to a height-adjustable aluminum frame, and configured with a retractable canopy, as shown in Fig. 1. The headboard is placed at the head of the patient bed, and the open-front canopy extended over the patient's pillow area to facilitate unidirectional, low-velocity airflow into the headboard. Medium efficiency (MERV 8) filters provide pressure and airflow distribution across the inlet

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cross-section of the headboard while functioning as pre-filters for the HEPA filter. A flexible duct connects the headboard to the HEPA system. By itself, the HEPA system provides a minimum of 12 air changes per hour (ACH) of dilution filtration to the patient room. When combined with the ventilated headboard, the operational intent is for patient-source aerosol to be captured within the protective canopy, and pulled into the headboard and to the HEPA filter. The HEPA filter removes the aerosol contaminants from the air, and then discharges the cleaned air back into the room. The headboard canopy can be in its operating position (Fig. 1a), or retracted position (Fig. 1b). The isometric view of the patient room with the headboard canopy in the extended position is shown in Fig. 2.

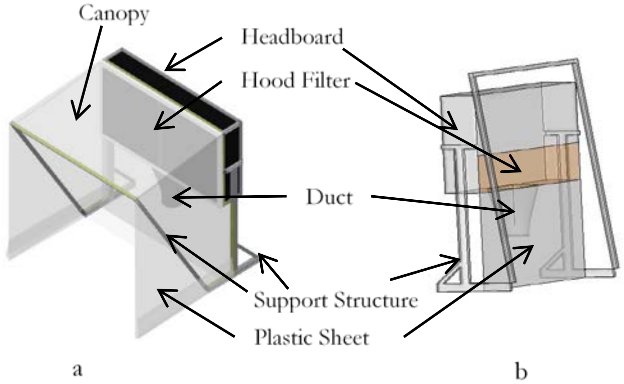


Figure 1. (a) Operating hood (b) Retracted hood

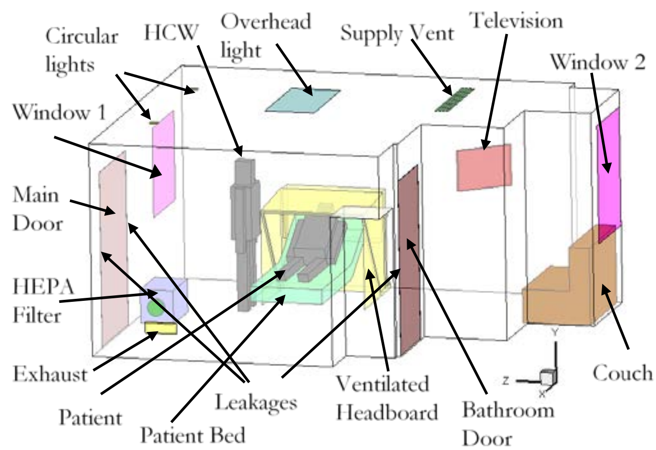


Figure 2. Isometric view of patient room

OBJECTIVES

The first research objective was to compare the ventilation in the patient room, including the ventilated headboard and the HEPA system intervention, to the ventilation in the room without this intervention. The geometric dimensions, spatial locations of the appliances/furniture, types and characteristics of the HVAC inlet vent and exhaust vent diffusers, flow rates at the inlet and exhaust vents, temperature, pressure, pressure differential between the patient room and the hospital corridor, and flow rate at the exhaust vent, all correspond to the prevailing room conditions measured in Ref. 3. Compared to the previous work, the bed height and HCW position were slightly adjusted to accommodate the headboard canopy, so the case of the patient room without the headboard intervention was re-done to incorporate the new bed and HCW positions. The ventilated headboard intervention was designed by the Centers for Disease Control and Prevention's (CDC's) National Institute for Occupational Safety and Health (NIOSH). The ventilated headboard was tested in both extended and retracted canopy positions, with the HEPA system turned on or off for the retracted canopy. To study the aerosol transport, a single cough was ejected from the patient's mouth, and its dispersal was tracked with time. The HCW exposure was evaluated and compared for each case with an objective to analyze the change in aerosol behavior with time, and to recommend the best headboard canopy configuration for HCW protection from the patient-source aerosol. Table 1 lists the cases for the various configurations of the headboard and the HEPA filter arrangement considered in this study.

Table 1. Cases Investigated

Case	Hood and HEPA filter arrangement	Hood Position	HEPA Filter on/off	Total number of cells	Aerosol Coalescence
1	Absent	NA	NA	2,690,387	Enabled
2	Absent	NA	NA	2,690,387	Disabled
3	Present	Operating	on	2,400,000	Enabled
4	Present	Retracted	on	1,800,000	Enabled
5	Present	Retracted	off	1,800,000	Enabled

METHODOLOGY

As shown in Fig. 2, the HEPA system was near the wall behind the HCW, with its discharge directed towards the HVAC exhaust. The duct between the headboard and HEPA system was not included in the CAD model. Inlet and outlet flow rates were provided at the headboard filter intake and HEPA system discharge, respectively.

Boundary Conditions

The boundary conditions in this Computational Fluid Dynamics (CFD) model are chosen from the previous study Ref. 3, and only the newly added conditions for the headboard and HEPA system are discussed here.

Headboard inlet filter. The headboard inlet filter is 1.2192 m (48") wide and 0.6096 m (24") tall, and is positioned at the head of the patient bed. Its airflow capacity is 0.1321 m^3/sec (280 CFM), and the air is assumed to be at a room temperature of 294.11 K. In the retracted configuration, the canopy retracts like the hood over a baby carriage, and the effective filter inlet area is reduced as the folded canopy sheeting obstructs half of this area. However, the volumetric flow rate remains unchanged, resulting in increased velocity at the unobstructed portion of the inlet filter. Boundary values for turbulence intensity, kinetic energy, and dissipation rate were estimated from the Reynolds numbers at these boundaries, as detailed in Ref. 4, to be 5.19%, 8.533e-05 m^2/s^2, and 1.593e-07 m^2/s^3, respectively, for the headboard with extended canopy, and 5.04%, 5.4705e-04 m^2/s^2, and 1.593e-07 m^2/s^3, respectively, for the retracted-canopy, HEPA "On" configuration.

HEPA system discharge. The HEPA system's discharge diameter is 0.2032 m (8"), and the system discharges clean air into the room at 0.1321 m^3/sec (280 CFM), the same as the headboard flow rate. The calculated boundary values for turbulence intensity, kinetic energy and dissipation rate are 6.17%, 0.06338 m^2/s^2, and 5.355e-06 m^2/s^3, respectively; (Ref. 4).

Solution Procedure

The solution procedure was the same as in Ref. 3. The unsteady, 3D, incompressible, Reynolds-Averaged Navier-Stokes equations, including gravity, were solved, as was the energy equation, to account for temperature variations. O'Rourke's stochastic algorithm was used to model droplet collision, and the Taylor analogy breakup *(*TAB*)* model was used for droplet breakup (Ref. 4). The patient room's computational grid was generated using Gambit software. A multi-block approach (Ref. 4) created the grid which consisted of both tetrahedral and hexahedral cells. Further grid refinement at the flow inlets and outlets, including the patient mouth, accounted for high velocity gradients in these regions. The total number of cells in the room was selected following a grid-independence study with 3 different meshes, for the velocity profiles in the room, Ref. 3. First, the air flow pattern is studied for all the cases listed in Table 1. Then, cough aerosol dispersal is computed and compared between cases. Lastly, aerosol behavior with time and HCW exposure to the aerosol is evaluated.

RESULTS AND DISCUSSION

Flow Pattern inside the Room

For each case, first the steady-state flow in the room was established. For all the cases, the resulting air velocities near the patient and HCW were lower than the maximum ASHRAE comfort zone velocity of 0.25 m/s (50 fpm), and the computed temperatures were also within the range of 23°C to 25°C (73°F to 77°F), thus, meeting the comfort conditions.

Case 1, Case 2 and Case 5 exhibited almost identical flow patterns, as expected, as there was no difference in the flow conditions for these cases. The headboard and the HEPA system in Case 5 did not contribute to the flow pattern as the HEPA system was turned off to stop airflow into the headboard, thus disguising its presence. The flow inside the room for these cases was governed mainly by the HVAC inlet vent operating at 227 CFM.

The flow patterns in Case 3 and Case 4 were governed by the HVAC supply and the HEPA system discharge operating at 227 CFM and 280 CFM, respectively. In Case 3, the canopy is extended, and the headboard provides suction flow within the canopy region, whereas in Case 4, the canopy is retracted, partially blocking the headboard inlet filter and reducing the effective suction area which is now below and behind the inclined patient bed. In both cases, the HEPA system's discharge directs air towards the wall facing the patient. A part of the air from the discharge is exhausted directly, while a part of it rises along the wall facing the patient. Interestingly, an x-plane cutting the HVAC supply vent at x = 2.61 m (102.756") shows recirculation zones below the inlet vent and behind the HCW (Fig. 3). These recirculation zones are stronger in Case 3 compared to Case 4, indicating the risk of any contaminants entering the region to stay in that region for a longer time.

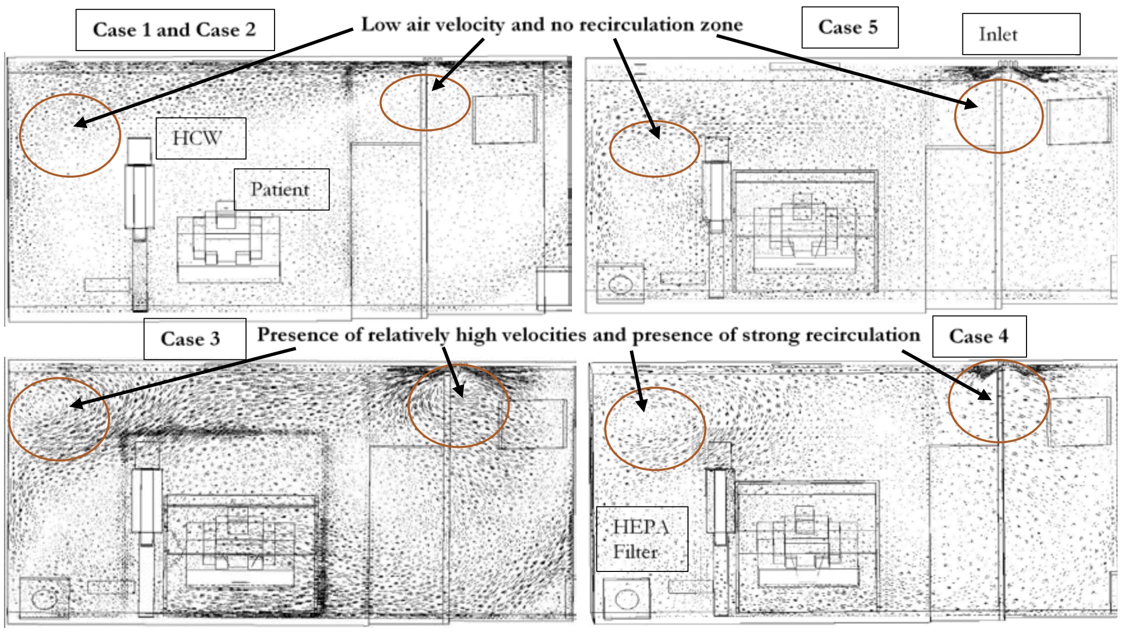


Figure 3. x-plane at inlet vent showing recirculation

Comparison of Cough Dispersal

After a steady air flow pattern was established in the room for each headboard/canopy configuration listed in Table 1, a cough aerosol was ejected from the patient's mouth, normal to the mouth opening, for a duration of 0.5 s. Cases 1, 2 and 4 are compared in Fig. 4, and Case 3 is shown separately in Fig. 5 to highlight the high efficiency of Case 3 in removing patient-source "infectious" aerosol. Cough aerosol ejection normal to the mouth is the common, real-world scenario.

Case 1: Patient Room without ventilated headboard and HEPA system arrangement (droplet coalescence enabled). A typical cough is an aerosol containing 1,000 to 10,000 droplets (Ref. 5). At the end of the cough, 7,000 of these droplet nuclei remain in the room due to coalescence. Figure 4, Column 1, shows aerosol positions at various time instants. At 5 s, some aerosol rises above the HCW's head level, while some reaches below this level. At 15 s, the aerosol is found descending, moving away from the HCW, and towards the exhaust and the main-door leakages. At 25 s, the aerosol is found drifting towards the exhaust, and away from the main-door leakages. The aerosol velocities are relatively low, without the HEPA system's discharge blowing air back into the room. At 35 s, 560 droplet nuclei (24.39% of initial aerosol mass) remain airborne inside the room, and are found moving slowly towards the exhaust. As in Ref. 3, the HCW is found exposed to the airborne "infection", as aerosol is found in the HCW's vicinity. This exposure is quantified in a later section.

Case 2: Patient Room without ventilated headboard and HEPA system arrangement, with droplet coalescence disabled (Figure 4, Column 2). Even though aerosol coalescence occurs during a real cough, it is disabled in Case 2, in order to determine the dispersal of smaller aerosols. The flow pattern is identical to that for Case 1. To ensure that the number of droplets at the end of the cough is close to that in Case 1, fewer droplets were ejected per computational time step. At the end of the cough, 6,956 droplet nuclei have emerged from the patient's mouth. At 5 s, the aerosol starts rising and moving towards the HCW. At 15 s, most of the aerosol is above the HCW's head. Similar to Case 1, the aerosol movement tends toward the main-door leakages and exhaust. At 25 s, unlike in Case 1, the aerosol still does not descend, owing to its lighter weight (no coalescence). It moves towards the exhaust at a much slower pace, and some of it is still near the HCW. At 35 s, all aerosol remains airborne, slowly descending and moving towards the exhaust.

Case 3: Patient room with ventilated headboard canopy extended and HEPA system on. Figure 5 shows the aerosol dispersal for Case 3. At the cough's end, around 2,500 droplet nuclei remain in the room, all within the headboard canopy; hence, only this region is shown in the figure. The number of droplets is smaller because the cough aerosol from the patient's mouth immediately strikes the canopy and deflects back where it is carried into the headboard filter by the suction-induced airflow. The results show that all of the aerosol are contained within the canopy. At the end of 25 s, only 34 droplet nuclei (0.3 % of initial mass) remain, and all are still within the canopy. Thus, this test condition is very effective in containing the patient cough aerosol and preventing it from circulating through the room.

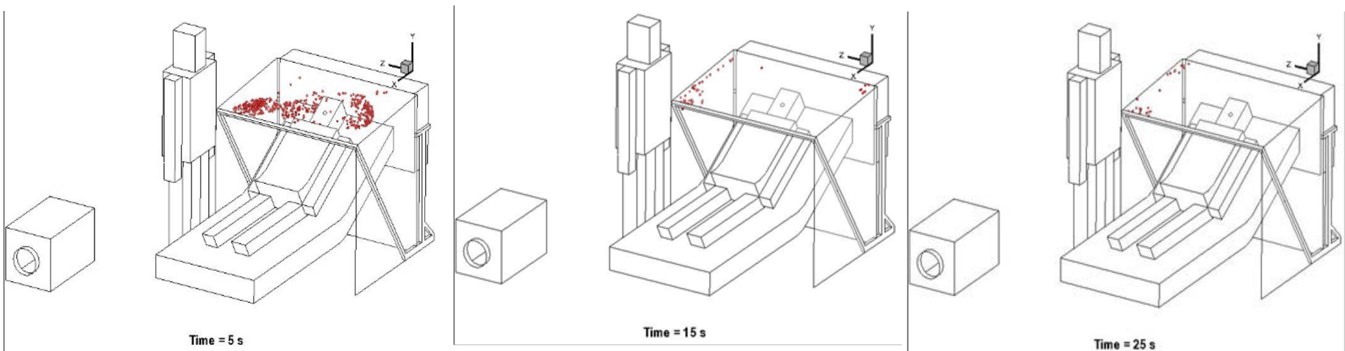


Figure 5. Cough dispersal for Case 3

Case 4: Patient room with headboard canopy in retracted position and HEPA system on (Figure 4, Column 3)**.** At the end of the cough, the aerosol in the room contains around 6800 droplet nuclei. At 5 s, the aerosol rises above the HCW's head, and starts descending before coming under the influence of the HEPA system's discharge. Even though the HEPA system is 'on', the cough aerosol is not pulled into the headboard. This is due to the retracted configuration of the canopy covering half of the headboard inlet filter, reducing the effective suction area. At 15 s, unlike in Case 1 and Case 2, the aerosol has already crossed the HCW, and is moving rapidly towards the main-door leakages and the exhaust. The HEPA system discharge strongly drives the motion of the aerosol. At 25 s, much of the aerosol is approaching the main door and the HVAC exhaust, creating a high risk of aerosol escaping through the leakages to the corridor. At 35 s, some aerosol is exhausted, while the remaining aerosol rises up the wall towards the inlet vent where it is deflected back into the room. While the HEPA system increases the room air changes per hour (ACH) in this test case, cough aerosol capture and removal through the headboard does not occur in the initial 35 s, although it would be expected to occur later.

Case 5: Patient room with headboard canopy retracted and HEPA system off. Due to the identical flow pattern of this case with Case 1, the cough aerosol dispersal was also found identical, and hence, it is not discussed again.

Cough Aerosol Behavior

To minimize the HCW exposures, it is important to understand the aerosol behavior. Figure 6 shows the time variation of the cough aerosol present in the room. Due to coalescence, the number reduces exponentially during the initial two seconds, and then, the reduction becomes gradual with time. For Case 2 (without coalescence), the number of droplet nuclei in the aerosol is constant with time. Since the aerosol diameter is constant at 1 μm for this case (representing airborne infectious droplet nuclei), the aerosol does not settle under gravity within the 35 s observed time period. For other cases, initial close aerosol proximity results in coalescence during this period, reducing the number of droplet nuclei in the aerosol to below 1,000 within 5 s. Later, as the distance between droplet nuclei increases, coalescence decreases, then stops. The aerosol droplet nuclei reduction with time is greatest in Case 3 due to coalescence plus the headboard's effective capture and

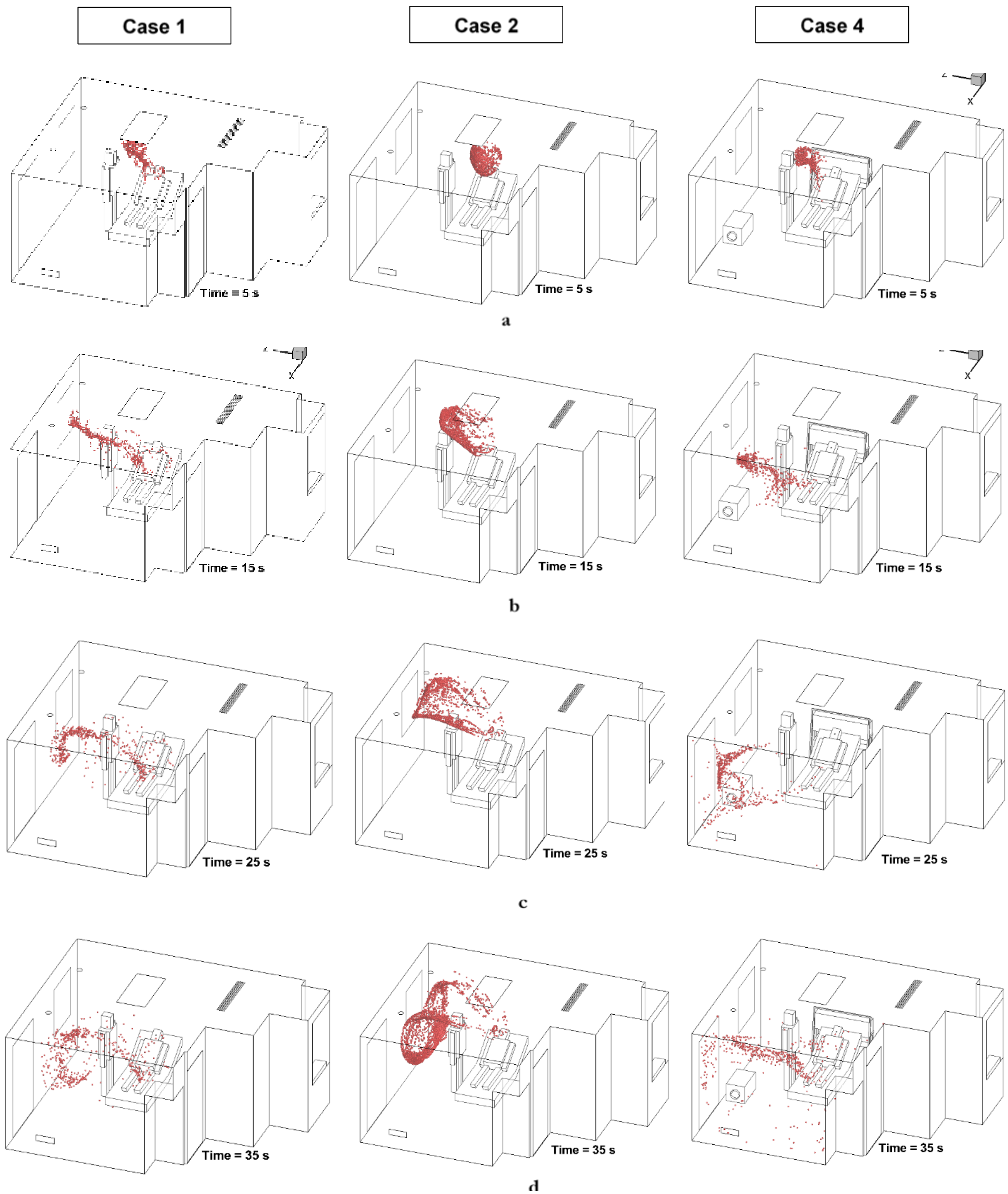


Figure 4. Cough dispersal for Cases 1, 2 and 4 at (a) 5 s (b) 15 s (c) 25 s (d) 35 s

removal of the aerosol. The headboard inlet suction is also present in Case 4 when the headboard canopy is retracted, but the suction area is not properly positioned to effectively capture and remove aerosol during the 35 s of the simulation.

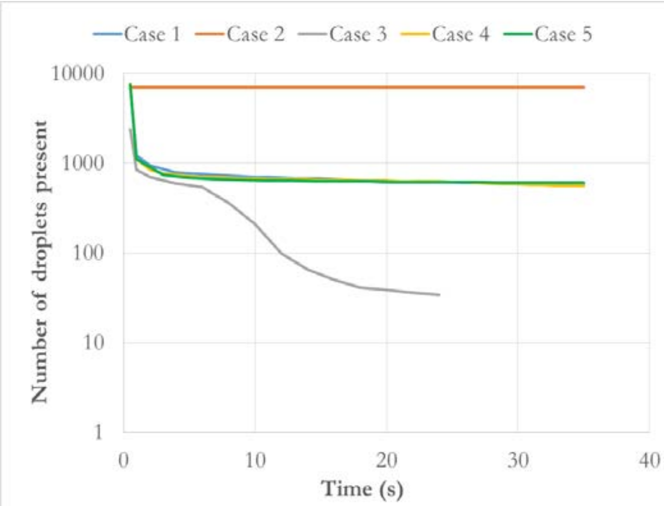


Figure 6. Remaining droplets

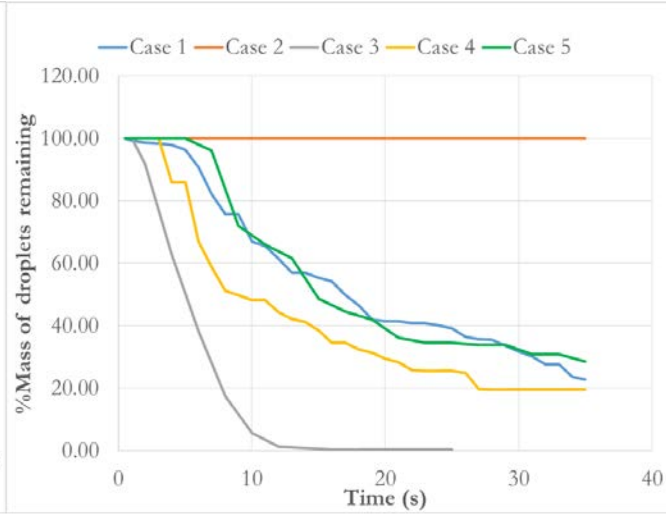


Figure 7. Remaining percentage droplet mass

Figure 7 shows the percentage mass of aerosol remaining inside the room for each case. Note that the percentage mass of aerosol decreases with time in all cases except Case 2. The maximum reduction (exceeding 99%) occurs for Case 3 due to effective capture and removal of the aerosol into the headboard. For the other cases, within 35 s, the percentage falls to approximately 28% for Case 5, 23% for Case 1 and 19% for Case 4. Thus, the headboard with extended canopy not only succeeds in containing the infectious aerosol from spreading throughout the room, but it also reduces the HCW exposure to the cough aerosol by not letting the aerosol come out of the headboard's canopy.

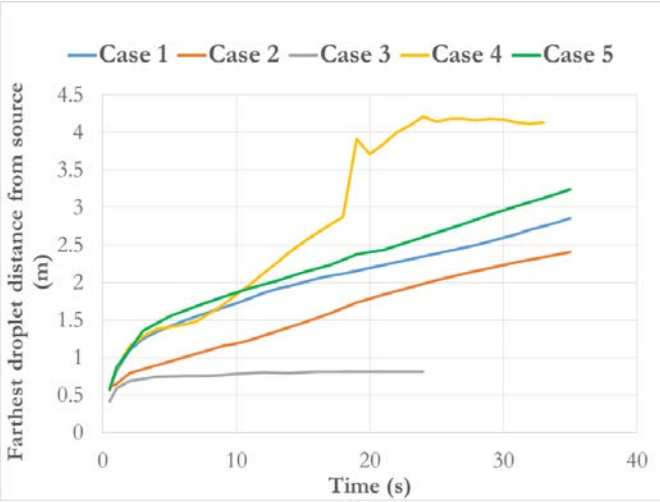
Figure 8 shows the aerosol distance from the patient mouth with time; the farthest-droplet distance represents the greatest infection risk. The aerosol travels much farther in Case 4 with the retracted headboard canopy and the HEPA system on, due to higher room air velocities as compared to other cases. Aerosol in Case 3 is never allowed to disperse.

Evaluation of HCW exposure to the Cough Aerosol

To quantitatively evaluate the HCW exposure to the cough aerosol for different headboard/canopy/HEPA test conditions, a volume of size 0.4 x 0.4 x 0.4 m is considered around the HCW's head. Aerosol entering this volume is considered to be in the HCW's vicinity. Re-entering aerosol is re-counted, as this represents real-world exposure. This aerosol is taken as a measure of the HCW exposure, and is shown in Fig. 9. Case 2 disregards coalescence, and so has a very large number of droplet nuclei in this region, and the scale for the figure would mask the result for the other cases; hence, this case is not included in this figure. In any case, coalescence must be considered in real applications. This exposure is estimated only for the current position of the HCW working with the patient. Case 1 and Case 5 have similar HCW exposure to cough aerosol due to similar flow patterns in the room, while Case 3 has the minimum HCW exposure to the cough aerosol. Case 4, with the headboard canopy retracted and the HEPA filter on, exhibits maximum HCW exposure to the cough aerosol. The HCW exposure might change, however, if the HCW or the HEPA system were repositioned.

CONCLUSION

A traditional patient room and 5 configurations of a ventilated headboard intervention were carefully analyzed for resulting airflow patterns and cough aerosol removal. In Case 1 and Case 5, aerosol migrates past the HCW and near the vicinity of the main-door before drifting towards the exhaust. The HCW is exposed to the aerosol for these cases. The headboard canopy in the retracted position with the HEPA filter 'on' (Case 4) is less effective. Even though the effective ACH is increased in the room via HEPA filtration, no aerosol was removed through the headboard during the 35 s simulation and



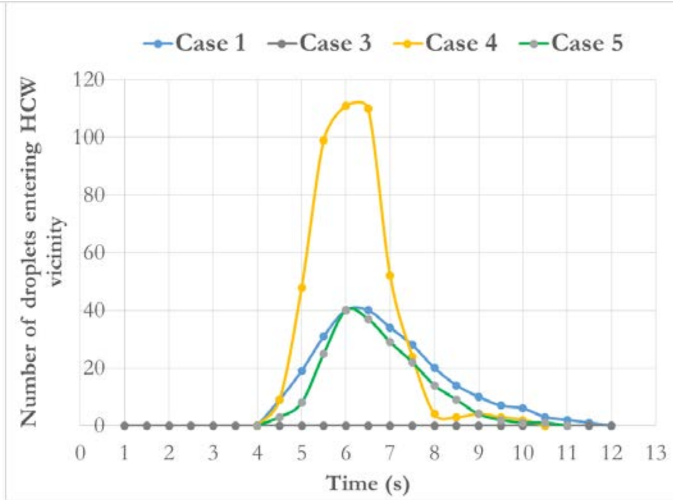


Figure 8. Distance of farthest droplet nuclei from source

Figure 9. HCW exposure to cough aerosol

room airflow induced by the HEPA's discharge pulled the cough aerosol towards the HCW position and the room entry door. Overall, the removal rate of virus aerosol in all the configurations can be compared as Case 3 << Case 4 < Case 1 < Case 5. HCW exposure comparison to the aerosol was Case 3 << Case 1 and Case 5 < Case 4.

The results indicate that the local isolation technique of a ventilated headboard with extended canopy and HEPA filtration fan system is very beneficial. This arrangement limits dispersal of patient source aerosol to the confines of the canopy where it removes 99% within 20 s after the start of the cough. It also virtually eliminates the HCW exposure to the cough aerosol, irrespective of the HCW's position or location. Hence, the ventilated headboard with extended canopy intervention shows significant protective potential as a method of producing surge capacity in airborne infection isolation. However, the local source control of cough aerosol is lost in the retracted canopy configuration, and any protective features are limited to those resulting from the enhanced effective ventilation rate. Facilities considering deployment of the ventilated headboard should adopt policies to maintain the extended canopy as much as possible, and utilize smoke visualization during HEPA placement to minimize the exposure potential to HCWs during any retracted-canopy operational conditions.

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DISCLAIMER

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