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Technical note

Potential airborne pathogen transmission in a hospital with and without surge control ventilation system modifications

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Abstract

To better understand the transport of airborne particulate matter (PM) in hospital environments when surge control strategies are implemented, tests were conducted in a recently decommissioned hospital during a one-week period. An aerosol was released within a patient room and concentrations measured in the room and hallway with and without surge control ventilation system modifications. The average hallway protection efficiencies were high (>98%) both for the baseline ventilation configuration and when the ventilation system was modified for whole floor negative pressure, indicating very little PM reached the hallway. During entry/exit events through the patient room door into the hallway, the average minimum hallway protection efficiencies were lower during the modified ventilation operation (93–94%) than for the baseline operation (98–99%). These lower hallway protection efficiencies may be explained by the 52% reduction in the outdoor air ventilation being supplied to the hallway during the modified operation mode. This suggests that patient room doors should remain closed to control PM movement into the hallway. In addition, if there is concern about airborne infection transmission, an anteroom may be used to further reduce the transport of particles from the patient rooms to the hallways of the ward.

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1. Introduction

The emergence of the Ebola virus, Severe Acute Respiratory Syndrome (SARS), 2009 H1N1 pandemic influenza, Middle Eastern Respiratory Syndrome (MERS) and the ongoing threat of bioterrorism underscore the need to prepare for large scale outbreaks of communicable infectious diseases. To minimize transmission during these outbreaks, it has been emphasized by public health agencies and infection control experts that stringent hospital infection control and prevention measures be implemented [4,5,8,14]. In addition, it is suggested that healthcare facilities isolate patients in spaces with directional flow and other features. Surge capacity strategies are needed, during unexpected medical exigencies, to safely house large numbers of patients with airborne transmissible infections in negative-pressure isolation spaces that encompass an entire clinical ward or patient care area. Reasoned and practical engineering ventilation system controls are an essential component of effective surge strategies.

Previous studies have explored different methods for expanding surge capacity in healthcare facilities. The efficacy of a temporary structure that housed three single-patient rooms was evaluated using fluorescent tracer particles [10]. Each room was ventilated at 382 m3/h, equivalent to 15 air-changes per hour (ACH). Containment was very good, higher than 99.7%. Particles escaped with simulated traffic and it did not appear that an anteroom made much of a difference with this structure.

Air volume migration from a laboratory-based negative-pressure isolation room with an anteroom was investigated using a tracer gas and either six or 12 ACH ventilation [7]. This study concluded that an anteroom offered containment during entry and exit. Results showed that door type, operating speed of door, entry to or exit from the room did not change the air volume migration that was observed.

The containment of an airborne infectious isolation room with
an anteroom was investigated at a range of negative pressures and provider traffic using fluorescent tracer particles [1]. Lowest containment with provider traffic was measured in the test that generated a negative pressure of 1.5 Pa between the anteroom and the patient room (95.8%) and 2.1 Pa between the corridor and patient room (99.9%). Highest containment was observed in the test that generated a negative pressure of 12.5 and 20.7 Pa between the anteroom—patient room and corridor—patient room, respectively. Overall the study concludes that containment effectiveness increases with increasing pressure differential.

The purpose of this project was to study the feasibility of turning an entire ward into a negative pressure ward to handle a surge of airborne infectious patients. To accomplish this objective, we investigated specifically how to contain inert airborne particulates (surrogates for infectious micro-organisms), to a single hospital ward using modified ventilation airflow designs to increase capacity to care for large numbers of patients. We also sought to understand particulate movement from rooms to hallways with door openings. To this end, the ventilation air supply to a decommissioned hospital ward was modified and a tracer aerosol was released and monitored in real-time on the ward.

Ref. [6] and [11] have previously published a paper on the data set collected from these tests. Upon examination of the data set, we observed that the much of the data utilized in both papers was aerosol concentration data that exceeded the instrument’s maximum capability (i.e. coincidence errors). In addition, neither paper reported quantitatively on the transport of the test aerosol from the patient room to the hallway under normal and modified (surge strategy) HVAC configurations, which was the primary study objective.

Thus, in this paper we utilized only that data that was not compromised by coincidence errors, and quantitatively calculated the transport of aerosol from the patient room to the hallway under normal and modified (surge strategy) HVAC configurations.

2. Methodologies

This study was conducted in a patient test room on the fifth floor of a decommissioned and unoccupied 8-story hospital. The fifth floor consisted of a North and South hallway, each with 16 patient rooms. In between the North and South hallway there was a core area consisting of a Nurses Station and various support rooms. The total floor area of the fifth floor was 1520 m². Each floor of the hospital had a separate constant-volume ventilation system that provided 100% outdoor air (OA) at a volumetric flow rate of 160 m³/min. Filtration was achieved using minimum efficiency reporting value (MERV) 8 panel filters, followed by MERV 14 bag filters [2]. During the tests on the fifth floor, the ventilation systems serving the other floors were not operational.

Air in the patient test room (Fig. 1) was exhausted through the bathroom ceiling. A fan coil unit above the suspended ceiling provided temperature control. A duct connected the return air of the fan coil to the fifth floor ventilation system. There was one ceiling supply diffuser and one ceiling return air inlet by the hallway door with a connection directly to the fan coil unit. The fan coils had MERV 8 panel filters.

Tests were conducted under two ventilation system operating modes: baseline and modified. The modified mode, in which negative pressure was achieved for the entire 5th floor, was accomplished by reducing the constant-volume OA flow rate to the 5th floor by 52% while maintaining the same exhaust airflow rate. Unfortunately the testing contractor’s air pressure instrumentation was not capable of measuring differential air pressures less than 5 Pa, and the air pressures measured between the patient room and the hallway were less than -5 Pa with the ventilation system in the modified negative pressure mode.

The baseline ventilation airflow rates in the patient test room were 2.7 air changes per hour (ach) for supply OA, 2.7 ach for exhaust air (EA), and 8.4 ach for total air (TA). When the ventilation system was modified the room airflow rates changed to 2.0 ach for supply OA, 2.5 ach for EA, and 8.1 for TA. These airflow rates were measured with an airflow capture hood. The total supply airflow rates were measured at the single ceiling supply diffuser and represents the combination of the return air entering the fan coil from the patient room and the outdoor air supplied by the fifth floor 100% outdoor air ventilation system to the patient room fan coil return. The outdoor airflow rates were measured as the difference of supply and return airflow rates. The airflow rates for both ventilation system operation modes met or exceeded the recommended 2.0 ach for outdoor air and 4.0 ach for total air [3].

During the study a tracer aerosol (polyalphaolefin, PAO) was released into the air at bed height in the patient room for a 2.5-hr period to simulate constant generation of airborne particles. Aerosol was produced with a NUCON SN-10 pneumatic aerosol generator. The generation rate was constant for each test, but we are uncertain of the testing contractor’s generation rates between the different tests.

Optical particle counters (Lighthouse Handheld 3016 six-channel laser particle counters) were used to measure number concentrations of particles in six diameter ranges: 0.3–0.5, 0.5–1.0, 1.0–2.5, 2.5–5.0, 5–10.0 and > 10.0 µm. One particle counter was placed on the sink in the bathroom, which represented the average concentration in the patient room since all the air was exhausted from the bathroom. Another particle counter was located in the hallway at the top of the door to the patient room.

We note that the aerosol concentration was also measured in the patient room at multiple locations and height with a Solaire 3100, which is a laser particle counter that measures the number concentrations in eight diameter ranges.

Unfortunately, the aerosol concentrations exceeded the measurement capability of the Solaire 3100, which is designed to accurately measure only low aerosol concentrations (e.g. clean rooms) and not high aerosol concentrations such as those in the patient room for these tests. The high aerosol concentrations resulted in “coincidence” measurement error, where more than one particle is in the laser view area, resulting in an under-counting the true aerosol concentration. The coincidence errors associated with the Solaire 3100 are estimated to undercount the true concentrations by 30–90%, as well as shift the particle size distribution towards larger particles. For the Handheld 3016 instrument data, which we used in our analyses in this paper, the instrument is capable of measuring much higher concentrations with minimal (i.e. < 10%) coincidence error.

During the aerosol release the bathroom door remained open and the hallway door remained closed except for during four staged 2-s entry and exits into and out of the patient room.

The hallway Protection Efficiency (PE, %) was calculated using Equation (1):

\[ \text{PE} = 100\% \times (1 - \frac{C_{\text{hall}}}{C_{\text{room}}}) \]  

(1)

\( C_{\text{hall}} \) = concentration in the hallway adjacent to the room with the aerosol release and \( C_{\text{room}} \) = concentration in the room with the aerosol release.

3. Results and discussion

Fig. 2 shows the particle concentrations measured in the patient room and hallway with the ventilation system in the baseline and modified operation mode.
During each test there were a total of four staged entry/exits into/out of the patient room. Each entry/exit represented two 4-s door openings over a 3-min period. The impact of these door openings can be seen in the momentary sharp increase in hallway aerosol concentrations in Fig. 2. In addition, when the hallway door to the patient room was opened at the end of the test, Fig. 2 shows the rapid spillage of aerosol out of the patient room into the adjacent hallway, resulting in a reduction of the aerosol concentration in the patient room and a concurrent increase of the aerosol concentration in the hallway.
A significant drift in the background hallway concentration of particles was observed in the 0.5–1.0 μm size range during both the baseline and in the modified mode tests (Fig. 2). Since the 100% outdoor air ventilation system utilized MERV 14 filters with an approximate 83% efficiency for 0.5-μm diameter particles, as compared to 95% for 1.0 μm particles and greater than 99% for 2.5 μm particles [2], changes in the outdoor particle concentration of 0.5–1.0 μm particles are expected to have some impact on the indoor concentrations.

As a result of this drift, PEs were calculated only for the 1.0–2.5 and 2.5–5.0 μm particle concentrations. Table 1 details the protection efficiencies for the hallway adjacent to the patient room during aerosol release into the room with the ventilation system in the baseline and modified (whole floor negative air) operation modes. The maximum measurable PE was greater than 99% for the 1.0–2.5 μm and 2.5–5.0 μm particles during both the baseline and modified operation modes. The average PE, as measured during the 2.5-hr test in the baseline mode, and including the four entry/exits into the patient room, was 99.8% for the 1.0–2.5 μm particles and >99.7% for the 2.5–5.0 μm particles. During the modified mode, the

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**Fig. 2.** Aerosol concentrations in patient room and adjacent hallway with the ventilation system in the (a) baseline and (b) modified (whole floor negative air) operation mode.
average PE was slightly lower: 99.1% and 98.9% for the 1.0–2.5 μm and 2.5–5.0 μm particles respectively.

The minimum PEs during the four entry/exit periods into the room during the normal mode averaged 98.7% and 98.6% for 1.0–2.5 μm and 2.5–5.0 μm particles respectively. During the modified mode, the minimum PEs were lower, averaging 93.6% and 93.5% for 1.0–2.5 μm and 2.5–5.0 μm particles.

On average, the PE was statistically significantly lower using the modified ventilation airflow rate compared to the baseline condition (p < 0.0001). During the four door entry/exit periods the average minimum PEs were lower during the modified mode (93.5–93.6%) than those for the normal mode (98.6–98.7%). Lower observed PEs in the modified mode may be explained, at least in part, by the 52% reduction in the outdoor air ventilation in the hallway. Thus, particles released into the hallway from the patient room accumulated to higher concentrations with the lower ventilation rate. The measurement uncertainty of the particle counters is estimated to be ±10%. For a PE of 98%, this measurement uncertainty translates into an uncertainty for the PE of approximately 0.5% (i.e. 97.6–98.4%).

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### Table 1

Protection efficiencies for the hallway adjacent to the patient room during aerosol release into the room with the ventilation system in the baseline and modified (whole floor negative air) operation modes.

| Measurement period | Baseline ventilation | Modified ventilation |
|--------------------|----------------------|----------------------|
|                    | 1.0–2.5 μm Particles | 2.5–5.0 μm Particles |
|                    | 1.0–2.5 μm Particles | 2.5–5.0 μm Particles |
| Average (2-h test period) | 99.8 | >99.7 |
| Minimum – Door Opening 1 | 98.1 | 97.9 |
| Minimum – Door Opening 2 | 99.4 | 99.5 |
| Minimum – Door Opening 3 | 98.8 | 98.5 |
| Minimum – Door Opening 4 | 98.4 | 98.4 |
| Average for Minimum Door Openings 1–4 | 98.7 | 98.6 |

4. Conclusions

The average hallway PEs remained relatively high (>98%) when the ventilation system was modified to achieve negative pressure for the entire hospital floor. This level of protection may be compared to a full-face respirator with an Assigned Protection Factor of 50, as defined by the Occupational Safety and Health Administration [12].

In this study, the PAO aerosol that was released could not be differentiated from the particles present in the ambient air. Thus, changes in the ambient aerosol concentrations produced errors in the interpretation of the aerosol concentrations. This was especially evident in the small size particles (i.e. 0.5–1.0 μm), which were not removed with high efficiency by the air filtration system. Some researchers [13] have used a tracer gas such as sulfur hexafluoride (SF6), which is a unique tracer not present in significant concentrations in the outdoor air. However, since SF6 is a gas and not a particle, the transport and removal mechanisms will differ from that of particles. Ideally we would use a unique aerosol with an aerodynamic size similar to that of infectious disease droplet nuclei, however there currently is no instrumentation capable of real-time measurements a unique aerosol tracer. Some researchers [9] have used unique fluorescent particles, but these studies typically involve collecting non-real time integrated air samples on filters with subsequent analyses.

The PEs were high for both the baseline and modified ventilation configurations, and decreased in both cases when the door was opened. This suggests that the doors should remain closed as much as possible for optimal infection control to limit particulate movement into the hallway. In addition, if there is concern about airborne infection transmission, an anteroom may be used to further reduce the transport of particles from the patient rooms to the hallways of the ward.

### Disclaimer

The findings and conclusions in this article are the authors’ own and do not necessarily represent the views of the University of Colorado, Indoor Environmental Engineering, the U.S. Department of Veterans Affairs, or other affiliates.
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