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Directional Airflow and Ventilation in Hospitals: A Case Study of Secondary Airborne Infection

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Abstract

Since the 1990s, improvements in ventilation techniques and isolation procedures have been widely credited with the decline in nosocomial transmission of tuberculosis and other airborne diseases. Little effort, however, has been made to study the risk of isolation patients acquiring secondary infections from contaminated air migrating into negatively pressurized isolation rooms from adjacent spaces. As a result, an actual hospital was used to observe the transport of aerosol from a nursing station and general patient room to a nearby airborne infectious isolation room (AIIR). Aerosols \( \leq 3.0\mu m \) (viruses and most airborne bacteria) were found to be capable of migrating 14.5m from a general patient room to an AIIR anteroom entrance in <14 minutes at concentrations 2-5 times greater than ambient (e.g. background). Concentrations of aerosols within the anteroom and isolation room, however, remained virtually unchanged from ambient levels, indicating the effectiveness of door position and (or) ventilation. In contrast, gravitational settling and surface deposition appeared to limit the migration of aerosols >3.0\( \mu m \) to the entrance of the general patient room (4.5m).

1. Introduction

Airborne isolation is in part created by placing infectious patients into rooms having inward air flow and sustained negative air pressure to prevent the spread of pathogens. Airborne isolation is required for patients diagnosed with...
varicella, rubella and tuberculosis as well as an increasing number of new and emerging diseases suspected of being transmitted via the airborne route such as severe acute respiratory syndrome (SARS)[1]. Several organizations including the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) provide ventilation requirements for airborne isolation[2]. According to ASHRAE Standard 170-2008, an AIIR must sustain inward airflow and a -2.5Pa pressure relationship with the corridor and all other adjacent spaces. An AIIR must maintain a minimum of two outside air changes and 12 total air changes per hour (ACH). AIIR anterooms must meet the same requirements as the isolation room, except the minimum number of total air changes is reduced to 10. Moreover, the anteroom should be positively pressurized with respect to the isolation room and negatively pressurized with respect to the corridor.

Beginning in 1993, airborne isolation has been widely credited with the steady decline in secondary transmission of tuberculosis and other airborne diseases in U.S. hospitals[3]. On the other hand, patients in AIIRs may be vulnerable to pathogens generated outside the room due to negative pressurization requirements. Many isolation patients, are immunosuppressed and if exposed to contaminated air from adjacent spaces, may be at greater risk for acquiring secondary infections.

In response, an actual hospital was used to study the particle transport from a patient room, and to assess secondary exposure risk of patients in airborne isolation. Specifically, the movement of synthetic aerosols (0.3-10.0µm) released from a general patient room were tracked to a nearby airborne infectious isolation room (AIIR). The purpose of this study was to observe the movement of a simulated bioaerosol with respect to particle size, time, distance, and airflow between a general patient room, an AIIR and adjacent spaces. Computation Fluid Dynamic (CFD) models were also developed to validate and explore this phenomenon in more depth.

2. Methods

2.1. Experiments

A 37,510m² hospital was used to simulate the aerodynamic behavior of surrogate respiratory aerosols under various ventilation alignments in various function spaces. The test area consisted of a general patient room (22.5m²), an infectious isolation room (25.8m²) and nursing station located within a patient ward (1,613.7m²) on the 5th floor of an eight-story ‘bed’ tower. The ward consisted of twenty-eight general patient rooms, two airborne infectious isolation rooms (AIIRs) and ancillary function spaces. The ward was supplied with 136.7m³/min of 100% outside air (as verified by duct traverse measurements) from a single air handling unit (AHU) providing conditioned air directly to the corridor, ancillary spaces and isolation rooms and indirectly to general patient rooms via re-circulating fan coil units. Exhaust air within the ward was removed by two exhaust air risers serving other zones on other floors.

Flow hood measurements in the general patient test room indicated that supply air (7.2m³/min), return air (5.4m³/min) and bathroom exhaust air (2.2m³/min) produced a slightly negative air pressure relationship with respect to the corridor. Flow hood measurements in the isolation patient test room indicated that exhaust air exceeded supply air by 4.2m³/min, producing a strongly negative air pressure relationship (-5.0Pa) with respect to the corridor (Figure 1). Spatial uniformity testing for the single zone ward was conducted according to ASTM E741. Tracer gas (SF6) concentrations within the general patient room (137.5ppm) and isolation room (120.5ppm) were comparable to the average SF6 concentration within the zone (124.0ppm ). The average temperature and relative humidity in the general patient room, isolation room and nursing station was 21.3°C and 49.3% respectively.

To simulate a respiratory aerosol, a synthetic aliphatic hydrocarbon (polyaliphaticolefin) approximately 84.7% of the density of water (at 20°C) was aerosolized at a rate of approximately 1.0g/min at 0.4L/s airflow rate to generate a 0.5µm-10µm poly-disperse liquid aerosol. The production rate and particle size distribution was consistent with findings of other recent studies pertaining to human lung capacity and respiratory aerosol generation [4–7]. Background concentrations of ambient airborne particles were sampled for 15 minutes prior to PAO aerosol injection. The PAO aerosol was then continuously injected at the approximate location of a patient’s nose-mouth at rest (0.8m) in the general patient room (Figure 2) using a NUCON SN-10 pneumatic aerosol generator for a total of 30 minutes (Table 1).
Particle size distribution measurements (particles/L) ranging from 0.5-10.0µm were collected using a NUCON F-1000-DD forward light scattering photometric aerosol detector at a total of five (5) sampling locations (Figure 2). Air samples from each sampling point were drawn at 30 second intervals for a total of 30 minutes each. Sampling instrumentation was calibrated prior to testing using 2.5mg of PAO per m3 of air as part of a calibration procedure developed with guidance from ANSI 510 and 511, ASME AG-1 and ASHRAE 52.2. During testing, the entry door to the general patient room was fully open and the entry doors to the isolation anteroom and isolation patient room were fully closed as per standard operating procedures.
2.2. Computer Modeling

Computational Fluid Dynamics (CFD) models were developed to further analyze the particles’ fate and transport mechanism. The model geometry adopted from the actual ward plan. In the nurse station vicinity, the model encompassed the distance between the isolation room and the patient on one direction, and it ended by the nearest walls in the perpendicular direction (Figure 2). A commercial software (Ansys Fluent 15.0) was used to simulate the air motion (primary phase) and the particles (discrete phase). The Realizable K-ε method was employed to model the turbulence as an inherent part of all indoor air motions. The entire domain was discretized by tetrahedral meshes with a total of approximately 2.5 million nodes. The discrete phase (particles) was assumed to move based on the resultant of forces exerted on each particle (i.e. Eulerian-Lagrangian method). For this study, the drag force, Brownian force, Saffman’s lift force, and pressure gradient force were placed on each particle in addition to gravity [8]. A total of 500 particle were injected from the patient room and tracked to their ultimate fate. Particles assumed to ‘escape’ from the outlets (e.g. exhaust fans, pressure outlets) and ‘trap’ when colliding solid surfaces. Only 1.0µm particle size was modeled.

3. Results

Approximately 5 minutes following release of the PAO aerosol in the general patient room, concentrations of aerosols ≤3.0µm increased significantly at the nursing station 9.5m away from the aerosol injection point (Figure 3). Specifically, the average concentration of 0.5µm, 1.0µm, and 3.0µm aerosols increased by a factor of 1.90, 4.31 and 4.27, respectively, above background levels. Approximately 14 minutes following release of the PAO aerosol in the general patient room, concentrations of aerosols ≤3.0µm increased slightly at the isolation anteroom entrance 14.5m
away from the aerosol injection point (Figure 4). The average concentration of 0.5µm, 1.0µm, and 3.0µm aerosols increased by a factor of 1.35, 2.32 and 2.55, respectively, above background levels. By comparison, concentrations of aerosols >3.0µm did not increase significantly above background levels at either the nursing station or isolation anteroom entrance.

Although significant transport behavior was observed in aerosols ≤3.0µm, changes in concentration relative to time and distance were different between 0.5µm, 1.0µm, and 3.0µm aerosols. Specifically, concentrations of 0.5µm, 1.0µm, and 3.0µm aerosols decreased on average 36.4%, 58.9% and 65.6%, respectively, every 5.0m between the general patient room entrance and nursing station, and, between the nursing station and isolation anteroom entrance. In like manner, particles migrated to the nursing station after 2.5 minutes from the injection. 21 out of 500 tracked
particles (4.5%) were able to migrate out of the patient room (Table 2). Only 7 particles (1.4%) migrated to the nursing station and none could reach to the isolation room door way.

Table 2. Particle concentrations for 1.0μm CFD vs. EXP

| Sample point            | Computer model (CFD) | Experiment (EXP) |
|-------------------------|----------------------|------------------|
| Inside Patient Room     | 472                  | 32,342           |
|                         | 94.4%                | 94.0%            |
| Patient Room Doorway    | 21                   | 1,534            |
|                         | 4.2%                 | 4.5%             |
| Nurse Station           | 7                    | 467              |
|                         | 1.4%                 | 1.4%             |
| Isolation Room Doorway  | 0                    | 50               |
|                         | 0.0%                 | 0.1%             |
| Total                   | 500                  | 34,393           |
|                         | 100%                 | 100%             |

The CFD results agreed with the experimental findings suggesting that the model was successfully simulated the particle transport mechanism. Thus, the CFD results were further analyzed to explore more details of particle behavior. Inside the patient room, almost 60% of particles were removed by the ventilation system. The deposition rate was 35% distributed over wall-, ceiling-, and floor-deposition. Statistical analysis revealed that particles traveled 44m on average (σ=18.57m). The average time particles suspended in the space was 13.7 minutes (σ =11min) and the distribution was skewed to the left (g=2.729). Moreover, the average height of particles was 1.8m (σ =0.43). The height distribution seemed to be appreciably skewed to the right (g=−1.554). More than 35% of particles were observed to be in the breathing zone (0.7m<h<1.80m) [9] which showed the propensity of particles to rise and be effectively removed by the ceiling level ventilation system.

4. Discussion

Test results support the premise that bioaerosols can be readily suspended and mobilized by directional airflow currents between patient rooms and adjacent healthcare spaces. Specifically, aerosols ≤3.0μm (viruses and most airborne bacteria) were found to be capable of migrating 9.5m from a general patient room to nursing station in <14 minutes at concentrations 2-5 times greater than ambient (e.g. background). This migration can be exacerbated when an isolation room is located right across the hallway (≈2.5m) given the negative pressurization of isolation rooms. Thus, the idea of designing the isolation room with sufficient distance from the adjacent patient rooms and placing supply diffusers near its doorway could reduce the risk of secondary airborne infection. It should also be noted that the source could have been closer in the nursing station instead of the patient room, and thus, increasing the contaminant concentration at the AIIR entrance and the risk of secondary infection to isolation patients.

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