Airflow patterns in double occupancy patient rooms may contribute to roommate-to-roommate transmission of severe acute respiratory syndrome coronavirus 2

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ABSTRACT

Background: Hospitalized patients are at risk to acquire severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) from roommates with unrecognized coronavirus disease 2019 (COVID-19). We hypothesized that airflow patterns might contribute to SARS-CoV-2 transmission in double occupancy patient rooms.

Methods: A device emitting condensed moisture was used to identify airflow patterns in double occupancy patient rooms. Simulations were conducted to assess transfer of fluorescent microspheres, 5% sodium chloride aerosol, and aerosolized bacteriophage MS2 between patient beds 3 meters apart and to assess the effectiveness of privacy curtains and portable air cleaners in reducing transfer.

Results: Air flowed from inlet vents in the center of the room to an outlet vent near the door, resulting in air currents flowing toward the bed adjacent to the outlet vent. Fluorescent microspheres (212-250 µm diameter), 5% sodium chloride aerosol, and aerosolized bacteriophage MS2 released from the inner bed were carried on air currents toward the bed adjacent to the outlet vent. Closing curtains between the patient beds reduced transfer of each of the particles. Operation of a portable air cleaner reduced aerosol transfer to the bed adjacent to the outlet vent but did not offer a benefit over closing the curtains alone, and in some situations resulted in an increase in aerosol exposure.

Conclusion: Airflow patterns in double occupancy patient rooms may contribute to risk for transmission of SARS-CoV-2 between roommates. Keeping curtains closed between beds may be beneficial in reducing risk.

Keywords: SARS-CoV-2, ventilation, carbon dioxide, privacy curtains, bacteriophage MS2

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INTRODUCTION

Healthcare personnel and patients are at risk to acquire severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) in hospitals [1]. Infection control measures including universal masking, use of personal protective equipment, and pre-admission and pre-procedure screening are commonly used to minimize the risk for transmission [1]. These measures are effective in reducing, but not eliminating, the risk for acquisition of SARS-CoV-2 [2-5]. In several studies, viral sequencing has confirmed transmission of SARS-CoV-2 in healthcare settings, particularly between co-workers and from patients with unrecognized coronavirus disease 2019 (COVID-19) to personnel not wearing appropriate protective equipment 2,6-10]. Transmission from infected personnel to hospitalized patients has also been demonstrated, but infrequently [2,11-12].

In 3 recent reports, acquisition of SARS-CoV-2 by hospitalized patients has been linked to roommates with unrecognized COVID-19 in double occupancy rooms [3,11-12]. The source patients often tested negative for SARS-CoV-2 on admission with subsequent onset of symptoms during their hospital stay. In these cases, the secondary attack rate has been surprisingly high, ranging from 19% to 89% [3,11-12]. High viral burden and aerosol-generating procedures were associated with increased risk for transmission to roommates [3,11-12].

The mechanism of transmission of SARS-CoV-2 to hospital roommates is uncertain. However, patients in shared rooms typically do not have close contact and are spaced more than 2 meters apart with closed curtains between beds. Thus, airborne transmission seems likely, particularly given the association with aerosol-generating procedures [3,11]. However, in contrast to many indoor community settings, hospital rooms have ventilation requirements that should reduce the risk for airborne transmission (ie, more than 6 air changes per hour versus 1 to 2 in many community buildings) [13-14]. In recent studies, it has been proposed that patterns of

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airflow might have contributed to long-distance transmission of large and small droplets containing SARS-CoV-2 in restaurants and in a patient transport van [15-18]. Here, we performed simulations to test the hypothesis that similar directional airflow patterns might contribute to SARS-CoV-2 transmission in double occupancy patient rooms. We also evaluated the effectiveness of privacy curtains and a portable air cleaner in reducing exposure to aerosol.

METHODS

Carbon dioxide monitoring to assess ventilation in double occupancy patient rooms

Carbon dioxide monitoring was conducted as part of a quality improvement assessment approved by the Infection Control Committee of the Louis Stokes Cleveland VA Medical Center. Six positive pressure double occupancy patient rooms with 8 to 11 air changes per hour were studied. Carbon dioxide levels were continuously monitored every 1 minute between 7 AM and 1 PM using an IAQ-MAX CO2 Monitor and Data Logger (CO2Meter, Inc) [19]. The time of the readings was selected because personnel commonly enter the rooms at that time for work rounds. All readings were collected in rooms occupied by 2 patients. Carbon dioxide levels were graphed along with the number of people present in the rooms.

The Centers for Disease Control and Prevention (CDC) has recommended that carbon dioxide readings above 800 ppm in buildings may be considered an indicator of suboptimal ventilation [13]. Peak levels above 800 ppm were therefore considered an indicator of suboptimal ventilation for the number of occupants present [13].

Assessment of airflow patterns in double occupancy patient rooms

A condensed moisture (fog) airflow visualizer (CBreeze, Degree Controls, Inc., Milford, NH) were used to assess the direction of airflow in 5 of the double occupancy rooms with or without the privacy curtain in place between the 2 beds. The door to the room and bathroom were closed

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during the assessment. Fog was released in multiple room locations and the direction of airflow was correlated with the location of incoming and outgoing air vents.

Transfer of fluorescent microspheres in double occupancy rooms with or without closed privacy curtains

Fluorescent microspheres (Cospheric) were used to assess the potential for particles to travel in air currents from patient to patient in unoccupied double occupancy patient rooms with or without closed privacy curtains. Microspheres with 212-250 µm diameter were chosen to be consistent in size with large respiratory droplets (100-1000 µm) [20]. All tests were completed with the room and bathroom doors closed. Dry powder containing 7,970 of the microspheres (50 mg) was poured slowly over 10 seconds from the center of each bed at the position of the patient's head 0.9 meters above the surface of the bed. The distance between the head positions on each bed was approximately 3 meters. After 5 minutes, a 395 nm ultraviolet blacklight flashlight (TaoTronics) was used to detect and enumerate microspheres on the surface of the other bed. To further assess the impact of airflow currents on transfer of microspheres, experiments were conducted with the incoming air vents covered to prevent air movement into the room versus uncovered. Five tests were performed in 3 of the double occupancy rooms.

Effectiveness of privacy curtains and portable air cleaners in reducing transfer of aerosol particles between beds in double occupancy patient rooms

An Aerogen Solo (Aerogen) nebulizer was used to release 200 µL of droplets of 5% sodium chloride solution over 30 seconds from the center of each bed at the position of the patient's head 0.9 meters above the surface of the bed. Based on particle count readings, 99% of particles generated from 5% sodium chloride by the Aerogen Solo are ≤5 µm in diameter. The nebulizer was directed toward the bottom (foot) of the bed. The room and bathroom doors were closed

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during the assessments. A particle counter (Fluke 983, Fluke) was positioned at the center of the other bed at the position of the patient's head to measure particles during release and for up to 6.5 minutes after release. To determine the impact of airflow patterns on exposure to the aerosol particles, experiments were conducted both under normal ventilation conditions and with the incoming air vents covered to minimize air entry into the room.

To assess the impact of privacy curtains and portable air cleaners on aerosol exposure, experiments were conducted with or without the privacy curtain closed between the 2 beds and with or without operation of a portable air cleaner with high efficiency particulate air (HEPA) filtration. The portable room air cleaner was a Germ Guardian 5-in-1 28" Pet Pure Air Purifier with HEPA, UVC & Digital (Guardian Technologies, LLC) intended for use in rooms up to 117.6 m^2. It was placed between the bed farthest from the door and the wall farthest from the door (site 1) or between the 2 beds (site 2). The airflow was set at 11.63 m^3/min (device setting 5). Experiments were performed in 3 double occupancy rooms. The condensed moisture airflow visualizer was used to assess the impact of the portable air cleaners on airflow patterns. To assess potential for movement of particles outside the room, additional experiments were conducted with the room door open with the particle counter positioned in the hallway just outside the door.

Efficacy of privacy curtains in reducing exposure to aerosolized bacteriophage MS2

We conducted simulations to assess the effectiveness of privacy curtains in reducing exposure to an aerosolized benign virus in 3 of the double occupancy rooms under normal ventilation conditions with the doors closed and with no portable air cleaner. For each simulation, the Aerogen Solo (Aerogen) nebulizer was used to release 1 mL of droplets containing 10^8 plaque-forming units (PFU) of bacteriophage MS2 in phosphate-buffered saline over 3 minutes. Based on particle count readings, 99% of particles generated from the MS2 solution by the Aerogen

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Solo are ≤5 µm. The nebulizer was positioned as described previously. The aerosol was released from bed 2 (furthest from the door).

Simulations were conducted with and without the privacy curtain pulled between the beds. To assess the effectiveness of the curtains, air samples were collected ~3 meters from the aerosol release site at the center of bed 1 (nearest to the door) at the position of the patient's head using a NIOSH two stage bio-aerosol sampler (Tisch Environmental). The air samples were collected over an 8-minute period after aerosol release with samples collected every 2 minutes. Quantitative cultures for bacteriophage MS2 were processed as previously described [22-23]. Analysis of variance (ANOVA) for repeated measures was used to compare concentrations of bacteriophage MS2 in air with versus without the curtain closed.

RESULTS

Carbon dioxide monitoring to assess ventilation in double occupancy patient rooms

During the 8-hour monitoring periods in 6 patient rooms, carbon dioxide levels remained below 800 ppm, ranging between 420 to 650 ppm. In addition to the 2 patients, each room was intermittently occupied by 1 to 5 healthcare personnel conducting routine care activities over periods of 2 to 20 minutes. Carbon dioxide levels consistently increased when personnel entered the rooms for 10 minutes or more; the peak carbon dioxide level of 650 ppm occurred when 5 staff members were in a room for 10 minutes.

Assessment of airflow patterns in double occupancy patient rooms

Figure 1 illustrates the direction of airflow in the double occupancy rooms based on the movement of fog released at the head of each patient bed. Each room had 2 air inlet vents located on the ceiling at approximately the foot of each bed and a single air outlet vent located near the door. Fog released from the head of each bed rose upward then flowed primarily toward the

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outlet vent; a small portion of the smoke was drawn toward the closest inlet vent where it swirled briefly prior to flowing toward the outlet vent. Fog released from bed 2 (farthest from the door) flowed directly toward bed 1 (nearest to the door), whereas fog released from bed 1 flowed away from bed 2. Fog released in other locations in the room similarly flowed toward the air outlet vent. With the door open, fog flowed from the room to the hallway as well as to the outlet vent.

As shown in Figure 1.B, when the curtains were closed between the 2 beds fog flowed above and to a lesser extent around the curtain before exiting through the outgoing air vent. The curtains had openings extending 0.46 meters from the ceiling to the top of the curtain and 0.46 meters from the floor to the bottom of the curtain. When the curtain was maximally closed, there was an opening of approximately 1.5 meters between the edge of the curtain and the wall. Supplementary Figure A-H provides illustrations of fog movement with the curtain open or closed.

Simulations to assess transfer of fluorescent microspheres between beds in double occupancy rooms with or without closed privacy curtains

Table 1 shows the number of fluorescent microspheres detected on the patient beds with or without closed privacy curtains and with or without the incoming air vents covered. With the privacy curtain open, fluorescent microspheres released from bed 2 (farthest from the door) were consistently detected on bed 1 (nearest to the door), whereas no microspheres released from bed 1 were detected on bed 2. Closing the curtains between the beds reduced the number of microspheres transferred to bed 1. No microspheres were detected on either bed when the incoming air vents were covered.

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Efficacy of privacy curtains and a portable air cleaner in reducing exposure to aerosol particles in double occupancy patient rooms

Figure 2 shows the particle counts detected at bed 1 (nearest to door) over 660 seconds after release of 5% sodium chloride aerosol from bed 2 (farthest from door) with normal ventilation versus with the incoming air vents covered. With normal ventilation, particle counts peaked 90 seconds after release at 58,045 particles detected and then rapidly declined to baseline. With the vents closed, particle counts peaked at a much lower level 480 seconds after release but persisted at above 6,000 particles detected through the 660 seconds of monitoring.

Figure 3 shows the impact of privacy curtains with or without a portable air cleaner on the average peak number of aerosol particles detected at bed 1 (after release from bed 2) and bed 2 (after release from bed 1) for the 3 experiments. With the curtain open, peak particle counts were much higher at bed 1 versus bed 2. Closing the curtain substantially reduced the average peak particle counts detected at bed 1 (44,064 to 2,218) and bed 2 (5,470 to 1,162).

With the curtain open, operation of the portable air cleaner in either position substantially reduced peak particle counts detected at bed 1. However, operation of the air cleaner in either location did not substantially decrease the average particle counts detected at bed 2; release of fog in the room demonstrated that the air cleaners created turbulent airflow in proximity to the device that altered the normal airflow such that some outgoing air was pulled toward bed 2. Operation of the air cleaner at either location in combination with closing the curtains resulted in higher average peak particle counts at bed 1 and bed 2 than closed curtains alone. In both cases, release of fog demonstrated that the air cleaners created turbulent airflow that pulled fog toward the beds where particle counts increased.

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When the door of the room was open, particles released from bed 1 were detected in the hallway just outside the door. The particle count peaked at 5700 particles between 1 and 2 minutes after release. With the door closed, no particles were detected in the hallway.

Efficacy of privacy curtains in reducing exposure to aerosolized bacteriophage MS2

Figure 4 shows the concentration of bacteriophage MS2 recovered from air samples collected at bed 1 (nearest to the door) after release from bed 2 (farthest from the door) with versus without the curtain closed between the beds. Recovery of bacteriophage MS2 was significantly lower when the curtain was closed versus open (P=0.0034).

DISCUSSION

We found that air in double occupancy rooms in our facility flowed from 2 inlet vents in the center of the room to an outlet vent near the door, resulting in air currents flowing from the inner bed farthest from the door toward the bed adjacent to the door and outlet vent. Fluorescent microspheres (212-250 μm diameter), 5% sodium chloride aerosol, and aerosolized bacteriophage MS2 released from the inner bed were carried on air currents to the bed adjacent to the outlet vent; substantially less transfer occurred from the bed adjacent to the outlet vent to the inner bed. Closing curtains between the patient beds reduced transfer of each of the particles. Our results provide support for the hypothesis that airflow patterns in double occupancy patient rooms may contribute to risk for transmission of SARS-CoV-2 between roommates and suggest that keeping curtains closed between beds may be beneficial in reducing risk.

Our findings are consistent with recent reports that have implicated patterns of airflow in transmission of SARS-CoV-2 in restaurants and motor vehicles [15-18]. Jones et al. [15] reported transmission of SARS-CoV-2 from an infected van driver to passengers sitting in the back seat >3 meters away; with the heater fan operating, microspheres with 1-5 μm and 212-250

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µm diameter were transported by airflow from the front to the back of the van. Additional studies are needed to investigate the potential role of airflow patterns in transmission in other healthcare and community settings.

Several recent simulation studies have demonstrated that portable air cleaners can reduce infectious aerosols [22-26]. Our results provide support for use of portable air cleaners in double occupancy patients rooms but also highlight some limitations of these devices. First, although the portable air cleaner substantially reduced aerosol transfer from the inner bed farthest from the door to the bed adjacent to the door and air outlet when the curtain was open, use of the device did not substantially decrease aerosol transfer from the bed adjacent to the air outlet to the inner bed, in part because it caused turbulent airflow. Second, the air cleaner was more effective when positioned between the inner bed and wall rather than between beds. In addition to airflow rates, positioning has been shown to have a substantial impact on efficacy of portable air cleaners [22,24-25]. Finally, operation of the air cleaner when curtains were closed did not offer a benefit over closing the curtains alone, and in fact resulted in increased aerosol exposure.

Our study has several limitations. The assessment was conducted in 1 hospital with 1 configuration of ventilation ducts in double occupancy rooms. Additional studies are needed in other facilities with other types of ventilation systems. Second, the privacy curtains had openings at the top and bottom. Additional studies are needed with different types of privacy curtains. Others have demonstrated that the design of barriers can have a substantial impact on the levels of protection against aerosol exposure [23,27-28]. Third, the patient rooms had a minimum of 6 air changes per hour. Our results may not be applicable to community settings that have lower levels of ventilation and rooms of varying size. Fourth, the locations where the particles were released and detected were positioned where patients would be when in bed. In actual rooms,

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patients would likely move to various locations in the room. The fluorescent microspheres may not be practical for healthcare facilities to use on a routine basis to assess the potential for particle transfer. However, similar results were obtained when experiments were conducted with a commercial ultrafine glitter product (Greenbriar International, Inc.) that contains particles of varying size. Products such as glitter could provide an easily accessible option for assessment of airflow patterns. Finally, only 1 type of portable air cleaner was studied in 2 positions in the room while operating at a single airflow rate. Additional studies are needed to assess the efficacy of different types of portable air cleaners with varying airflow rates and positioning.

In conclusion, our findings suggest that airflow patterns in the double occupancy patient rooms in our facility could contribute to risk for transmission of SARS-CoV-2 between roommates. Keeping the curtains closed between beds may reduce but not eliminate the risk for transmission. Future studies are needed to determine if current ventilation systems could be modified to produce airflow patterns that minimize movement of air from patient-to-patient.

Notes

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Potential conflicts of interest. C.J.D. has received research funding from Clorox, PDI, and Pfizer. All other authors report no potential conflicts. All authors have submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest.

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Table 1. Detection of fluorescent microspheres (212-250 µm) on hospital beds after release from the other bed in double occupancy rooms

Type of particles and conditions	**Release from bed 1 (closest to door); recovery from bed 2**	**Release from bed 2 (farthest from door); recovery from bed 1**
Fluorescent microspheres; median no. detected on bed (range)		
No curtain	0 (0-0)	2 (2-3)
Curtain closed	0 (0-0)	0 (0-1)
No curtain; incoming air vents covered	0 (0-0)	0 (0-0)

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Figure legend

Figure 1. Illustration of the direction of airflow in the double occupancy rooms based on the direction of movement of condensed moisture released from the head of each patient bed. A, curtains open. B, curtains closed. Air inlet vents and single outlet vent are shown.

Figure 2. Aerosol particle counts detected at bed 1 (nearest to door) over 660 seconds after release of 5% sodium chloride aerosol from bed 2 (farthest from door) with normal ventilation versus with the incoming air vents covered.

Figure 3. Impact of closed privacy curtains with or without addition of a portable air cleaner on the peak number of 5% sodium chloride aerosol particles detected at bed 1 (after release from bed 2) and bed 2 (after release from bed 1) under normal ventilation conditions. Average results for 3 experiments in 3 different double occupancy patient rooms are shown. Error bars represent standard error. Site 1, between bed 2 and the wall farthest from the door. Site 2, between beds.

Figure 4. Concentration of bacteriophage MS2 recovered from air samples collected at bed 1 (nearest to the door) after release from bed 2 (farthest from the door) with versus without the curtain closed between the beds under normal ventilation conditions.

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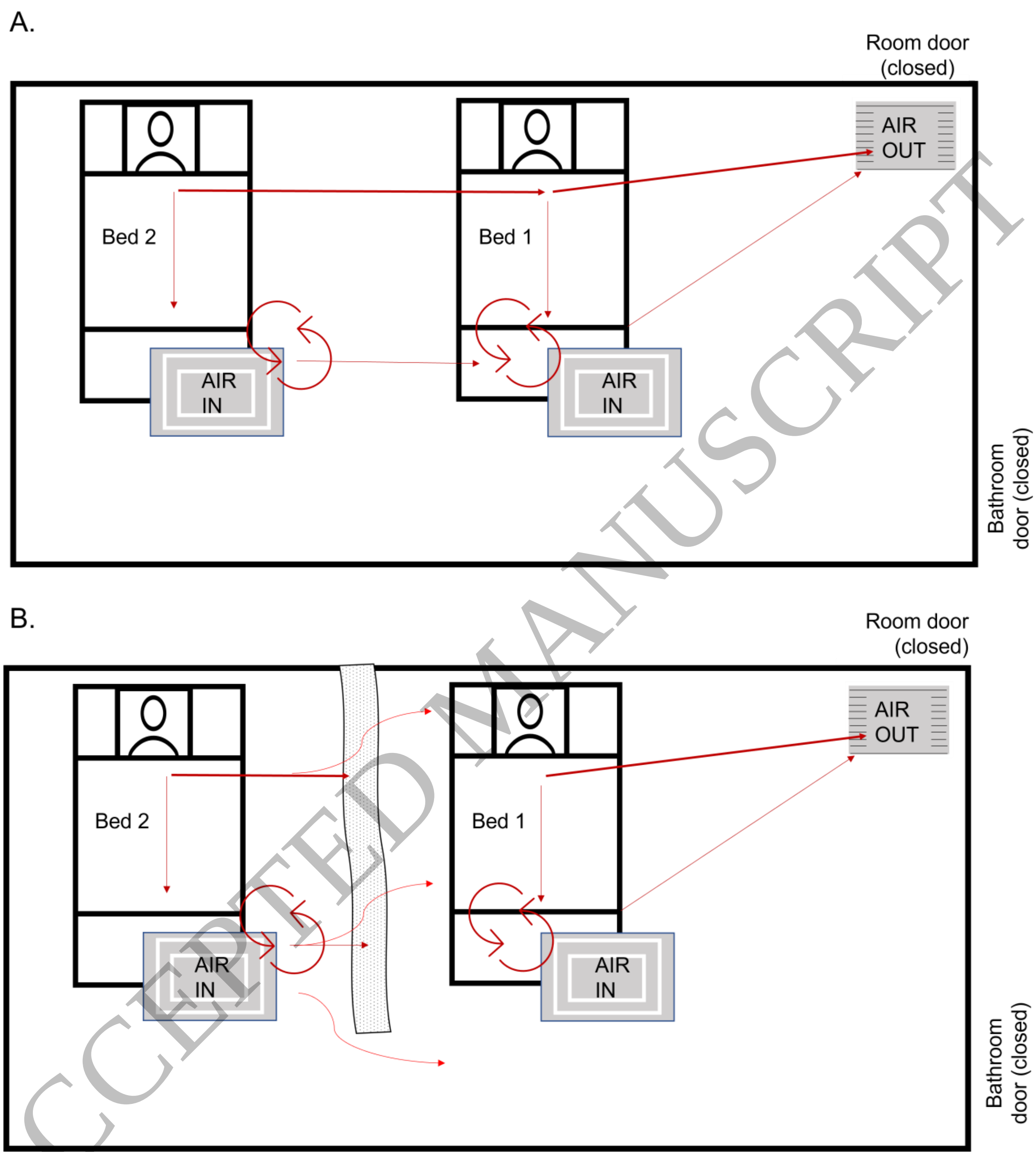

Figure 1
165x181 mm (0.2 x DPI)

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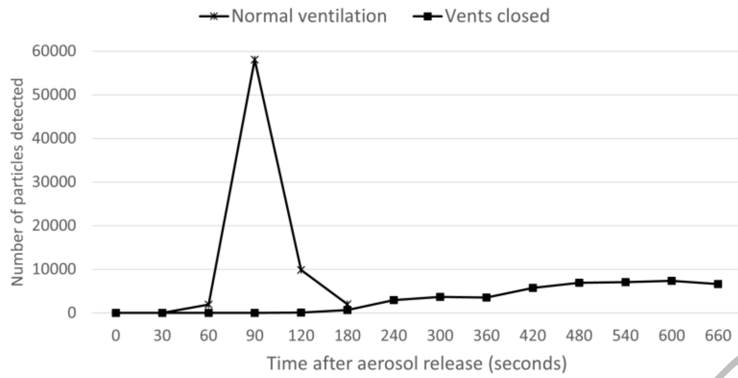

Figure 2
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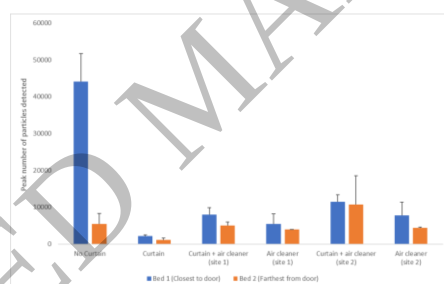

Figure 3
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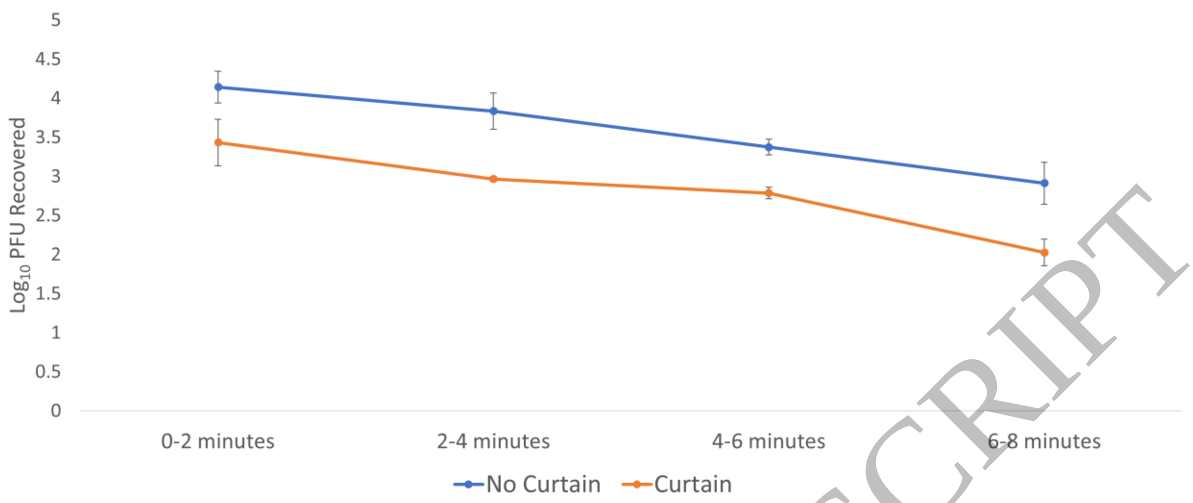

Figure 4
161x68 mm (0.2 x DPI)

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