Ventilation and Transport

Bioaerosols in Health-Care Environments

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The average U.S. health-care facility uses three to five times more energy than a comparable size office building.[1] More than two-thirds of total energy consumption is dedicated to maintaining climate control and indoor air quality (IAQ). In spite of this, hospital acquired infections (HAIs) claim more than 90,000 lives and cost more than $28 to $45 billion each year.[2,3] As a result, a series of tests were conducted in an actual hospital to observe containment and removal of synthetic respiratory aerosols with respect to directional airflow and air change rate within a general patient room, an airborne infection isolation room and patient corridor.

Air change rates were not found to be effective in proportionately reducing aerosol concentrations within patient rooms. Specifically, increasing air change rates from two to five air changes per hour (ach) reduced concentrations of aerosols <5 µm only 30% on average. Directional airflow, however, was found to be effective in containing aerosol movement from patient rooms to adjacent corridors. Door position, door motion and personnel movement were also found to have a significant effect on aerosol containment in patient rooms. Within corridors, aerosols <5 µm were found capable of migrating distances exceeding 80 ft (25 m). The results of this case study, when compared to other similar studies, may help identify optimal levels of ventilation that maximize airborne infection control while minimizing energy use.

Case Study

In an effort to better understand the relationship between airborne disease transmission and ventilation, an actual hospital was used to observe the effectiveness of directional airflow and air change rate to contain, dilute and remove synthetic bioaerosols within in a general patient room, an airborne infection isolation room, and, a patient corridor. Three test series were conducted; two each in a general patient room (Test 1), an airborne infection isolation room (Test 2), and, a patient corridor (Test 3) located in a 30-room nursing

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Airborne Infection Control

Although hours of operation and equipment plug loads contribute to high energy consumption in hospitals, HVAC systems account for more than two-thirds of all energy use (*Figure 1*). Unlike office buildings, hospital HVAC is generally not load driven, but is predicated on providing adequate ventilation air to maintain a wide range of directional airflow relationships and air change rates to contain, dilute and remove hazards such a volatile medical gases, particulates and airborne disease. Airborne disease refers to any disease that is caused by infectious particles, usually desiccated respiratory (or device generated) droplets <5 µm in size, that can be transmitted in the air over long distances. Patients with known or suspected airborne diseases, such as Mycobacterium tuberculosis, are generally placed into airborne infection isolations rooms.[4,5]

According to ASHRAE/ASHE Standard 170-2008,[6] airborne infection isolation rooms must maintain a minimum 0.01 in. w.g. (2.5 Pa) negative pressure relationship to adjacent spaces, 2 outdoor air changes per hour (ach), and 12 total ach (6 ach for existing facilities). By comparison, general patient rooms and corridors do not have a requirement to maintain a differential pressure relationship to adjacent spaces, yet require 2 outdoor ach, and 4 to 6 total ach. Air change rates, or how many times the air within a room is replaced, may reduce both the concentration and time patients and health-care workers are exposed to pathogenic microorganisms. Air pressure relationships creating directional airflow, may control the movement of pathogenic organisms between patient rooms, corridors and other clinical spaces.

The scientific basis for these and other health-care ventilation standards, however, is limited. Of 183 epidemiological studies published worldwide from 1960–2005 with keywords or medical subject headings (MeSH) pertaining to airborne transmission of communicable respiratory diseases, only 40 studies provided data on ventilation. Of these, only 10 studies were deemed by an international panel of engineering and epidemiology experts as having conclusively demonstrated an association between airflow and the transmission of airborne disease.

Collectively, data was insufficient to specify minimum ventilation standards to control the spread of airborne disease in any setting.[7] Retrospective case studies attempting to link ventilation to airborne disease transmission assumed that environmental conditions at the time of testing were the same during the outbreak and often ignored other possible routes of transmission.

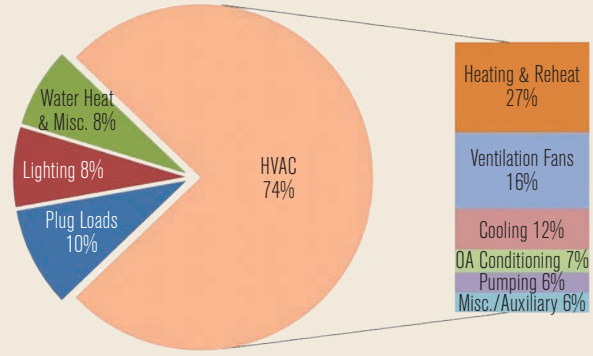

FIGURE 1 Hospital energy use by source.[1]

Analytical studies based on concentration decay, dilution, infection probability (e.g., Wells-Riley) and other computational methods assumed uniform distribution of contaminates in steady-state environments—as may exist for gaseous pollutants. Airborne disease, however, consists of pathogenic microorganisms aerosolized on small particles or in droplets. The aerodynamic behavior of small particles or droplets is not uniform, but is determined by particle size, settling velocity, surface deposition, airflow and many other particle and environmental factors.

ward (*Figure 2*). A nursing ward was chosen for this study given the potential for airborne disease transmission to large numbers of cohort patients and health-care workers during epidemics, such as the 2003 severe acute respiratory syndrome (SARS) outbreaks in Hong Kong and Toronto.[8,9,10]

The nursing ward was comprised of a single-zone, constant air volume (CAV) distribution system. Specifically, a dedicated outdoor air system (DOAS) supplied conditioned ventilation air directly to the corridors and airborne infection isolation rooms, and, indirectly to recirculating fan coil units in each patient room. Duct traverse and flow hood measurements (*Photo 1*) found that the outdoor airflow rate (85 cfm [40.1 L/s]) and exhaust airflow rate (86 cfm [40.6 L/s]) were nearly balanced in the general patient test room, producing roughly 2 ach, and, a neutral air pressure relationship with the corridor. Airflow measurements in the airborne infection isolation patient test room found that the exhaust airflow rate (218 cfm [102.9 L/s]) exceeded the outdoor airflow rate (137 cfm [64.7 L/s]), producing roughly 5 ach of exhaust airflow rate, and, a 0.01 in. w.g. (2.5 Pa) negative air pressure relationship with the corridor. Pressure relationships

FIGURE 2 Aerosol movement in hospital patient ward (probability of contamination).

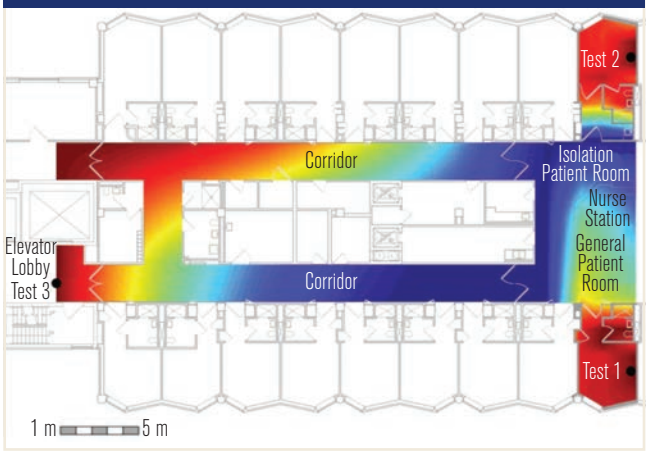

PHOTO 1 Airflow measurement in hospital patient ward corridor.

PHOTO 2 Aerosol generator & particle sampling equipment in isolation patient room.

between the anteroom and isolation room were not tested. Ventilation rates and spatial uniformity were also observed by means of ASTM E741 tracer gas (SF_6) dilution in the general patient room (137.5 ppm) and airborne infection isolation patient room (120.5 ppm). Indoor temperature, relative humidity and air density were continuously recorded during the tests. Outdoor wind speed and direction, precipitation, temperature, relative humidity and barometric pressure were recorded during the tests from three meteorological stations placed outside patient rooms.

For each test, mineral oil (polyaliphaticolefin) approximately 85% density of water was continuously aerosolized at a constant rate of 15 mg per 0.4 L/s of air to simulate the respiratory production of a human patient. The production rate was consistent with other studies using synthetic respiratory aerosols.[11,12] The aerosol, with mean aerodynamic diameters (d_a) of 0.3 µm to 10 µm, was released at the approximate height of a patient at rest (2.5 ft [0.8 m]) in each patient room, and, in an elevator lobby at the end of the patient ward corridor (*Figure 2*). Again, the particle size distribution of the aerosol was consistent with other studies indicating that human respiratory activity (e.g., coughing, sneezing, etc.) generates between 500 to 10,000 particles with d_a ~ 0.1 to 15 µm.[13,14,15,16] Particle measurements (particles/L) were collected at 2 ft (0.6 m), 4 ft (1.2 m) and 6 ft (1.8 m) sampling heights above the floor (*Photo 2*) at a total of 12 locations in each patient room, and at 31 additional sampling locations approximately 10 ft (3 m) apart in the patient ward corridors (*Figure 2*). Samples were drawn at 30 second intervals throughout the four to five hour duration of each test. All equipment and instrumentation were calibrated prior to testing in accordance with ASHRAE Standard 52.2.[17]

At the start of testing in the patient test rooms, entry doors from the corridors were closed and bathroom doors were opened. Concentrations of ambient (e.g., background) airborne particles were then sampled in patient rooms and corridors for 30 minutes prior to aerosol injection (*Table 1*). Once the aerosol injection began, a technician briefly entered the patient test rooms six times, opening and closing the entry doors once every 30 minutes, to simulate the movement of health-care workers attending to patients. Following the sixth entry, the door from the corridor to the general patient room was left open for the remainder of testing. Similarly, the door from the anteroom to the isolation patient room was left open for the remainder of testing. Thirty minutes later, the door leading from the corridor to the isolation anteroom was left open for the

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TABLE 1 Summary of test procedure.

	TEST 1 GENERAL PATIENT ROOM	TEST 2 ISOLATION PATIENT ROOM	TEST 3 PATIENT ROOM CORRIDORS
0:00 – 0:30	Background	Background	Background
0:30 – 1:00	Injection Started	Injection Started	Injection Started
1:00 – 1:30	Sampling	Sampling	Sampling
1:30 – 2:00	Sampling	Sampling	Sampling
2:00 – 2:30	Sampling	Sampling	Sampling
2:30 – 3:00	Sampling	Sampling	Sampling
3:00 – 3:30	Entry Door Opened	Sampling	Sampling
3:30 – 4:00	Bathroom Door Closed	Anteroom Door Opened	Sampling
4:00 – 4:30	Injection Stopped	Entry Door Opened	Sampling
4:30 – 5:00		Injection Stopped	Injection Stopped

remainder of testing. Aerosol injection was terminated 30 minutes after the second door position change and samples collected for an additional 30 minutes (*Table 1*). Doors separating the elevator lobby and patient area were closed during testing in the corridors. All doors were solid and opaque without ventilation louvers or fenestration.

Patient Rooms (General and Airborne Infection Isolation)

Within both general and airborne infection isolation patient rooms, continuous aerosol production and constant volume ventilation appeared to achieve a steady-state condition where aerosols <5 µm remained uniformly distributed at concentrations 1.4 to 2.7 times background levels to distances of 10 ft (3 m) from the aerosol injection point (e.g., "patient"). Concentrations of aerosols <5 µm in the general patient room with 2 ach decreased slightly, 6.1% on average, to a distance of 10 ft (3 m) from the aerosol injection point (r^2 = –0.63). Conversely, concentrations of aerosols <5 µm in the isolation patient room with 5 ach increased slightly, 8.2% on average, to a distance of 10 ft (3 m) from the aerosol injection point (r^2 = 0.71), possibly due to turbulent or short-circuiting airflow between supply and exhaust air vents. Overall, ventilation rates were not found to be effective in proportionately reducing aerosol concentrations within patient rooms. Specifically, increasing air change rates from 2 to 5 ach of outdoor air (OA), reduced concentrations of aerosols <5 µm only 30% on average (*Figure 3*). By comparison, concentrations of aerosols ≥5 µm in the general patient room decreased rapidly with

FIGURE 3 Particle concentration relative to air change rate per hour in patient rooms.

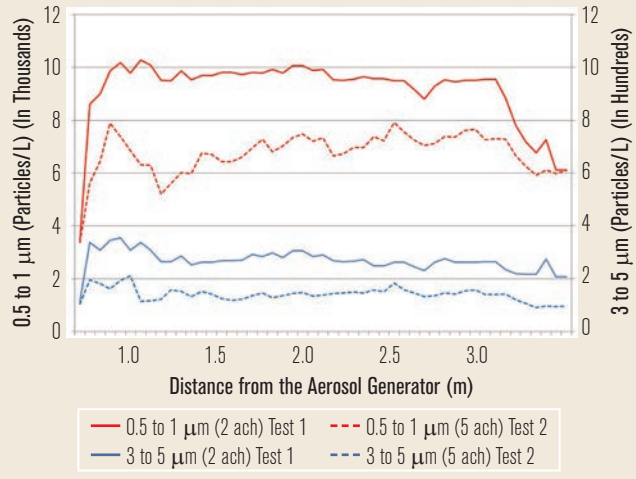
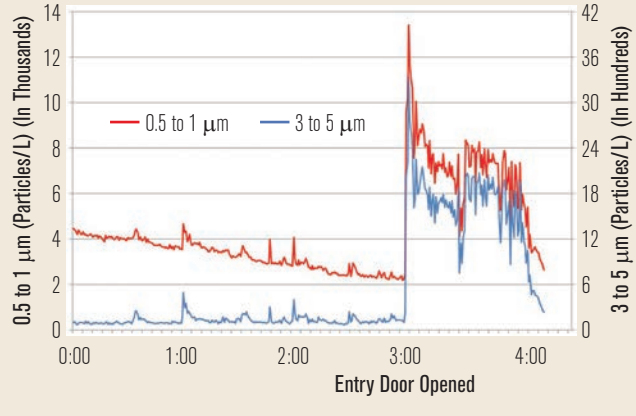


FIGURE 4 Particle concentration relative to entry door position in general patient room.



respect to distance, approaching background concentrations less than 6 ft (2 m) from the aerosol injection point, presumably under the effects of gravitational settling and surface deposition. In the airborne infection isolation patient room, concentrations of aerosols ≥5 µm remained above background concentrations to distances approaching 10 ft (3 m), again, most likely due to higher air change rates and turbulent airflow mixing. The effects of fiber return air filters (MERV<4) on aerosol concentrations in the general patient room were considered negligible as filters of this type have a filtration efficiency of <20% for particles ≤10.0 µm.

Outside of the general patient 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 technician entered the test space once every 30 minutes (*Figure 4*). When the entry door was left open (t = 3:00 hr),

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FIGURE 5 Particle concentration at nurse station 16 ft (5.0 m) from general patient room.

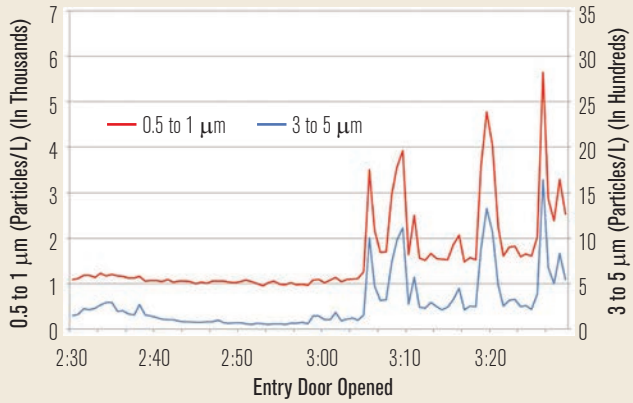
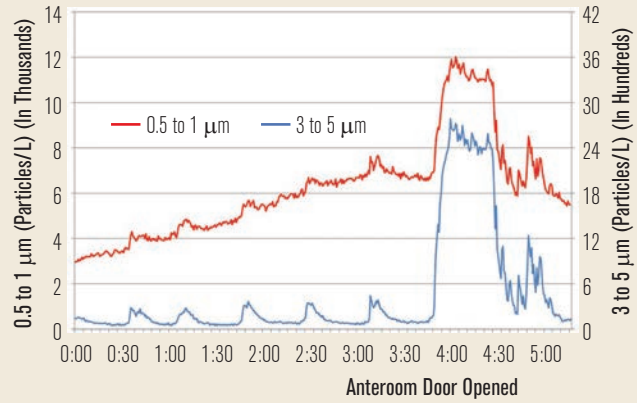


FIGURE 6 Particle concentration relative to anteroom door position in isolation patient room.



however, a significant and sustained release of <5 µm aerosols from the doorway to the corridor were observed despite a neutral air pressure relationship between the general patient room and corridor (*Figure 4*). Less than five minutes later, concentrations of aerosols <5 µm increased significantly at the nursing station 16 ft (5 m) away from the general patient room doorway (*Figure 5*). After 15 minutes, trace amounts of aerosol <5 µm were detected at the isolation room entrance 33 ft (10 m) away from the general patient room. Concentrations of aerosols ≥5 µm did not increase significantly above background levels at either the nursing station or airborne infection isolation room entrance.

Outside of the airborne infection isolation patient room, aerosol concentrations remained near background levels in both the corridor and anteroom while the entry and anteroom doors remained closed. A small, intermittent release of aerosol was observed in the anteroom when a technician entered the test space once every 30 minutes (*Figure 6*). No significant release of aerosol was observed from the anteroom to the corridor. When the inner anteroom door was left open (t = 3:30 hr), however, a significant and sustained release of <5 µm aerosols from the isolation room to the anteroom was observed, despite a neutral air pressure relationship between the two spaces (*Figure 6*). Approximately 30 minutes after the inner anteroom door to the isolation room was left open, the outer anteroom door to the corridor was also left open. Concentrations of <5 µm and ≥5 µm aerosol increased only briefly in the corridor, suggesting that the 0.01 in. w.g. (2.5 Pa) negative air pressure relationship between the anteroom and corridor (e.g., inward airflow from corridor to anteroom) was effective in containing the release of aerosols into the corridor.

Patient Corridors

Within corridors, concentrations of <5 µm aerosols decreased gradually with respect to distance, remaining above background levels to distances exceeding 80 ft (25 m) in some cases. By comparison, concentrations of aerosols ≥5 µm decreased rapidly with respect to distance, falling below background concentrations 10 ft (3 m) or less from the aerosol injection point. Among aerosols <5 µm, concentrations of 0.5 µm particles decreased slightly, 5.6% on average, every 10 ft (3 m) from the aerosol injection point (r^2 = 0.57) and remained above background levels to a maximum distance of 83 ft (26 m). In contrast, concentrations of 1.0 µm to 3.0 µm particles decreased more rapidly, 21.8% to 24.2% on average, every 10 ft (3 m) from the aerosol injection point ($r^2 \geq 0.91$), remaining above background levels only half the distance of 0.5 µm particles (*Figure 7*). No significant differences in particle concentrations were observed with respect to sampling height or proximity to patient rooms among 0.5 µm particles. Concentrations of 1.0 µm and 3.0 µm particles, however, were greater for all sampling heights on the patient room side of the corridors, especially in the corridor adjacent to the negatively pressurized isolation rooms (*Figure 2*).

Conclusions

The purpose of this study was to observe the effectiveness of directional airflow and air change rate to contain, dilute and remove respiratory aerosols (<5 µm)

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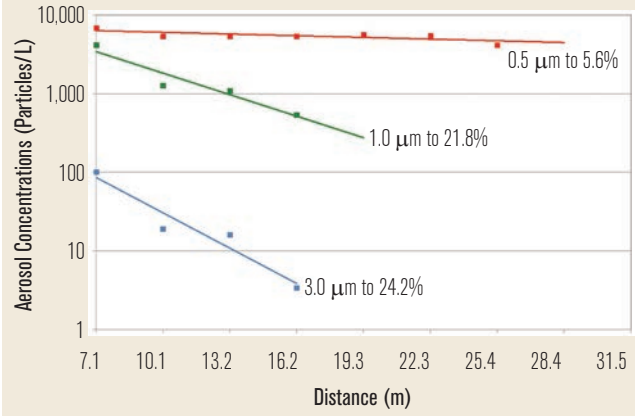
within a general patient room, an isolation patient room, and, corridor. The major findings include:

- Air change rate was not found to be effective in reducing respiratory aerosol concentrations within patient rooms. Increasing air change rates from 2 to 5 ach reduced concentrations of aerosols <5 µm only 30% on average.
- Directional airflow was found to be effective in containing respiratory aerosol movement from patient rooms to adjacent corridors. A neutral air pressure relationship between general patient room and corridor, and, isolation room and anteroom, was found to be effective in containing <5 µm aerosols only when the door separating these spaces was closed. A 0.01 in. w.g. (2.5 Pa) negative air pressure relationship between anteroom and corridor was found to be effective in containing <5 µm aerosols regardless of door position or door motion.
- Particle size was found to influence aerosol movement in patient rooms and corridors. Within patient rooms, aerosols <5 µm remained uniformly distributed at concentrations twice background levels to distances of 10 ft (3 m) from the aerosol injection point (e.g., "patient"). Within corridors, concentrations of <5 µm aerosols remained above background levels to distances exceeding 80 ft (25 m). Concentrations of aerosols ≥5 µm decreased rapidly with respect to distance, falling below background concentrations 10 ft (3 m) or less from the aerosol injection point in both patient rooms and corridors. Among aerosols <5 µm, 0.5 µm particles appeared to diffuse randomly and uniformly in the environment. In contrast, particles 1.0 to 3.0 µm appeared to mobilize and disperse under the influences of airflow (e.g., patient rooms), yet, decay in the absence of airflow (e.g., corridors).

FIGURE 7 Particle concentration relative to distance in corridors.



In summary, the results of this study suggest that current health-care ventilation standards can be effective in containing respiratory aerosol transport when proper air pressure relationships and door positions between patient rooms and corridors are maintained. However, results also indicate that higher ventilation rates may not be effective in significantly reducing respiratory aerosol concentrations within patient rooms, but rather, may mobilize and disperse aerosols within and between patient rooms as was observed between the general patient room and corridors, and, the isolation room (*Figure 2*). This may be true of larger respiratory aerosols (1.0 µm to 3.0 µm), particularly for HVAC systems with excessive airflow velocity. With comparatively less regard to airflow, smaller respiratory particles (<0.5 µm), may readily diffuse into the air under the influences of kinetic (Brownian) particle movement and prove more difficult to contain and remove from the health-care environment.

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