

Hospital Indoor Air Quality (IAQ): Best Management Practices during Construction and Renovation

K.R. Grosskopf, Ph.D. and Ehsan Mousavi-Rizi, Ph.D.
University of Nebraska-Lincoln
Lincoln, NE

Renovation of occupied healthcare facilities can pose significant risks to patients, and, significant liabilities to healthcare contractors. Patient death rates have been found to be significantly higher in healthcare settings undergoing renovation. In these environments, patient mortality has been directly linked to inhalation of bioaerosols and other airborne contaminants generated by renovation activities. As part of a 5-year study, a series of experimental tests and computational analyses were conducted in an actual hospital to observe containment and removal of respiratory particulates with respect to directional airflow, ventilation rate, door position and worker movement between occupied patient spaces, and, patient spaces simulating work zones. Directional airflow from patient spaces to negatively pressurized (-2.5Pa) work zones was found to be effective in containing 0.3-10 μ m particulates. Door motion and personnel movement, however, was found to have a detrimental effect on directional airflow and subsequent particulate containment. Once escaping containment, particulate aerosols were capable of migrating more than 80ft (25m) in patient corridors. Increasing ventilation from 2 to 5 air changes per hour (ACH) did not significantly reduce concentrations of continuously generated particulates, and, is not considered an effective 'stand-alone' method of protecting workers within work zones, or, patients in adjacent spaces.

Key Words: Hospital, construction, IAQ, infection control.

Introduction

Atmospheric dust contains 30-40% organic matter by mass (Kuehn, 2003). This particulate matter contains microbial spores and sufficient nutrients to support microbial growth in hospitals whenever suitable moisture and temperature are present. Dust produced from construction activities may contain significantly greater quantities and concentrations of spores and organic matter, particularly from porous, organic insulation and finish materials disturbed during renovation. As a result, control of airborne contaminants in healthcare settings is critical given that many particulates can remain airborne indefinitely, be transported throughout the facility and cause a wide range of potentially fatal complications, particularly among immunocompromised populations. Control of airborne contaminants generated or aerosolized by renovation activities is primarily achieved by source controls and *ventilation* within work zones, and, *directional airflow* from occupied spaces to adjacent spaces undergoing renovation. Directional airflow confines contaminated air to its source. Ventilation dilutes contaminated air with fresh air and removes contaminants by exhaust. Both ventilation and directional airflow require a physical barrier and controlled access between occupied spaces and work zones.

Directional airflow is achieved by maintaining positive air pressure on the occupied side of the barrier with respect to the construction side. Maintaining a continuous pressure difference is achieved using filtered mechanical ventilation on the occupied side and temporary exhaust equipment on the construction side. Although the U.S. Center for Disease Control (CDC) recommends a pressure difference of 2.5Pa for infectious isolation, the pressure difference necessary to maintain directional airflow sufficient to contain particulates generated by renovation activities in hospitals is not known (Kuehn, 2003). Numerous penetrations in the barrier separating the occupied side and construction side (e.g. utilities, ductwork, access doors, etc.) pose a challenge, as do natural phenomenon such as wind and stack effect. Similarly, the scientific basis for code-required ventilation rates in patient spaces is weak (ASHRAE, 2013). As part of a 5-year study, a series of experimental tests and computational analyses were conducted in an actual hospital to observe containment and removal of respiratory particulates with respect to directional airflow, ventilation rate, door position and worker movement between occupied patient spaces, and, patient spaces undergoing renovation. The results of this study as well as a list of best management practices (BMPs) are summarized herein.

Method

A total of six (6) tests were conducted; two (2) in a patient room under neutral (e.g. non-directional) airflow and 2 ventilation air changes; two (2) in a patient room under negative (e.g. inward directional) airflow and 5 ventilation air changes, and, two (2) in a corridor adjacent to the patient rooms. In each patient room, a benign, synthetic aerosol was released to simulate the generation of particulates from renovation activities. Aerosol concentrations within the patient rooms were continuously measured from several sampling stations to observe the change in aerosol concentrations with respect to the change in ventilation rate. Aerosol concentrations were also measured in corridors adjacent to the patient test rooms to observe the effectiveness of directional airflow to contain particulates within patient rooms. Finally, the effects of door position and door motion (e.g. worker movement) on particulate containment were also observed.

In the 'neutral' patient test room, the ventilation rate (85cfm, 40.1L/s) and exhaust air rate (86cfm, 40.6L/s) were nearly balanced, producing 2 air changes per hour (ACH) and a non-directional airflow relationship with the corridor. In the 'negative' patient test room, the exhaust air rate (218cfm, 102.9L/s) exceeded the ventilation rate (137cfm, 64.7L/s), producing 5 ACH and a negative air pressure (-2.5Pa), inward directional airflow relationship with the corridor. Airflow rates were observed by means of duct traverse and flow hood measurements (Figure 1). For each test, mineral oil (polyaliphaticolefin) was continuously aerosolized at a rate of 15mg/0.4L/sec of air to produce particulates ranging in size from 0.3-10 μ m in diameter. This size range is consistent with bacterial and fungal spores capable of causing respiratory infections (Nicas, 2005). Particle measurements (particles/L) were collected at 2ft (0.6m), 4ft (1.2m) and 6ft (1.8m) sampling heights above the floor (Figure 2) at a total of 12 locations in each patient room (Figure 3) and at 30 additional sampling locations approximately 10ft (3m) apart in the patient ward corridors. Samples were drawn at 30 sec intervals throughout the 4-5 hour duration of each test. All equipment and instrumentation was calibrated prior to testing in accordance with ASHRAE 52.2.



Figure 1: Duct traverse (left) and flow hood (right) airflow measurements (Grosskopf and Mousavi, 2014).

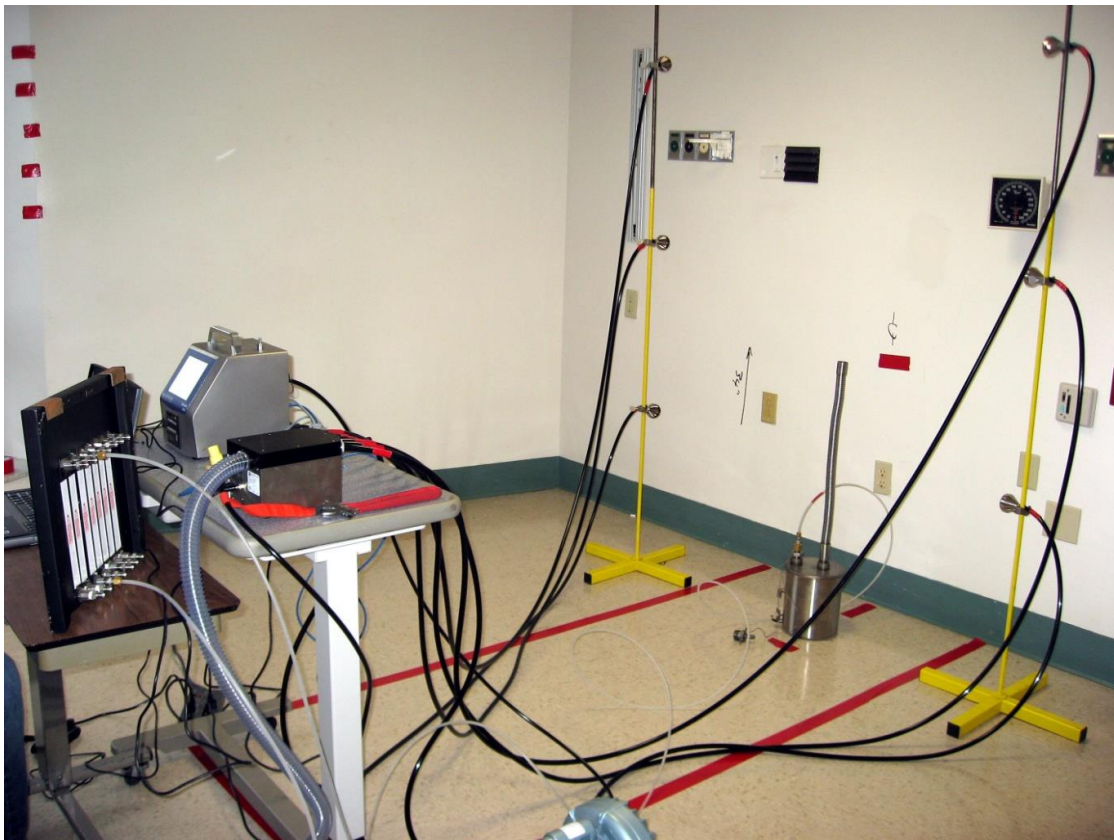


Figure 2: Aerosol generator and particle sampling equipment in patient rooms (Grosskopf and Herstein, 2012).

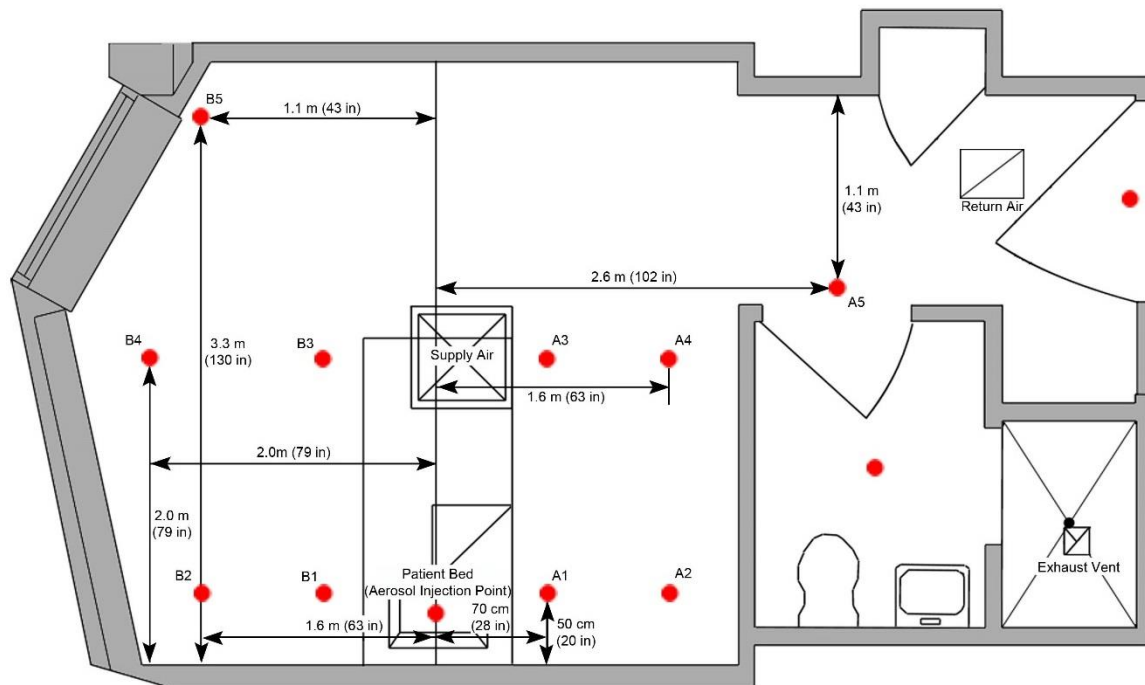


Figure 3: Aerosol generator and particle sampling locations in patient rooms (Grosskopf and Herstein, 2012).

Results

Ventilation rates were not found to be effective in *proportionately* reducing aerosol concentrations within patient rooms simulating work zones. Specifically, increasing outdoor air change rates from 2 to 5 ACH reduced concentrations of aerosols only 30% on average (Figure 4). In the ‘neutral’ patient test room, aerosol concentrations remained near background levels in the corridor while the entry door remained closed with small, intermittent releases of aerosol observed when a worker entered the patient room. When the entry door was left open, however, a significant and sustained release of aerosols from the doorway to the corridor was observed despite a non-directional airflow relationship between the patient room and corridor (Figure 5). Once in the corridors, concentrations of aerosols remained above background levels to distances exceeding 80ft (25m) from the patient room doorway. In the ‘negative’ patient test room, no significant release of aerosol was observed regardless of door open or closed position, suggesting that the -2.5Pa pressure difference and resulting inward airflow from the corridor to the patient room was effective in containing the release of aerosols. Door motion, however, was found to have an effect on patient room air pressure relationships, directional airflow and subsequent aerosol containment. Despite inward directional airflow from the corridor into the patient room, the turbulence created by the door-opening motion allowed the release of aerosol from the patient room to the corridor. The concentration of aerosol released, however, was significantly less than the same door-opening scenario under neutral or non-directional airflow, suggesting that the directional airflow strategy was partially effective (Figure 6).

Using ANSYS Fluent 15.0, computational fluid dynamic (CFD) models were developed to further explore the airflow characteristics of door motion. In the ‘neutral’ patient test room, the volume of air exchanged between the patient room and corridor during a 5-sec door opening and closing cycle (33.2ft^3 , 0.94m^3) was comparable to the swept volume of the door (39.9ft^3 , 1.13m^3), a finding that was consistent with several previous studies (Eames et al., 2009 and Kalliomaki et al., 2014). In the ‘negative’ patient test room, the volume of air exchanged between the patient room and corridor during a 5-sec door cycle was a factor of 10 less (3.2ft^3 , 0.09m^3), a finding that was consistent with experimental results. Increasing the door cycle speed from 5 sec to 3 sec increased air exchange three-fold from 0.09m^3 (3.2ft^3) to 0.26m^3 (9.3ft^3). Decreasing the door cycle speed from 5 sec to 7 sec decreased air exchange from 0.09m^3 (3.2ft^3) to 0.04m^3 (1.3ft^3). Combining directional (inward) airflow with a sliding door assembly, air exchange from the patient room work zone to the corridor was reduced to near trace levels (Figure 7).

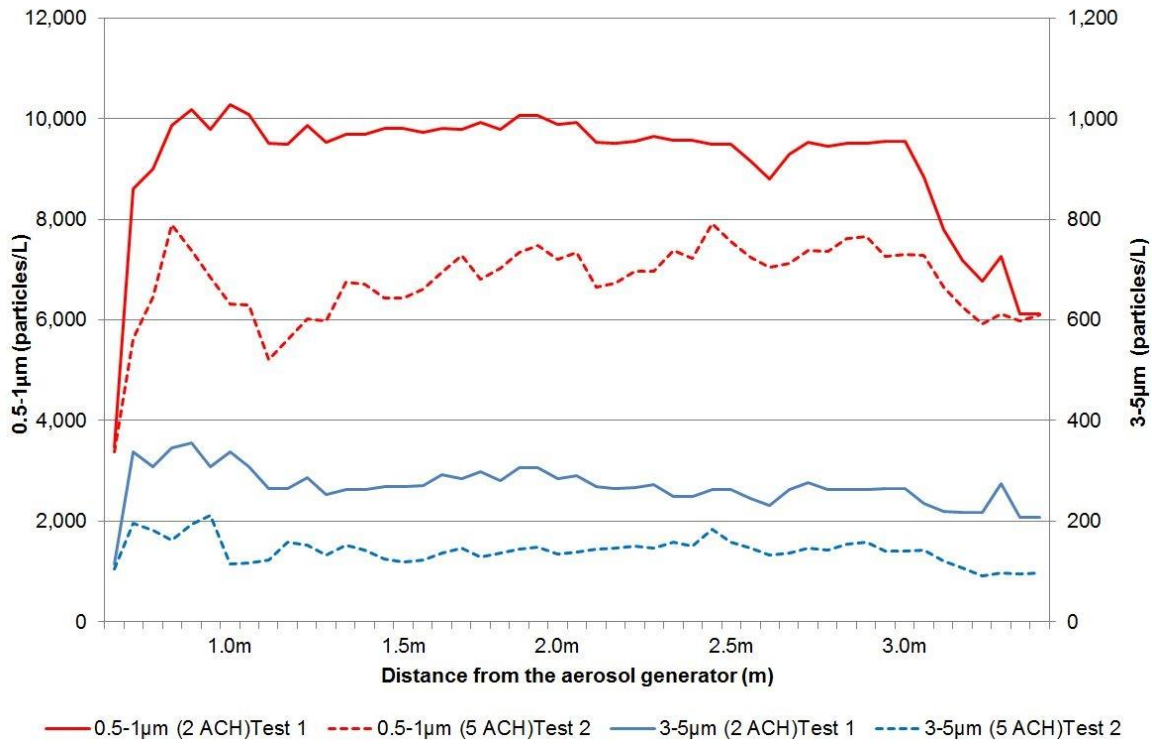


Figure 4: Particle concentration vs. ACH in patient rooms (Grosskopf and Mousavi, 2014).

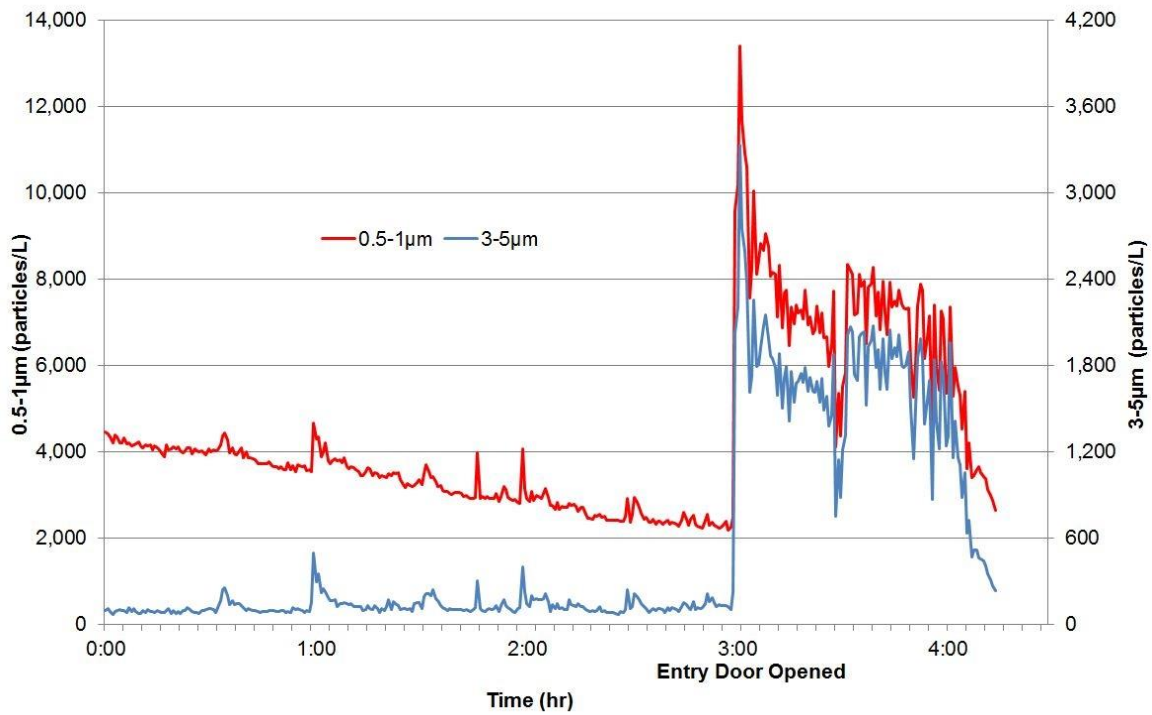


Figure 5: Particle concentration vs. door position in patient rooms (Grosskopf and Mousavi, 2014).

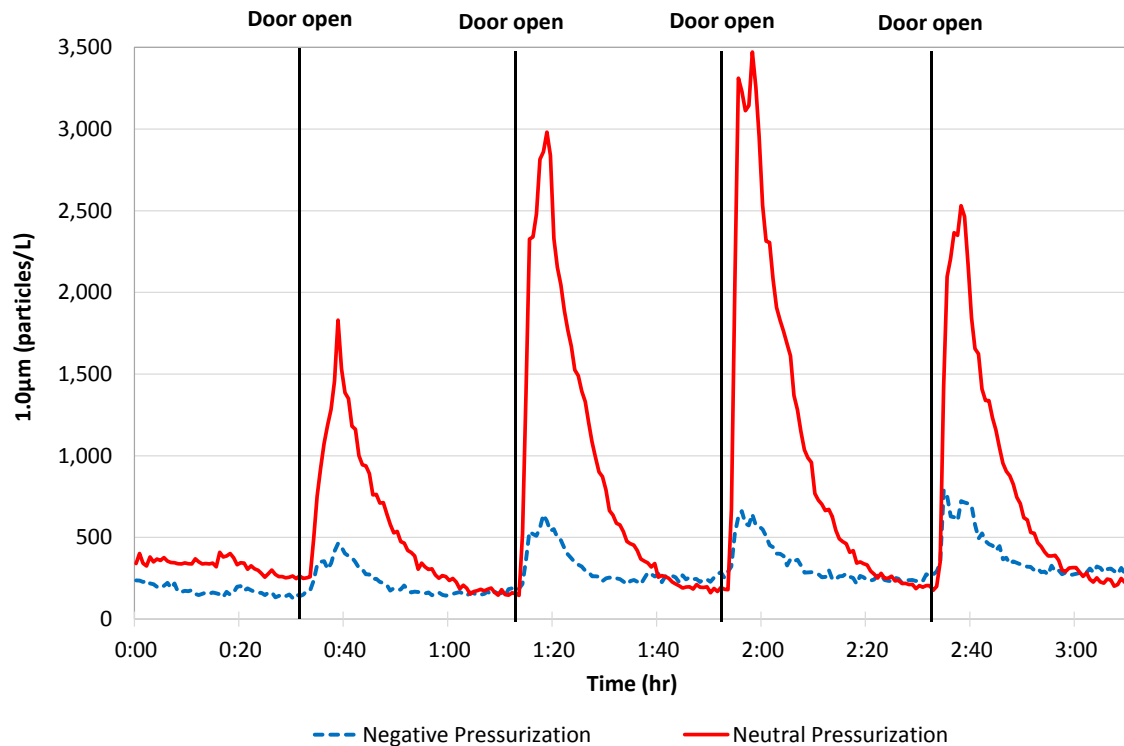


Figure 6: Particle concentration vs. door motion in patient rooms.

Discussion

The purpose of this study was to observe containment and removal of respiratory particulates with respect to directional airflow, ventilation rate, door position and worker movement between occupied patient spaces, and, patient spaces undergoing simulated renovation. Significant findings of this study include:

- *Ventilation rates* - not effective in proportionately reducing particulate concentrations within patient spaces simulating renovation activities. Increasing outdoor air change rates from 2 to 5 ACH reduced concentrations of aerosols only 30% on average.
- *Directional airflow* - effective in containing particulates to work zones when air pressure in occupied patient spaces is 2.5Pa or greater than air pressure in adjacent spaces simulating renovation activities.
- *Door position and motion* – effective in containing particulates to work zones when *closed* and used in conjunction with directional airflow from occupied patient spaces to adjacent spaces simulating renovation activities. Turbulence created by the door-opening motion may cause transient breakdown in air pressure relationships and directional airflow, allowing intermittent release of particulates from work zones to occupied patient spaces.

Using the results of this study together with peer-reviewed literature, the following list of best management practices are provided to reduce patient health risks, and, contractor liabilities associated with hospital renovation activities.

- *Risk assessment* – Determine occupant risk in adjacent spaces, including those above and below work zones (e.g. low risk – office; medium risk – radiology; high risk – surgical units; highest risk – ICU, burn units, oncology). Identify types of renovation activities (e.g. type A – non-invasive activities; type B – small scale, short duration activities that create minimal dust; type C – invasive activities that require demolition or removal of building components that create moderate to high levels of dust; type D – major demolition and construction or history of water damage in work zone). Determine level of precautions and contaminate control activities (below) based on occupant risk category and type of renovation activity.

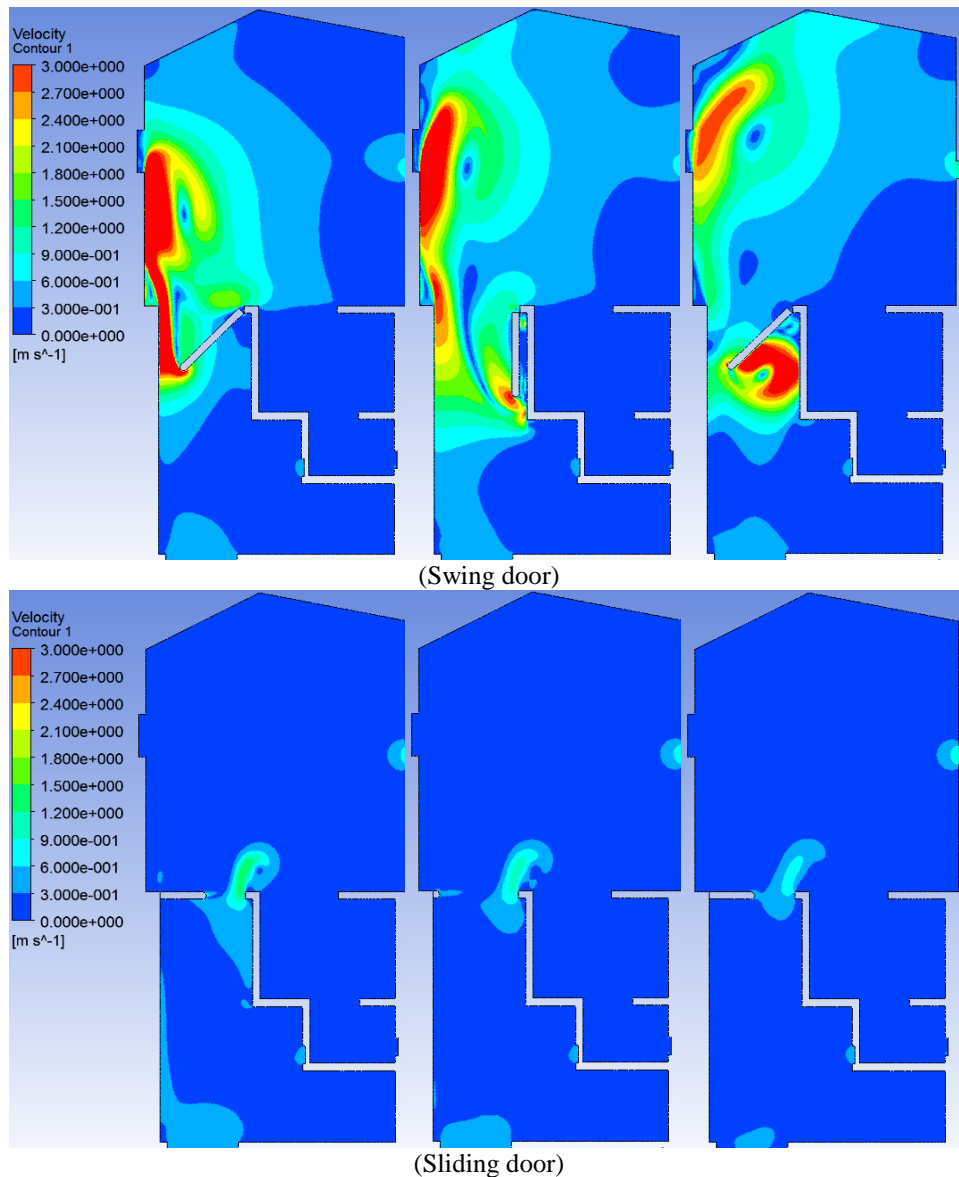


Figure 7: Air exchange vs. door type in patient rooms (ANSYS Fluent 15.0 CFD model).

- *Ventilation* – Do not use the hospital mechanical system to supply air to the construction zone. Ensure that the hospital mechanical system is disconnected and sealed off from the construction zone. Do not recirculate air supplied to the construction zone. Ensure return air grilles and return and (or) outdoor air side of coils serving areas adjacent to work zones are properly filtered and frequently inspected for dust loading. Do not locate construction zone exhaust proximate to outdoor ventilation air intakes.
- *Pressure control* – Maintain a -2.5Pa or greater pressure difference in work zone with respect to adjacent occupied spaces. Exhaust through work zone envelope directly to outside. Use electronic pressure gauges to confirm continuous negative pressure relationship with alarm (ASHRAE, 2013).
- *Air barriers* – Maintain an air-tight, 2-hour fire-rated barrier between occupied patient spaces and work zones. The air barrier must extend from the floor to the structural floor or roof above. Seal all seams, joints and utility penetrations through the air barrier. Eliminate unnecessary access between patient spaces and work zone. If access is necessary, control access and use airlock vestibule or anteroom to minimize effects of swing door motion (ASHRAE, 2013).

- *Filtration* – Use portable filtration units to reduce particulate load within work zone. Depending on types of renovation activities and particle sizes generated, HEPA filtration (>MERV 17) may be necessary. Filters should be inspected for excessive particulate loading and air pressure drop (ASHRAE, 2013).
- *Doors* – Use sliding doors (where practical) or doors with in-swing motion into work space and closure devices limiting door speed to ≥ 5 sec per door open-close cycle. Place ‘walk-off’ mats on work space side of doorway to remove debris from foot traffic(ASHRAE, 2013).
- *Temperature and humidity control* – Work space temperatures should be maintained above the dewpoint of the air to prevent condensation and mold growth on moisture vulnerable materials. Humidity should be maintained below 70% RH. Moisture meters should be used to ensure material moisture content is less than 20% especially for porous, organic materials (e.g. gypsum board, ceiling tiles, insulation, etc.).
- *Monitoring* – Use portable particle counters to continuously monitor particle size and concentration in both work zones and occupied patient spaces adjacent to work zones with special attention to areas proximate to penetrations in the air barrier (e.g. doors, utility penetrations, etc.). Compare particle concentrations prior to renovation (e.g. ‘background concentration’) to particle concentrations during construction. Ensure normal operation of occupied adjacent spaces (e.g. maintain ventilation requirements, minimize noise, vibration and odors, etc.).
- *Documentation* – Document air quality monitoring activities as part of a daily log to ensure target air quality conditions are being met. Document system performance, O&M activities and responses to unforeseen conditions or emergencies (ASHRAE, 2013).

References

1. ANSI/ASHRAE Standard 52.2-2012. Method of testing general ventilation air-cleaning devices for removal efficiency by particle size. American Society of Heating, Refrigeration and Air Conditioning Engineers.
2. ASHRAE, 2013. Healthcare facilities: best practice design and applications. ASHRAE professional development series.
3. CDC, 2007. Guideline for isolation precautions: preventing transmission of infectious agents in healthcare settings. Healthcare Infection Control Practices Advisory Committee (HICPAC). U.S. Centers for Disease Control and Prevention.
4. Eames, I. et al., 2009. Movement of airborne contaminants in a hospital isolation room. Journal of the Royal Society, Interface / the Royal Society, 6 Suppl 6, pp.S757–66.
5. Grosskopf, K. and E. Mousavi Rizi. “Ventilation and the Transport of Bioaerosols in Healthcare Environments,” ASHRAE Journal. Vol. 57, No. 8, pp. 54-60. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2014.
6. Grosskopf, K.R. and K. Herstein. “The Aerodynamic Behavior of Respiratory Aerosols within a General Patient Room,” International Journal of HVAC&R Research. Vol. 18, No. 4, pp. 709-722. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2012.
7. Kalliomaki P, Saarinen P, Tang JW, Koskela H. Airflow Patterns Through a Single Hinged and a Sliding-Door in Hospital Isolation Room. In: Indoor air Conference. 2014.
8. Kuehn, T., 2003. Airborne infection control in health care facilities. Journal of the American Society of Mechanical Engineers (ASME), Vol. 125, 366-371.
9. Nicas, M. et al., 2005. Toward understanding the risk of secondary airborne infection: emission of respirable pathogens. Journal of Occupational and Environmental Hygiene, 2(3), 143-154.
10. Vesely, R., and S. Hoppszallern. 2015 Hospital construction survey. American Society for Healthcare Engineering (ASHE). 2015.