ORIGINAL ARTICLE

Mathematical Modeling of Pathogen Trajectory in a Patient Care Environment

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OBJECTIVE. Minimizing healthcare worker exposure to airborne infectious pathogens is an important infection control practice. This study utilized mathematical modeling to evaluate the trajectories and subsequent concentrations of particles following a simulated release in a patient care room.

DESIGN. Observational study.

SETTING. Biocontainment unit patient care room at a university-affiliated tertiary care medical center.

METHODS. Quantitative mathematical modeling of airflow in a patient care room was achieved using a computational fluid dynamics software package. Models were created on the basis of a release of particles from various locations in the room. Computerized particle trajectories were presented in time-lapse fashion over a blueprint of the room. A series of smoke tests were conducted to visually validate the model.

RESULTS. Most particles released from the head of the bed initially rose to the ceiling and then spread across the ceiling and throughout the room. The highest particle concentrations were observed at the head of the bed nearest to the air return vent, and the lowest concentrations were observed at the foot of the bed.

CONCLUSIONS. Mathematical modeling provides clinically relevant data on the potential exposure risk in patient care rooms and is applicable in multiple healthcare delivery settings. The information obtained through mathematical modeling could potentially serve as an infection control modality to enhance the protection of healthcare workers.

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The threat of global emerging infectious diseases, bioterrorism attacks, and accidental exposures to contagious diseases with high morbidity and mortality has prompted the development of hospital biopreparedness programs. One aspect of biopreparedness is the availability of special isolation facilities called biocontainment patient care units (BPCUs) to provide medical care for individuals with hazardous infectious diseases.[1] One such unit is the Nebraska biocontainment patient care unit (NBPCU), which was designed to provide comprehensive care for up to 10 patients with contagious infectious diseases. The potential for transmission of highly infectious diseases to healthcare workers (HCWs) is well established and provides the background for the necessity of the BPCU to care for such patients.

Biocontainment units utilize a number of modalities to protect HCWs from exposure to infectious diseases, including limiting physical access to the unit, pass-through autoclaves, enhanced personal protective equipment, and vaccines. However, one of the most important aspects of a BPCU is a high-efficiency air handling system.[2] Previous studies have utilized mathematical modeling in an effort to better analyze air flow and turbulence in various settings.[3,4] This study used mathematical modeling and computational fluid dynamics (CFD) to evaluate particle trajectories and subsequent particle concentrations within regions of a patient care room. Smoke particles were used as a method to qualitatively corroborate the airflows predicted by the mathematical modeling. We hypothesized that the mathematical model would be useful in predicting areas of differential flow and eddy currents that impact potential exposure of HCWs to airborne infectious agents.

METHODS

Setting

The NBPCU is a 10-bed, 4,100-foot^2 unit located at the University of Nebraska Medical Center in Omaha, Nebraska. The patient rooms have negative pressure air flow with at least

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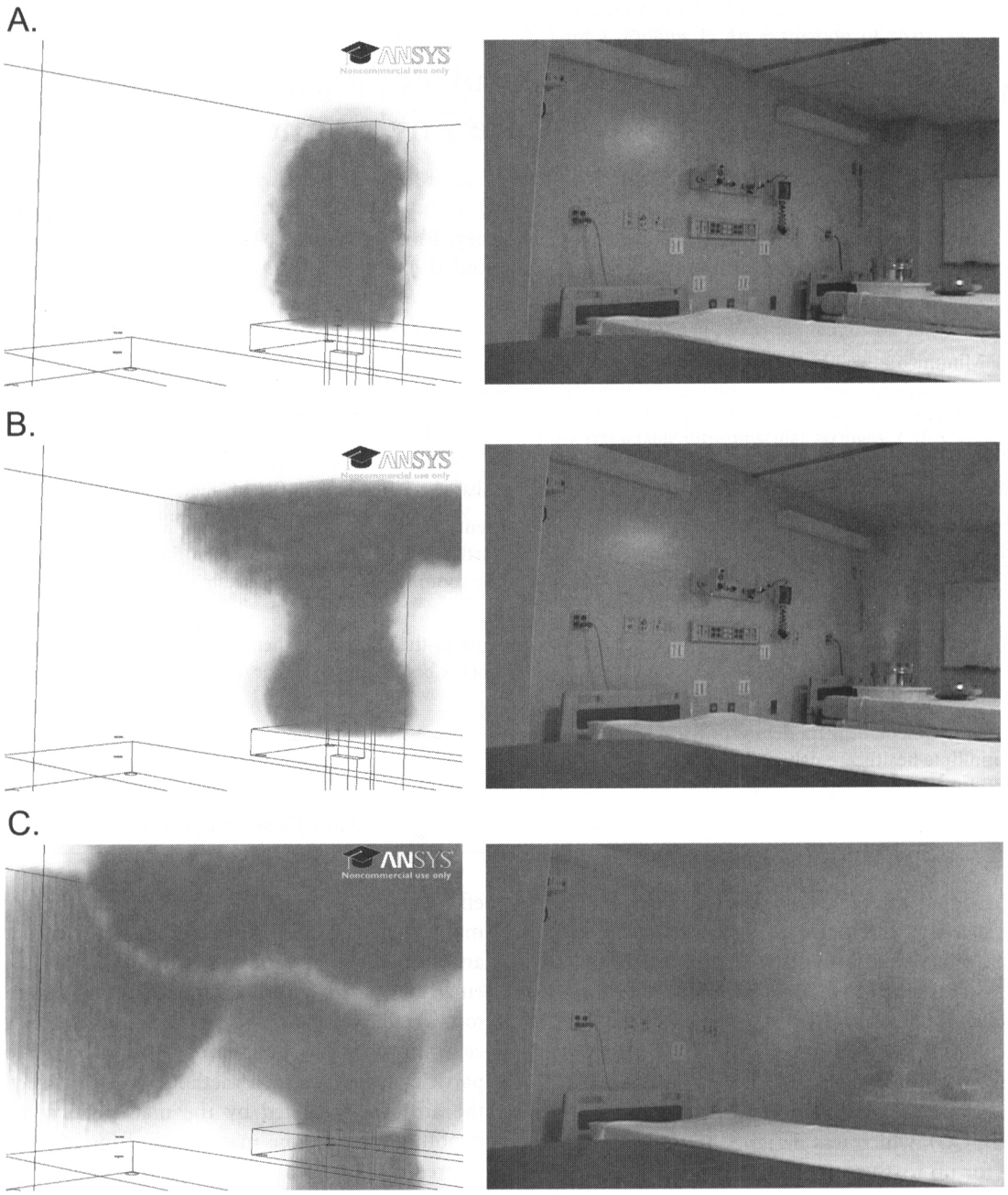


FIGURE 1. Computational fluid dynamics (CFD) model (*left*) and correlative smoke test (*right*) demonstrating the release of particles from bed 2 at time intervals $t = 20.5$ seconds (*A*), $t = 21.0$ seconds (*B*), and $t = 22.0$ seconds (*C*) with an open curtain. Time is reported as from the ignition of the smoke release candle; the time of the sneeze in the CFD model was started when the smoke was initially released from the candle. A color version of this figure is available in the online edition of the journal.

15 air exchanges per hour. The air flow is single pass with no recirculation, and a duplicate fan system assures continuous air flow. Exit air is high-efficiency particulate air filtered. Airflow is designed to maintain a negative pressure of no less than 0.03 inches water gauge between corridor and patient room, and rooms are alarmed to notify in the event of loss of negative pressure. The direction of airflow is from clean areas (staff nursing station and entrance) to corridor to dirty areas (patient rooms). A patient room in the NBPCU was utilized in this study. The room has 2 inlet air vents (supply) and 3 outlet returns (exhaust). As recommended, the inlet air vents are located on the ceiling, while the exit returns are located several inches above the floor.[1] The room contains a separate bathroom with an exit return. An anteroom intended

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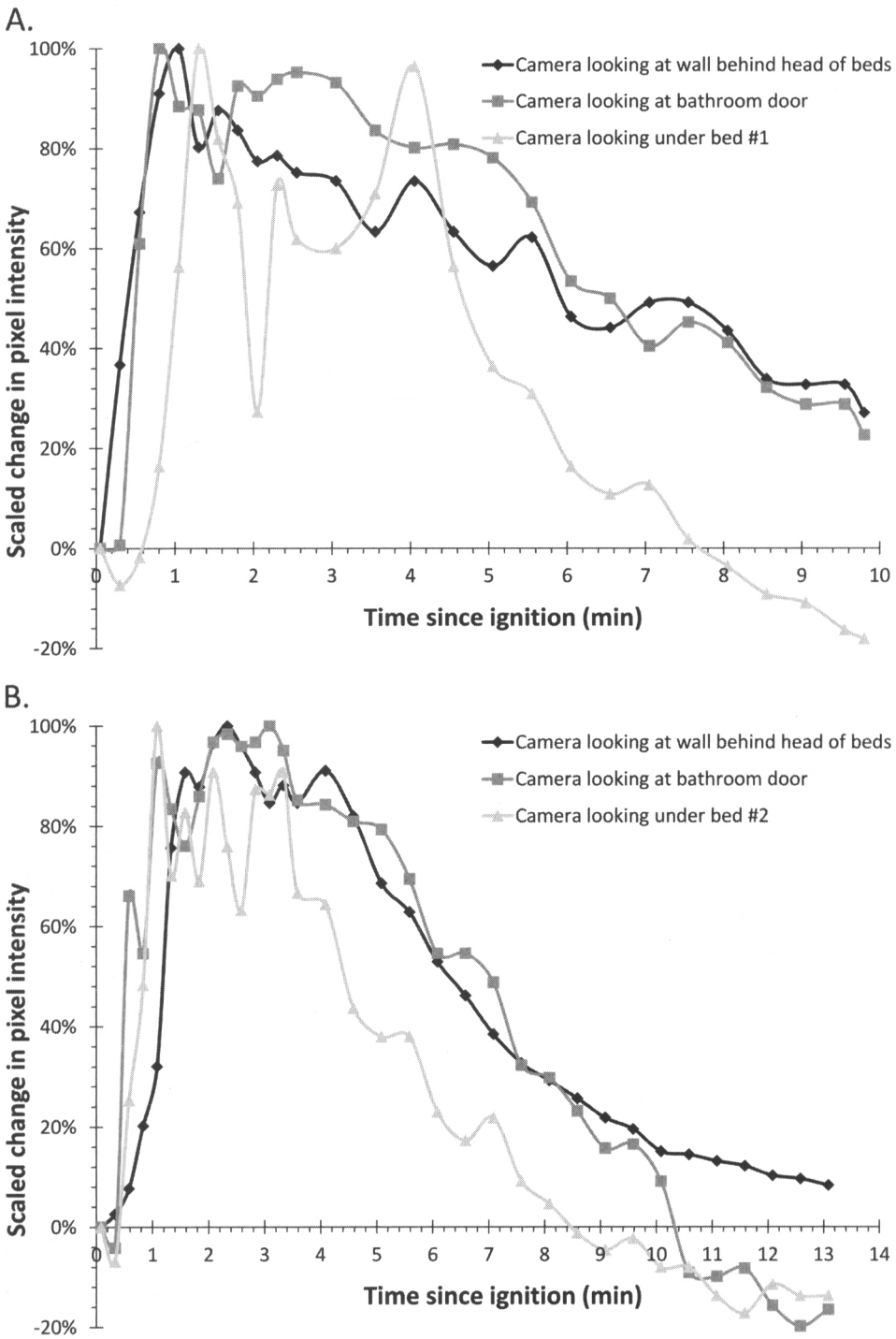


FIGURE 2. Relative smoke concentrations as measured by the average video pixel intensity. *A*, Smoke from bed 1, curtains fully open. *B*, Smoke from bed 2, curtains partially closed.

for the entry and exit of personnel serves as an air lock. The bathroom and the anteroom connect to the main room but not to each other.

The NBPCU room utilized in the model contains 2 patient beds (Figure 4). The height of the beds is set to the level personnel prefer for patient care. Additional furniture was not included in the model, since any noncritical movable items will be removed before patient arrival to minimize surfaces and contamination risks. The room contains a privacy curtain that can be drawn around bed 2. The curtain is sus-

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pended from a railing attached to the ceiling, but because of the fire code, there is a free space between the curtain and the ceiling that is open to air movement and would allow sprinklers to saturate the area in the event of a fire.

Mathematical Model

Detailed quantitative mathematical modeling of airflow in a patient care room was achieved using the ANSYS Fluent 13 CFD software package (ANSYS). The mathematical equations that describe the air flow in the NBPCU consist of the Navier-Stokes equations, a continuity equation, an equation of state, and a thermal energy balance (for supplementary material, contact the corresponding author). The relevant variables are air density, 3 velocity components, pressure, and temperature. In this study, the temperature was set as a constant at standard room temperature, so the thermal energy balance equation was not considered.

A computational mesh was assigned to the free space in the unit. The space-filling mesh is comprised of 760,000 tetrahedron (triangular pyramids)-shaped computational cells. Each cell on a surface (eg, wall, bed, door) was set to have a maximum cell size that was allowed to vary between 1.75 and 4.0 inches. Cells in the center of the airflow region were limited to a 1.75–8.0-inch range. The 3 momentum equations, the continuity equation, and the equation of state are solved in each cell, with boundary conditions at common interfaces with adjacent cells or solid structures, to assure the solutions regularity and nonslip conditions hold at solid surfaces.

Multiple model scenarios were created on the basis of a release of particles from various locations in the room. The series of mathematical models and smoke testing included the release of particles from the head of the bed with and without the privacy curtain drawn and the release of particles from the toilet in the bathroom. Computerized particle trajectories were determined in time-lapse fashion over a blueprint of the room. The study calculated particle concentrations relative to various simulated HCW positions in the room.

To mimic the situation of a patient who poses an infection risk through sneezing or coughing, particle release was modeled from the head of the bed in an upward direction with an initial velocity of 100 m/second for a period of 1 second. Estimates of air velocities from sneezes and coughs vary greatly, from about 10 m/second for a cough and 50 m/second for a sneeze to as fast as the speed of sound (343 m/second).[5,6] For this model, 100 m/second was chosen as a representative air flow velocity near the midpoint of the possible velocity ranges. In order to avoid computational difficulties arising from an abrupt change in source velocity from 100 m/second to a full stop at 0 m/second, the sneeze velocity was tapered following this profile: 100 m/second for the first 10 time intervals of 0.1 second each, 10 m/second for the eleventh time interval, 1 m/second for the twelfth interval, and 0 m/second for all subsequent intervals.

Smoke Tests

A series of smoke tests were conducted to evaluate the model under each scenario. Standard smoke test techniques were used along with the Superior Smoke 2B candle (Superior) for airflow studies, which generates 8,000 feet^3 of smoke over a 60-second period.[7,8] The smoke particles generated by the Superior Smoke 2B candle have been thoroughly described by the manufacturer and are known to be in the 0.01–1-μm mass diameter size range. This size range is comparable to those of aerosolized infectious bacterial and viral organisms. A series of video cameras were placed in the room at various angles in order to obtain multiple images of smoke particles releasing from each head of the bed, entering/exiting the bathroom, and underneath the bed as the smoke flowed toward the air returns on the NBPCU floor. These angles were selected to give complete coverage of the smoke's pathway as it both filled and left the room.

Approximate average smoke concentrations in the room were calculated on the basis of the average image brightness from a time series of video still shots spaced 15 seconds apart at the beginning of the smoke release and 30 seconds apart after 3 minutes had elapsed. Graphical image manipulation software (GIMP, ver. 2.6; GNU Image Manipulation Program) was used to calculate the average pixel intensity from the video stills. The average intensity was scaled by the maximum intensity (100% change) and the preignition intensity (0% change) to give a relatively quantitative measurement of the concentration as a function of time.

RESULTS

CFD Model Verification with Smoke Tests

The CFD results are compared side by side in a time-lapse fashion with the results of the smoke tests in Figure 1 for release of particles from bed 2 with the privacy curtain open. On the left side, the computational results of the concentration of particles in the air are plotted. Initially, the particles rose to the ceiling and then spread across the ceiling and throughout the room. While the CFD calculations and smoke tests are not quantitatively identical, qualitatively the predicted particle concentrations are similar to the smoke concentration that was visually recorded.

Particle Residence Time

CFD particle tracing simulations were performed (data not shown), which predict the motion of individual particles as they are released during a simulated sneeze. CFD simulations predict that the majority of particles exit the room through one of the air returns in 5–30 minutes from the initial particle release and that very few particles remain within the room

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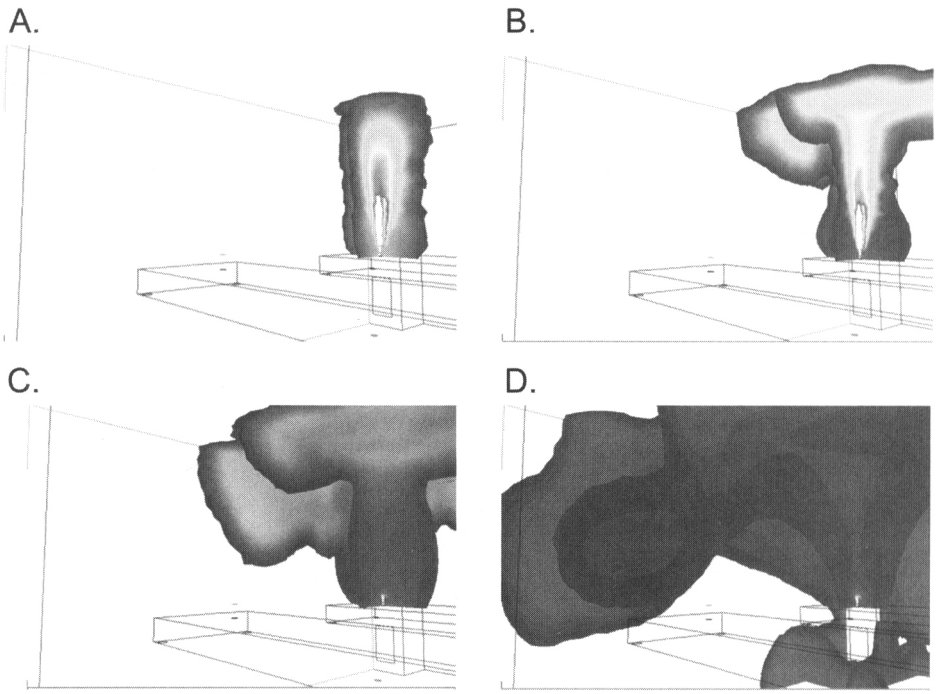


FIGURE 3. Perspective snapshots of the release of particles from bed 2 with the curtain in place at time intervals $t = 20.5$ seconds (*A*), $t = 21.0$ seconds (*B*), $t = 22.0$ seconds (*C*), and $t = 29.0$ seconds (*D*). A color version of this figure is available in the online edition of the journal.

beyond an hour (generally trapped on a surface or trapped within an air flow eddy). Figure 2 shows the average smoke concentration over time, as measured by several cameras placed throughout the room during the smoke test. The average concentration is significantly lowered by the 5-minute mark (no more than 80% of the peak concentration). The room is mostly cleared by the 15-minute mark (no more than 20% of the peak concentration). Smoke video data were not collected for a longer amount of time, since smoke was not visually present to the human eye after 15 minutes.

Particle Release from Other Scenarios

If the curtain is drawn around bed 2, then the particle plume dynamics (Figure 3) change from the scenario with the curtain open (Figure 1). After the particles have been released, a distinct plume develops above the head of bed 2 that reaches toward the ceiling. The plume spreads across the ceiling and crosses the opening between the partition and the ceiling, entering the bed space of the other bed. The floor air return near the floor of bed 2 causes the particles to be drawn down, but the particles that have crossed into the other bed space take much longer to descend to the return vent located at the head of bed 1.

The release of particles from the toilet in the bathroom with the door open was also modeled. When particles are released in the toilet, their trajectories were mostly limited to the bathroom space (data not shown).

Exposure Risk at Various Locations in the Patient Care Room

Particle concentrations in several areas where HCWs typically stand in a patient room were modeled in an attempt to stratify each location in terms of exposure risk (Figure 4) Each HCW position was modeled with the room curtain closed and with the curtain open. Since the smoke test results show that peak average particle concentration is reached in about 1 minute, followed by a gradual spreading and clearing of the particles, the CFD model focused on the initial 1-minute period after a sneeze to find the precise moment and locations of peak particulate concentrations. These results are graphically represented in Figure 5.

CFD results (data not shown) predict that particle concentrations 5 feet from the floor are negligible just inside the bathroom and anteroom throughout the modeled time. The CFD simulations were performed with the door closed and with the door open, and few particles crossed into these ancillary rooms. In general, the particles that spread across the ceiling (Figures 1, 3) reach the wall that separates the rooms and recirculate back into the room along the floor. Particulate concentrations just inside the bedroom near the anteroom

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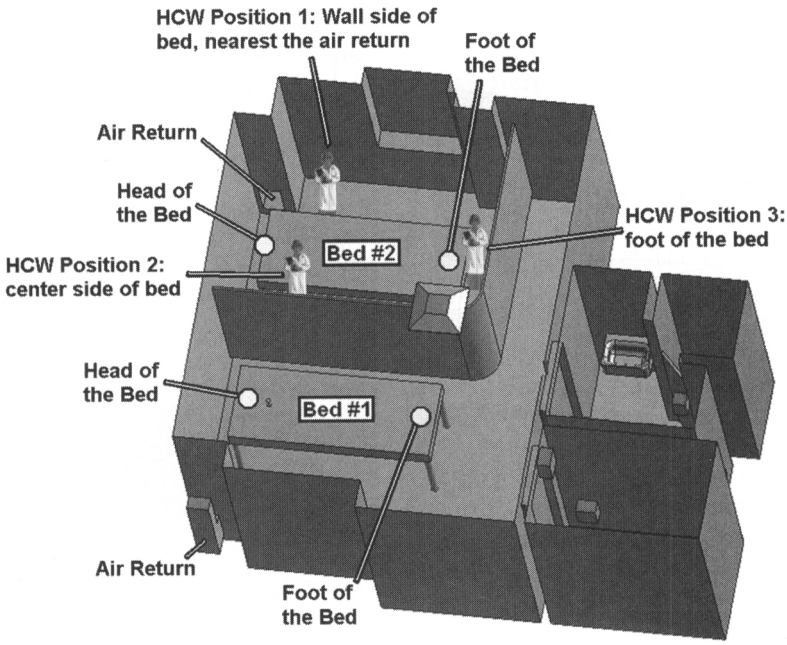


FIGURE 4. Layout of the Nebraska biocontainment patient care unit room, with different positions of the healthcare worker (HCW) utilized for the mathematical model. The HCW is modeled around 3 sides of the perimeter of the bed.

door (also 5 feet off the floor) were approximately half that of the concentrations at the foot of the bed at most times within the model.

DISCUSSION

Airflow dynamics is an important part of care provided in BPCUs and also in hospital airborne isolation rooms utilized for patients with tuberculosis and other airborne pathogens.[9] Air pressure in routine hospital rooms can be variable.[10] A number of factors beyond pressure differentials affect the airflow dynamics, including the presence of an anteroom, tightness of room seal, and HCW traffic.[11,12]

Several recommendations have been made for airflow, air pressures, and air exchanges in BPCUs.[1,2] However, little work has been done on air dynamics in these settings. Eddy currents and air vent placements could lead to variable particle concentrations in various areas of the room. Mathematical modeling of particle dynamics can be utilized to evaluate airflow and ultimately to assess variables such as bed placement and HCW positioning to minimize pathogen exposure.

The NBPCU was configured to perform at least 15 air changes per hour. If one were to assume that the NBPCU were well mixed, then 15 air changes per hour would result in a particle concentration half-life of approximately 4 minutes. The video evidence shows that the half-life was nearly twice that level. The particulate concentration half-life was approximately 7 minutes (Figure 2). This difference is likely due to the fact that the airflow in any room is uneven. Air turbulence forms eddies and vortices that can trap particles, especially in inside corners of the walls or in regions with poor airflow (such as behind the shower door in the bathroom). A full CFD simulation is therefore quite helpful in understanding real-world particulate concentrations instead of relying on simplified air exchange calculations.

Figure 5 demonstrates that a person at the foot of the bed will likely be exposed to much lower particle concentrations than someone at the head of the bed. The NBPCU air handling configuration—with an air supply in the center and returns at the perimeter—helps to draw particles toward the head of the bed, and levels remain higher in its proximity than elsewhere. When the concentrations closer to the head of the bed (Figure 5*A*, 5*B*, solid lines) are compared for the wall side (Figure 5*A*) and center side (Figure 5*B*), the initial exposure is less on the center side. However, after 60 seconds, the levels on the center side are equal or higher than on the wall side. These results can be explained by the position of the NBPCU room walls and air return. Air is drawn toward the return located at the floor at the head of bed 2 near the wall, thus exposing anyone standing on that side of the bed more than on the center side. However, when the curtain is closed, the plume that flows across from the ceiling (Figure 3) cannot readily spread across the room and descends on the center side, resulting in the secondary increase of concentration levels at the center side.

Several interesting conclusions can be drawn from this study. On the basis of the mathematical models and smoke testing, a general trend is observed that particles disperse primarily along the ceiling and later fill the lower space when

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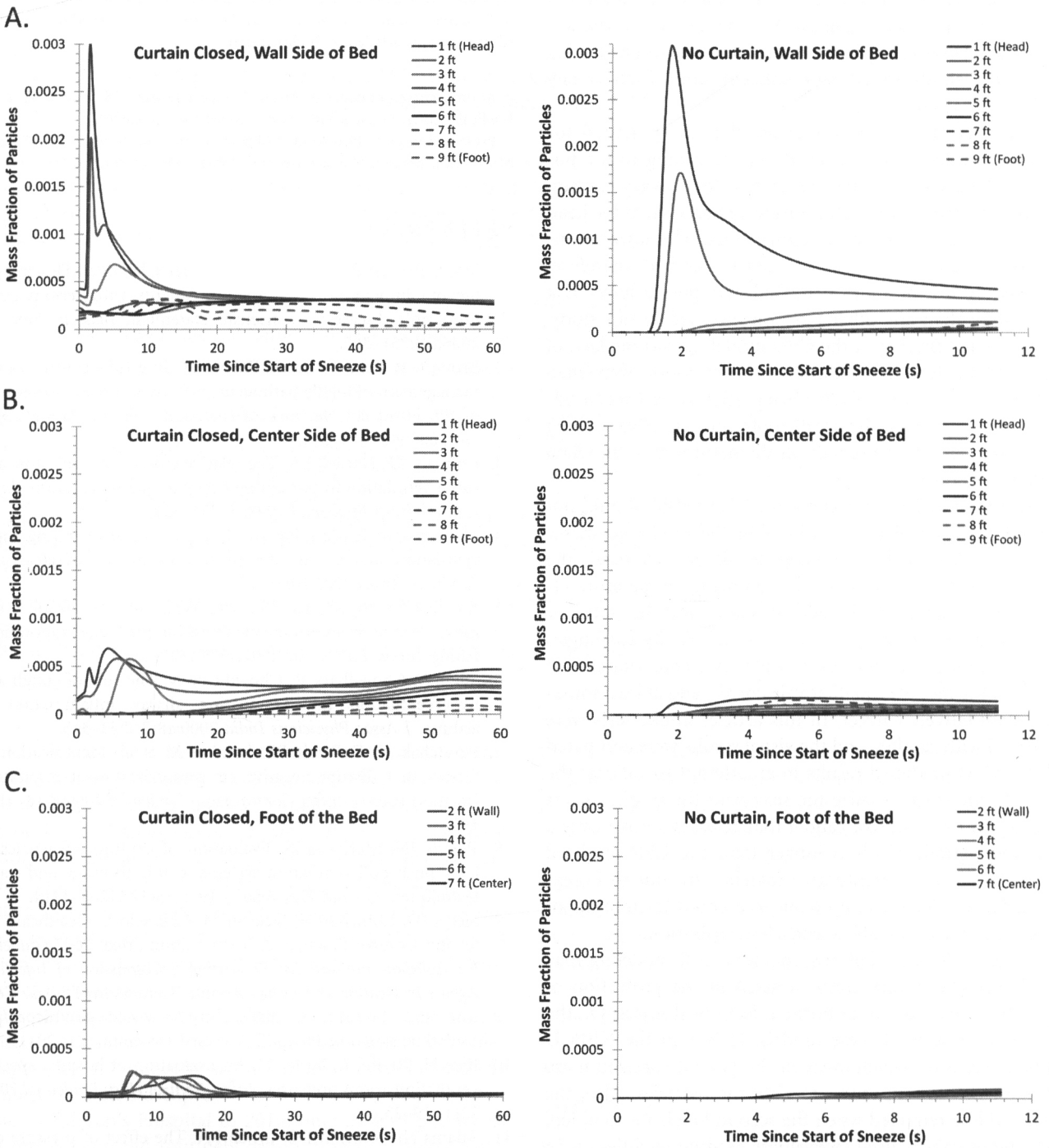


FIGURE 5. Particle concentrations versus time for simulated healthcare worker (HCW) positions. Results are shown at 5 feet off the floor (approximate mouth/nose height of an HCW) for an HCW standing next to the bed in 1-foot intervals around the perimeter of the bed. *A*, Predicted particle concentrations for an HCW standing next to the bed on the wall side. *B*, Particle concentration when HCW is standing next to the bed on the center side of the bed. *C*, Particle concentration when HCW stands at the foot of the bed. Note that a time scale change was made with the no curtain model to better focus on the peak concentration period immediately following a sneeze. A color version of this figure is available in the online edition of the journal.

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they are caught in the draft toward the floor vents. These results allow the formation of a visual image of the particle distribution, but they provide only a qualitative image. A more useful quantitative picture emerges if the particle concentrations are tracked at different positions over a period of time, as demonstrated using CFD modeling. Thus, the advantage of CFD over experimental results with smoke testing alone is the ability to estimate concentration levels at any position and at any time.

The results of this study indicate that the potential for exposure to infectious particles differs according to the position of the HCW and the presence of the privacy curtain. The highest particle concentrations were observed at the head of the bed nearest to the air return duct. The lowest concentrations were observed at the foot of the bed; therefore, positions toward the foot of the bed may pose a lower risk to the HCW than any other position modeled in this study. An unexpected finding of the CFD modeling was the lack of particles that entered the bathroom and anteroom, even when the door remained open. Even when particle release was modeled in the bathroom, the small room and effective venting allowed the particles to remain in the bathroom, even when the door was open.

This study has several limitations. CFD results should not be blindly trusted. Errors can arise in the model geometry (ie, a nonstraight wall or missing details on furniture), the equations used are incomplete (ie, ignoring temperature effects or using inexact turbulence models), and the initial or operating conditions may vary (ie, sneeze velocity and angles will vary, or the room air pressure will vary). Thus, one should verify that the model is qualitatively correct and at least somewhat quantitatively correct. In this article, smoke tests were performed with candles, and the visual results were compared with the CFD predicted results in an attempt to validate the model. In order to visualize the release of the smoke, it was necessary to use a smoke candle that releases smoke over a 60-second period, which is longer than the CFD-modeled sneeze. Thus, exact quantitative matches are not to be expected. The model was also unable to account for movement of HCWs, which may affect particle distribution.

In spite of these limitations, mathematical modeling may provide valuable information to assist in the protection of HCWs from exposure to airborne infectious diseases. On the basis of the results of these models, HCWs in the NBPCU will be advised on which areas in the patient care room are at highest risk for exposures to airborne particles. Also, the curtain will be retracted when the second bed is unoccupied. CFD studies can be used to evaluate existing facilities, as in this study, but may also have the potential to be useful in the design of new facilities. Mathematical modeling of particle flow in negative airflow settings may be applicable to multiple healthcare settings and could potentially serve as a modality to enhance the protection of HCWs.

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