ASHRAE Position Document on Airborne Infectious Diseases

Approved by ASHRAE Board of Directors
January 19, 2014

Expires
January 19, 2017

ASHRAE
1791 Tullie Circle, NE • Atlanta, Georgia 30329-2305
404-636-8400 • fax: 404-321-5478 • www.ashrae.org

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

COMMITTEE ROSTER

The ASHRAE Position Document on Airborne Infectious Diseases was developed by the Society's Airborne Infectious Diseases Position Document Committee formed on September 12, 2012, with Larry Schoen as its chair.

Lawrence J. Schoen
Schoen Engineering Inc
Columbia, MD

Michael J. Hodgson
Occupational Safety and Health Administration
Washington, DC

William F. McCoy
Phigenics LLC
Naperville, IL

Shelly L Miller
University of Colorado
Boulder, CO

Yuguo Li
The University of Hong Kong
Hong Kong

Russell N. Olmsted
Saint Joseph Mercy Health System
Ann Arbor, MI

Chandra Sekhar,
National University of Singapore
Singapore, Singapore

Former Members and Contributors

Sidney A. Parsons, PhD, deceased
Council for Scientific and Industrial Research
Pretoria, South Africa

Cognizant Committees

The chairperson(s) for the Environmental Health Committee also served as *ex officio* members.

Pawel Wargocki
Environmental Health Committee, Chair
Tech University of Denmark
Kongens, Lyngby, Denmark

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

HISTORY OF REVISION/REAFFIRMATION/WITHDRAWAL DATES

The following summarizes this document's revision, reaffirmation, or withdrawal dates:

6/24/2009—BOD approves Position Document titled Airborne Infectious Diseases

1/25/2012—Technology Council approves reaffirmation of Position Document titled Airborne Infectious Diseases

1/19/2014—BOD approves revised Position Document titled Airborne Infectious Diseases

Note: ASHRAE's Technology Council and the cognizant committee recommend revision, reaffirmation, or withdrawal every 30 months.

Note: ASHRAE position documents are approved by the Board of Directors and express the views of the Society on a specific issue. The purpose of these documents is to provide objective, authoritative background information to persons interested in issues within ASHRAE's expertise, particularly in areas where such information will be helpful in drafting sound public policy. A related purpose is also to serve as an educational tool clarifying ASHRAE's position for its members and professionals, in general, advancing the arts and sciences of HVAC&R.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

CONTENTS

ASHRAE Position Document on Airborne Infectious Diseases

SECTION **PAGE**

Abstract 1

Executive Summary 2

1 The Issue 3

2 Background 3

2.1 Introduction to Infectious Disease Transmission 3

2.2 Mathematical Model of Airborne Infection 5

2.3 For Which Diseases is the Airborne Transmission Route Important? 6

3 Practical Implications for Building Owners, Operators, and Engineers 7

3.1 Varying Approaches for Facility Type 8

3.2 Ventilation and Air-Cleaning Strategies 8

3.3 Temperature and Humidity 11

3.4 Non-HVAC Strategies 12

3.5 Emergency Planning 13

4 Recommendations 14

5 References 16

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

ABSTRACT

Infectious diseases spread by several different routes. Tuberculosis and in some cases influenza, the common cold, and other diseases spread by the airborne route. The spread can be accelerated or controlled by heating, ventilating, and air-conditioning (HVAC) systems, for which ASHRAE is the global leader and foremost source of technical and educational information.

ASHRAE will continue to support research that advances the state of knowledge in the specific techniques that control airborne infectious disease transmission through HVAC systems, including ventilation rates, airflow regimes, filtration, and ultraviolet germicidal irradiation (UVGI).

ASHRAE's position is that facilities of all types should follow, as a minimum, the latest practice standards and guidelines. ASHRAE's 62.X Standards cover ventilation in many facility types, and Standard 170 covers ventilation in health-care facilities. New and existing health-care intake and waiting areas, crowded shelters, and similar facilities should go beyond the minimum requirements of these documents, using techniques covered in ASHRAE's *Indoor Air Quality Guide* (2009) to be even better prepared to control airborne infectious disease (including a future pandemic caused by a new infectious agent).

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

EXECUTIVE SUMMARY

This position document (PD) has been written to provide the membership of ASHRAE and other interested persons with information on the following:

- the health consequences and modes of transmission of infectious disease
- the implications for the design, installation, and operation of heating, ventilating, and air-conditioning (HVAC) systems
- the means to support facility management and planning for everyday operation and for emergencies

There are various methods of infectious disease transmission, including contact (both direct and indirect), transmission by large droplets, and inhalation of airborne particles containing infectious microorganisms. The practice of the HVAC professional in reducing disease transmission is focused primarily on those diseases transmitted by airborne particles.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

1. THE ISSUE

The potential for airborne transmission of disease is widely recognized, although there remains uncertainty concerning which diseases are spread primarily via which route, whether it be airborne, short range droplets, direct or indirect contact, or multimodal (a combination of mechanisms).

Ventilation and airflow are effective for controlling transmission of only certain diseases. Several ventilation and airflow strategies are effective and available for implementation in buildings.

Although this PD is primarily applicable to diseases that spread from person to person, the principles also apply to infection from environmental reservoirs such as building water systems with *Legionella* spp. and organic matter with spores from mold (to the extent that the microorganisms spread by the airborne route).[1] The first step in control of such a disease is to eliminate the source before it becomes airborne.

2. BACKGROUND

2.1 Introduction to Infectious Disease Transmission

This position document covers the spread of infectious disease from an infected individual to a susceptible person, known as *cross transmission* or *person-to-person transmission*, by small airborne particles (an aerosol) that contain microorganisms.

This PD does not cover direct or indirect contact routes of exposure. Direct contact means any surface contact such as touching, kissing, sexual contact, contact with oral secretions or skin lesions, or additional routes such as blood transfusions or intravenous injections. Indirect contact involves contact with an intermediate inanimate surface (fomite), such as a doorknob or bedrail that is contaminated.

Exposure through the air occurs through (1) droplets, which are released and fall to surfaces about 1 m (3 ft) from the infected and (2) small particles, which stay airborne for hours at a time and can be transported long distances. The aerobiology of transmission of droplets and small particles produced by a patient with acute infection is illustrated in Figure 1.

Because large droplets are heavy and settle under the influence of gravity quickly, general dilution, pressure differentials, and exhaust ventilation do not significantly influence droplet concentrations, velocity, or direction, unless they reduce diameter by evaporation, thus becoming an aerosol. The term *droplet nuclei* has been used to describe desiccation of large droplets into small airborne particles (Siegel et al. 2007).

Of the modes of transmission, this PD's scope is limited to aerosols, which can travel longer distances through the airborne route, including by HVAC systems. The terms *airborne*, *aerosol*, and *droplet nuclei* are used throughout this PD to refer to this route. HVAC systems are not known to entrain the larger particles.

The size demarcation between droplets and small particles has been described as having a mass median aerodynamic diameter (MMAD) of 2.5 to10 µm (Shaman and Kohn 2009; Duguid 1946; Mandell 2010). Even particles with diameters of 30 µm or greater can remain suspended in the air (Cole and Cook 1998). Work by Xie and colleagues (2007) indicates that large droplets are those of diameter between 50 and 100 µm at the original time of release. Tang and others (2006) proposed a scheme of large-droplet diameter $\geq$60 µm,

[1] For ASHRAE's position concerning *Legionella*, see ASHRAE (2012a). Readers are referred to other resources that address mitigation of transmission of this waterborne pathogen (ASHRAE 2000; CDC 2003; the forthcoming ASHRAE Standard 188; OSHA 1999; SA Health 2013, and WHO 2007). For ASHRAE's position concerning mold and moisture, see ASHRAE (2013d).

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

small droplet diameter < 60 µm, and droplet nuclei with a MMAD of <10 µm. The exact size demarcation is less important than knowing that large droplets and small particles behave differently and that the latter can remain airborne.

Small particles that can become airborne are typically generated by coughing, sneezing, shouting, and to a lesser extent by singing and talking. Even breathing may generate such particles in sick and highly infectious individuals (Bischoff 2013). Particle size distributions of coughed materials are thought to encompass a broad range of diameters, from very small to large droplets, depending on differences in patients and diseases (Riley and Nardell 1989).

Fennelly et al. (2004) measured cough aerosol emanating directly from tuberculosis patients. The patients generated infectious aerosol that contained from three to four colony-forming units (CFU, a direct measure, using culturing techniques, of the number of viable, growing, and infectious organisms) to a maximum of 633 CFU. The size distributions that were measured in this study suggest that most of the viable particles in the cough-generated aerosols were immediately respirable, ranging from 0.65 to 3.3 µm. Wainwright et al. (2009) also measured cough aerosols from cystic fibrosis patients and documented that 70% of viable cough aerosols containing *Pseudomonas aeruginosa* and other Gram-negative bacteria were of particles ≤ 3.3 µm. Positive room air samples were associated with high total counts in cough aerosols.

There are not, however, enough data to fully describe or predict cough particle size distributions[2] for many diseases, and research is needed to better characterize them (Xie et al. 2009).

In the 1950s, the relationship among particle size, airborne suspension, and transmission implications began to become clear. The different routes require different control strategies, which have evolved over many years of infectious disease practice, and there are now standards of practice for infectious disease and hospital epidemiology. See the Professional Practice documents available from the Association for Professionals in Infection Control and Epidemiology at www.apic.org.

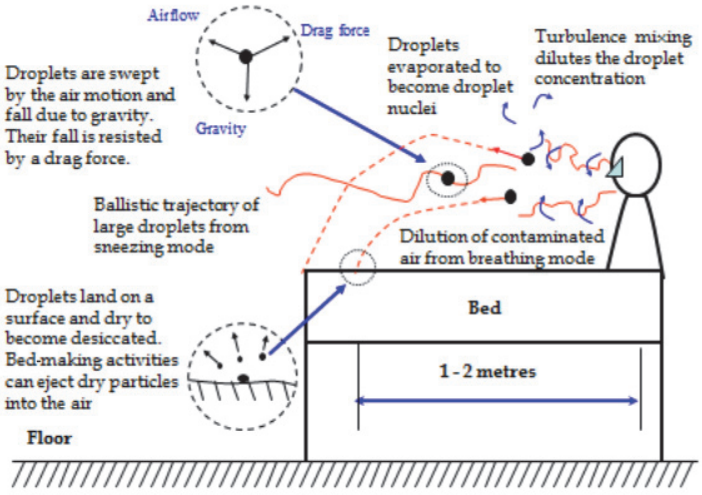

Figure 1 Droplet suspension: illustration of the aerobiology of droplets and small airborne particles produced by an infected patient.

[2] Cough particle size distributions are likely to vary based on the infected person's viscosity of secretions, anatomical structures in the oropharynx (roughly meaning throat) and airways, and disease characteristics.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Many diseases have been found to have higher transmission rates when susceptible individuals approach within close proximity, about 1 to 2 m (3 to 7 ft).[3] Over this short range, the susceptible person has a substantially greater exposure from the infected individual to droplets of varying size, both inspirable large droplets and airborne particles (e.g., see Figure 1). Nicas and Jones (2009) have argued that close contact permits droplet spray exposure and maximizes inhalation exposure to small particles and inspirable droplets. Thus, particles/droplets of varying sizes may contribute to transmission at close proximity (Li 2011).

To prevent this type of short-range exposure, whether droplet or airborne, maintaining a 2 m (7 ft) distance between infected and susceptible is considered protective, and methods such as ventilation dilution are not effective.

2.2 Mathematical Model of Airborne Infection

Riley and Nardell (1989) present a standard model of airborne infection usually referred to as the *Wells-Riley equation*, given below as Equation 1. Like all mathematical models, it has its limitations, yet it is useful for understanding the relationship among the variables such as the number of new infections (C), number of susceptibles (S), number of infectors (I), number of doses of airborne infection (q) added to the air per unit time by a case in the infectious stage, pulmonary ventilation per susceptible (p) in volume per unit time, exposure time (t), and volume flow rate of fresh or disinfected air into which the quanta are distributed (Q).

$$C = S(1 - e^{-Iqpt/Q}) \quad (1)$$

The exponent represents the degree of exposure to infection and $1 - e^{-Iqpt/Q}$ is the probability of a single susceptible being infected. Note that this model does not account for varying susceptibility among noninfected individuals. For this and other reasons, exposure does not necessarily lead to infection.[4] The parameter q is derived from the term *quantum*, which Wells (1995) used to indicate an infectious dose, whether it contains a single organism or several organisms. The ability to estimate q is difficult at best and has been reported in the literature to be 1.25 to 249 quanta per hour (qph) in tuberculosis patients (Riley et al. 1962; Catanzaro 1982) and 5480 qph for measles (Riley et al. 1978).

Because of the uncertainty in knowing q, Equation 1 is most useful for understanding the general relationships among the variables, for instance, the impact of increasing the volume of fresh or disinfected air on airborne infection. Increasing Q decreases exposure by diluting air containing infectious particles with infectious-particle-free air. Q can also be impacted through the use of other engineering control technologies, including filtration and UVGI, as discussed in Section 3.2. Therefore, a more complete representation of Q should include the total removal rate by ventilation, filtration, deposition, agglomeration, natural deactivation, and other forms of engineered deactivation.

[3] Infectious pneumonias, like pneumococcal disease (Hoge et al. 1994) or plague (CDC 2001) are thought to be transmitted in this way.

[4] This applies differently to various microorganisms, whether they be fungal, bacterial, or viral. After exposure, the microorganism must reach the target in the body (e.g., lung or mucosa) to cause infection. Some infective particles must deposit on mucosa to result in infection, and if they instead deposit on the skin, infection may not result. Another important element that influences a person's risk of infection is his or her underlying immunity against select microorganisms and immune status in general. For example, individuals with prior *M. Tuberculosis* infection who have developed immunity are able to ward off the infection and a person who had chicken pox as a child or received chicken pox vaccine is not susceptible even if living in the same household as an individual with acute chicken pox. On the other hand, individuals infected with human immunodeficiency virus (HIV) are more susceptible to becoming infected, for instance, with tuberculosis.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

2.3 For Which Diseases is the Airborne Transmission Route Important?

Roy and Milton (2004) describe a classification scheme of aerosol transmission of diseases as obligate, preferential, or opportunistic[5] on the basis of the agent's capacity to be transmitted and to induce disease. Under this classification scheme, tuberculosis may be the only communicable disease with obligate airborne transmission—an infection that is initiated only through aerosols. For *Mycobacterium tuberculosis*, the aerodynamic diameters of the airborne particles are approximately 1 to 5 µm.

Agents with preferential airborne transmission can naturally initiate infection through multiple routes but are predominantly transmitted by aerosols. These include measles and chicken pox.

There are probably many diseases with opportunistic airborne transmission—infections that naturally cause disease through other routes such as the gastrointestinal tract but that can also use fine-particle aerosols as an efficient means of propagating in favorable environments. The relative importance of the transmission modes for many of these diseases remains a subject of uncertainty (Shaman and Kohn 2009; Roy and Milton 2004; Li 2011).

The common cold (rhinoviruses) and influenza can both be transmitted by direct contact or fomites; there is also evidence of influenza and rhinovirus transmission via large droplets and the airborne route (D'Alesssio et al. 1984; Wong et al. 2010; Bischoff et al. 2013).

Work by Dick and colleagues (1967, 1987) suggests that the common cold may be transmitted through the airborne droplet nuclei route. Experimental studies (Dick et al. 1987) document the possibility of transmission beyond 1 m (3 ft) under controlled conditions in experimental chambers and strongly suggest airborne transmission as at least one component of rhinoviral infection. A recent field study (Myatt et al. 2004) supports this result and documents its likely importance in a field investigation.

Other literature acknowledges the potential importance of the airborne routes while suggesting that droplet transmission is far more important, at least for common viral diseases such as the common cold (Gwaltney and Hendley 1978).

Control of seasonal influenza has for decades relied on large-droplet precautions even though there is evidence suggesting a far greater importance for airborne transmission by small particles. For instance, a 1959 study of influenza prevention in a Veterans Administration nursing home identified an 80% reduction in influenza in staff and patients through the use of upper-room ultraviolet germicidal irradiation (UVGI) (McLean 1961). This suggests that air currents to the higher-room areas where the UVGI was present carried the airborne infectious particles, and they were inactivated. The inactivated (noninfectious) particles were therefore unable to infect staff and patients in control areas with UVGI, as compared to areas without UVGI.

Influenza transmission occurred from one index case to 72% of the 54 passengers aboard an airliner on the ground in Alaska while the ventilation system was turned off (Moser et al. 1979). This outbreak was widely thought to represent a second piece of evidence for airborne transmission, and it was also thought that the high attack rate was due in part to the ventilation system not being in operation (Moser 1979). A review by Tellier (2006) acknowledges the importance of these papers and suggests including consideration of airborne transmission in pandemic influenza planning. However, one systematic review by Brankston et al. (2007) concluded that the airborne transmission route was not important in the same outbreak.

[5] This use of the word *opportunistic* differs from the medical term of art, *opportunistic infection*, which refers to an infection caused by a microorganism that normally does not cause disease but becomes pathogenic when the body's immune system is impaired and unable to fight off infection.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

A 1986 outbreak from the H1N1 influenza virus among U.S. Navy personnel was attributed to their having flown on the same airplanes. Many of the infected susceptibles were displaced considerably more than 2 m (7 ft) from the infected individuals (Klontz et al. 1989). This suggests the airborne route of transmission.

A 2009 outbreak of influenza A pandemic (H1N1) developed from a single index case patient in nine tour group members (30%) who had talked with the index case patient and in one airline passenger (not a tour group member) who had sat within two rows of her. None of the 14 tour group members who had not talked with the index case patient became ill. The authors therefore concluded that this outbreak was caused by droplet transmission and that airborne transmission was not a factor (Han et al. 2009).

Chu et al. (2005) documented that airborne transmission of severe acute respiratory syndrome (SARS, a severe form of pneumonia caused by a member of the coronavirus family of viruses—the same family that can cause the common cold) could occur. In one dramatic outbreak of SARS in the Amoy Gardens high-rise apartment, airborne transmission through droplet nuclei seemed to represent the primary mode of disease spread. This was likely due to a dried-out floor drain and airborne dissemination by the toilet exhaust fan and winds (Yu et al. 2004; Li et al. 2005a, 2005b). The observed pattern of disease spread from one building to another, and particularly on the upwind side of one building, could not be explained satisfactorily other than by the airborne route.

A study of Chinese student dormitories provides support for the theory of the airborne spread of the common cold (Sun et al. 2011). Ventilation rates were calculated from measured carbon-dioxide concentration in 238 dorm rooms in 13 buildings. A dose-response relationship was found between outdoor air flow rate per person in dorm rooms and the proportion of occupants with annual common cold infections $\geq$6 times. A mean ventilation rate of 5 L/(s·person) (10 cfm/[s·person]) in dorm buildings was associated with 5% of self-reported common cold $\geq$6 times, compared to 35% at 1 L/(s·person) (2 cfm /[s·person]).

A literature review by Wat (2004) tabulates the mode of transmission and seasonality of six respiratory viruses, indicating that rhinovirus, influenza, adenovirus, and possibly coronavirus are spread by the airborne route.

The reader of this document should keep an open mind about the relative importance of the various modes of transmission due to the uncertainty that remains (Shaman and Kohn 2009) as illustrated by the studies described above. Disease transmission is complex, and one-dimensional strategies are not suitable for universal application.

3. PRACTICAL IMPLICATIONS FOR BUILDING OWNERS, OPERATORS, AND ENGINEERS

Small particles may be transported through ventilation systems, as has been documented for tuberculosis, Q-fever, and measles (Li et al. 2007). Therefore, when outbreaks occur in the workplace, transmission through HVAC systems must be considered. As disease transmission by direct contact, fomite, and large-droplet routes is reduced by more efficient prevention strategies, the airborne route is likely to become relatively more important.

If influenza transmission occurs not only through direct contact or large droplets, as is the long-standing public health tradition, but also through the airborne route, as newer data suggest, HVAC systems may contribute far more both to transmission of disease and, potentially, to reduction of transmission risk.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

There are practical limits to what HVAC systems can accomplish in preventing transmission of infections in large populations. In some cases, infections are transmitted in the absence of HVAC systems.

Owners, operators, and engineers are encouraged to collaborate with infection prevention specialists knowledgeable about transmission of infection in the community and the workplace and about strategies for prevention and risk mitigation.

3.1 Varying Approaches for Facility Type

Health-care facilities have criteria for ventilation design to mitigate airborne transmission of infectious disease (FGI 2010; ASHRAE 2008). Yet most infections are transmitted in ordinary occupancies in the community and not in industrial or health-care occupancies.

ASHRAE does not provide specific *requirements* for infectious disease control in schools, prisons, shelters, transportation, and other public facilities other than the general ventilation and air quality requirements of Standards 62.1 and 62.2 (ASHRAE 2013b, 2013c). However, the *guidance* in this PD does apply to these facilities.

In health-care facilities, many common interventions to prevent infections aim to reduce transmission by direct or indirect contact (for example, directly via the hands of health-care personnel). Interventions also aim to prevent airborne transmission (Aliabadi et al. 2011).

Because of the difficulties in separating out the relative importance of transmission modes, recent work in health-care facilities has focused on "infection control bundles" (i.e., use of multiple modalities simultaneously) (Apisarnthanarak et al. 2009, et al. 2010a, et al. 2010b; Cheng et al. 2010). For two prototype diseases, tuberculosis and influenza, this bundle includes administrative and environmental controls and personal protective equipment in health-care settings. Given the current state of knowledge, this represents a practical solution.

For studies and other publications with specific guidance on air quality and energy in biomedical laboratories, animal research facilities, and health-care facilities, see the National Institutes of Health (NIH) Office of Research Facilities' website (http://orf.od.nih.gov/PoliciesAndGuidelines/Bioenvironmental).

A prerequisite to all of the strategies is a well-designed, installed, commissioned, and maintained HVAC system (Memarzadeh et al. 2010; NIOSH 2009a).

In considering going beyond requirements that include codes, standards, and practice guidelines, use guidance from published sources such as "Guidelines for Preventing the Transmission of Mycobacterium Tuberculosis in Health-Care Settings" (CDC 2005), *Guidelines for Design and Construction of Health Care Facilities* (FGI 2010), *Indoor Air Quality Guide: Best Practices for Design, Construction and Commissioning* (ASHRAE 2009), apic.org, and Table 1 in the Recommendations section, and discuss risk with the facility user. HVAC system designers can assist closely allied professionals such as architects and plumbing engineers to understand how sources of unplanned airflow can impact airborne infectious disease transmission. Examples include wastewater drains (especially if improperly trapped) and wall and door leakage (including the pumping action of swinging doors).

3.2 Ventilation and Air-Cleaning Strategies

Because small particles remain airborne for some period of time, the design and operation of HVAC systems that move air can affect disease transmission in several ways, such as by the following:

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

- supplying clean air to susceptible occupants
- containing contaminated air and/or exhausting it to the outdoors
- diluting the air in a space with cleaner air from outdoors and/or by filtering the air
- cleaning the air within the room

The following strategies are of interest: dilution ventilation, laminar and other in-room flow regimes, differential room pressurization, personalized ventilation, source capture ventilation, filtration (central or unitary), and UVGI (upper room, in-room, and in the airstream).

ANSI/ASHRAE/ASHE Standard 170-2008, *Ventilation of Health-Care Facilities*, covers specific mandatory HVAC requirements including ventilation rates, filtration, and pressure relationships among rooms (ASHRAE 2008). The *Guidelines for Design and Construction of Health Care Facilities* (FGI 2010) include the Standard 170 requirements and describe other criteria that can guide designers of these facilities.

Ventilation represents a primary infectious disease control strategy through dilution of room air around a source and removal of infectious agents (CDC 2005). Directed supply and/or exhaust ventilation, such as nonaspirating diffusers for unidirectional low-velocity airflow, is important in several settings, including operating rooms (FGI 2010; ASHRAE 2008).

However, it remains unclear by how much infectious particle loads must be reduced to achieve a measurable reduction in disease transmissions and whether the efficiencies warrant the cost of using these controls.

Energy-conserving strategies that reduce annualized ventilation rates, such as demand-controlled ventilation, should be used with caution, especially during mild outdoor conditions when the additional ventilation has low cost. Greater use of air economizers has a positive impact both on energy conservation and annualized dilution ventilation.

Natural ventilation, such as that provided by user-operable windows, is not covered as a method of infection control by most ventilation standards and guidelines. There are very few studies on natural ventilation for infection control in hospitals. One guideline that does address it recommends that natural ventilation systems should achieve specific ventilation rates that are significantly higher than the ventilation rates required in practice guidelines for mechanical systems (WHO 2009).

Room pressure differentials are important for controlling airflow between areas in a building (Siegel et al. 2007; CDC 2005). For example, airborne infection isolation rooms (AIIRs) are kept at negative pressure with respect to the surrounding areas to keep potential infectious agents within the rooms. Some designs for AIIRs incorporate supplemental dilution or exhaust/capture ventilation (CDC 2005). Interestingly, criteria for AIIRs differ substantially between cultures and countries in several ways, including air supply into anterooms, exhaust from space, and required ventilation air (Subhash et al. 2013; Fusco et al. 2012). This PD takes no position on whether anterooms should be required in practice guidelines.

Hospital rooms with immune-compromised individuals are kept at positive pressure in protective environments (PEs) to keep potential infectious agents (e.g., *Aspergillus* sp. or other filamentous fungi) out of the rooms (Siegel et al. 2007; FGI 2010; ASHRAE 2008).

Personalized ventilation systems that supply 100% outdoor air, highly filtered, or UV disinfected air directly to the occupant's breathing zone (Cermak et al. 2006; Sekhar et al. 2005) may be protective as shown by CFD analysis (Yang et al. 2013). However, there are no known field studies that justify the efficacy. Personalized ventilation may be effective against aerosols that travel both long distances as well as short-range routes (Li 2011).

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

The addition of highly efficient particle filtration to central ventilation systems is likely to reduce the airborne load of infectious particles (Azimi and Stephens 2013).[6] This control strategy can reduce the transport of infectious agents within individual areas and from one area to another when these areas share the same central ventilation system (e.g., from patient rooms in hospitals or lobbies in public access buildings to other occupied spaces).

Local, efficient filtration units (either ceiling mounted or portable, floor-standing) reduce local airborne loads and may serve purposes in specific areas such as health-care facilities or high-traffic public occupancies (Miller-Leiden et al. 1996; Kujundzic et al. 2006).

There are two UVGI strategies for general application: (1) installation into air handlers and/or ventilating ducts and (2) irradiation of the upper air zones of occupied spaces with shielding of the lower occupied spaces because UV is harmful to room occupants (Reed 2010). Two strategies used in some but not all health-care occupancies are in-room irradiation of unoccupied spaces and of occupied spaces (e.g., operating suites) when personnel have appropriate personal protective equipment (PPE) (NIOSH 2009b).

All UVGI depends on inactivation of viable agents, both in the air and on surfaces, depending on the strategy. ASHRAE (2009) describes effective application of the first two UVGI strategies. For efficacy of in-room irradiation. see, for instance, “Decontamination of Targeted Pathogens from Patient Rooms Using an Automated Ultraviolet-C-Emitting Device” (Anderson et al. 2013).

In both duct-mounted and unoccupied in-room UVGI, the amount of radiation applied can be much higher compared to what can be used for upper-zone UVGI, resulting in higher aerosol exposure and quicker inactivation. Duct-mounted UVGI can be compared to filtration in the central ventilation system, because it inactivates the potentially infectious organisms while filtration removes them. UVGI does not impose a pressure drop burden on the ventilation system.

There is research that shows UVGI in both the upper-room and in-duct configurations can inactivate some disease-transmitting organisms (Riley et al. 1962; Ko et al. 2002; CDC 2005; Kujundzic et al. 2007; VanOsdell and Foarde 2002; Xu et al. 2003, et al. 2005), that it can affect disease transmission rates (McLean 1961), and that it can be safely deployed (Nardell et al. 2008).

Upper-zone UVGI, when effectively applied (ASHRAE 2009; NIOSH 2009a; Miller et al. 2013; Xu et al. 2013), inactivates infectious agents locally and can be considered in public access and high-traffic areas such as cafeterias, waiting rooms, and other public spaces. The fixtures are typically mounted at least 2.1 m (7 ft) above the floor, allowing at least an additional 0.3 m (1 ft) of space above the fixture for decontamination to occur. It is typically recommended when ventilation rates are low.

At air change rates much greater than 6 ach (air changes per hour), there is evidence that upper-room UVGI is less effective relative to particle removal by ventilation. This is thought to be because the particles have less residence exposure time to UV.

In-room UVGI may be performed in patient rooms between successive occupants using elevated levels of irradiation applied in the unoccupied room for a specified length of time. This is primarily a surface disinfectant strategy, though it also disinfects the air that is in the room at the time of irradiation (Anderson et al. 2013; Mahida et al. 2013). Because the UV is turned off before the next patient arrives, it has no continuing effect on the air.

[6] Filter efficiency varies with particle size, so the type of filtration required in order to be effective varies with the type of organism and the aerosol that carries it. ASHRAE Standard 52.2 (ASHRAE 2012b) describes a minimum efficiency reporting value (MERV) for filter efficiency at various particle sizes, and HEPA filtration may not be necessary. Specific personnel safety procedures may be required when changing filters, depending on the types of organisms and other contaminants that have been collected on the used media.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

A strategy of continuous irradiation of the air during surgery has been used, though this is not currently standard practice. When using this strategy, protection of operating room personnel from the UV radiation is advised.

Note that no controlled intervention studies showing the clinical efficacy of all of the above strategies have been conducted, *including dilution ventilation and pressure differential that are required under current practice standards and guidelines*.

If studies can be conducted, they should specifically include occupancies such as jails, homeless shelters, and health-care facilities. Compared to other facilities, these have a higher risk for both infected and susceptible individuals, which results in higher rates of disease transmission, making the impact more measurable and significant. Such research may lead to other recommended changes in HVAC system design. More research is also needed to document intrinsic (specific to microorganism) airborne virus and bacteria inactivation rates. See Table 1 for a summary of occupancy categories in which various strategies may be considered and priorities of research needs.

3.3 Temperature and Humidity

Many HVAC systems can control indoor humidity and temperature, which can in turn influence transmissibility of infectious agents. Although the weight of evidence at this time suggests that controlling relative humidity (RH) can reduce transmission of certain airborne infectious organisms, including some strains of influenza, this PD refrains from making a universal recommendation.

According to Memarzadeh (2011), in a review of 120 papers conducted on the effect of humidity and temperature on the transmission of infectious viruses, numerous researchers suggest that three mechanisms could potentially explain the observed influence of RH on transmission. One possible mechanism is slower evaporation from large droplets influenced by higher humidity that a lower humidity would more rapidly change them into droplet nuclei. Nicas and colleagues (2005) show by modeling that emitted droplets will evaporate to 50% of their initial diameter and that if the initial diameter is <20 μm this process will happen before the droplets fall to a surface. For larger diameters and higher humidity this does not happen quickly enough to change large droplets into droplet nuclei before they fall. Wang et al. (2005) found that people inhaled fewer droplets at a higher RH.

The second possible mechanism is that RH may act at the level of the host. Breathing dry air could cause desiccation of the nasal mucosa, which would in turn render the host more susceptible to respiratory virus infections. The third possible mechanism is that RH may act at the level of the virus particle to affect its virulence.

Yang and Marr (2012b) discuss in a minireview the complexities of the relationship between aerosolized viruses and RH, including multiple hypotheses such as water activity, surface inactivation, and salt toxicity, that may account for the association between humidity and viability of viruses in aerosols. They also propose their own hypothesis that changes in pH (induced by evaporation) within the aerosol compromise the infectivity. They conclude that the precise mechanisms underlying the relationship remain largely unverified; there are still large gaps in the literature, and a complete understanding will require more in-depth studies with collaboration across disciplines.

Memarzadeh (2011) further concludes that there is insufficient evidence to say that maintaining an enclosed environment at a certain temperature and at a certain RH, is likely to reduce the airborne survival and therefore transmission of influenza virus when compared with a similar environment that does not adhere to such tight control of indoor temperature and RH.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

A sample of the findings of numerous individual studies follows.

Schaffer et al. (1976) revealed that viral transmission at low (<40%) and high (>80%) relative humidity was much higher than at medium relative humidity (about 50%).

Lowen et al. (2007) and Shaman and Kohn (2009) conclude that low humidity and low temperature strongly increase influenza transmission between guinea pigs and hypothesize this is caused by rapid formation of droplet nuclei and increased survival of the infectious agent. Lowen suggests that humidification of indoor air (particularly in places, such as nursing homes and emergency rooms, where transmission to those at high risk for complications is likely) may help decrease the spread and the toll of influenza during influenza season.

Yang et al. (2012a) studied the relationship between influenza A virus (IAV) viability over a large range of RH in several media, including human mucus. They found the relationship between viability and RH depends on droplet composition: viability decreased in saline solutions, did not change significantly in solutions supplemented with proteins, and increased dramatically in mucus. Thus, laboratory studies that do not use mucus may yield viability results that do not represent those of human-generated aerosols in the field. Their results also suggest that there exist three regimes of IAV viability defined by three different ranges of RH.

Noti et al. (2013) found that at low relative humidity (23%), influenza retains maximal infectivity (71% to 77%) and that inactivation (infectivity 16% to 22%) of the virus at higher relative humidity (43%) occurs rapidly (60 min) after coughing. This study used manikins and aerosolization in a nebulizer, using a cell culture medium.[7]

Another factor to consider before using higher indoor humidity to reduce airborne disease transmission is that it may interfere with the effectiveness of UVGI. Two studies with *S. marcescens* showed an increased survival in the presence of UV light at higher RH levels. This was suggested to be due to the protective effect of larger particle sizes, as evaporation would be less at these higher RH levels, thus indicating a protective effect of a thicker water coat against UV radiation (Tang 2009). Two other studies also show that UVGI is less effective at higher RH and suggest it is due to a change in DNA conformation (Peccia et al. 2001; Xu et al. 2005).

In addition to the above, there are comfort issues to be considered when selecting indoor temperature and humidity parameters for the operation of buildings. For instance, the optimum temperature to reduce the survival of airborne influenza virus may be above 30°C (86°F) at 50% rh (Tang 2009), which is not usually acceptable for human thermal comfort (ASHRAE 2013a). Furthermore, higher humidity increases the potential for mold and moisture problems (ASHRAE 2013b).

For all of the above reasons, this PD does not make a broad recommendation on indoor temperature and humidity for the purpose of controlling infectious disease. Practitioners may use the information above to make building design and operation decisions on a case-by-case basis.

3.4 Non-HVAC Strategies

Building owners and managers should understand that education and policies, such as allowing and encouraging employees to stay at home when ill, are more effective than any HVAC interventions. Administrative measures such as prompt identification of patients with

[7] Email correspondence with coauthor Linsley on November 22, 2013, explains that the medium used was complete Dulbecco's modified Eagle's medium (CDMEM), which consists of Dulbecco's modified Eagle's medium, 100 U/ml penicillin G, 100 µg/ml streptomycin, 2 mM L-glutamine, 0.2% bovine serum albumin, and 25 mM HEPES buffer.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

influenza-like illness and use of source control (respiratory hygiene[8]) are also important, especially in health-care settings. In some cases, high-efficiency personal protective equipment (e.g., N95 respirators [CDC 2014]) may be considered.

Vaccination, a general public health measure, is efficient and effective for many diseases, in part because it does not rely on facility operation and maintenance. On the other hand, vaccination is sometimes unavailable or insufficiently effective. For example, despite an average effectiveness of 60% to 70% for influenza (Osterholm et al. 2012), effectiveness can decline to as low as 10% in "bad match" years (Belongia et al. 2009). In such a case, HVAC interventions may be more important, even though they are less well understood. For example, recent modeling (Gao et al. 2012) suggests that dilution ventilation can support pandemic management as an essential complement to social distancing and can reduce the necessity of school closures.

For current information on these nonventilation strategies, readers should consult websites maintained by public health and safety authorities, such as the Centers for Disease Control and Prevention (CDC), Department of Homeland Security (DHS), flu.gov, the official influenza website of the U.S. Department of Health and Human Services (USDHHS), and the World Health Organization (WHO) (in particular, www.who.int/influenza/preparedness/en/, WHO 2014).

3.5 Emergency Planning

Four worldwide (pandemic) outbreaks of influenza occurred in the twentieth century: 1918, 1957, 1968, and 2009 (BOMA 2012). Not classified as true pandemics are three notable epidemics: a pseudopandemic in 1947 with low death rates, an epidemic in 1977 that was a pandemic in children, and an abortive epidemic of swine influenza in 1976 that was feared to have pandemic potential. The most recent H1N1 pandemic in 2009 resulted in thousands of deaths worldwide but was nowhere near the death toll of the 1918 Spanish flu, which was the most serious pandemic in recent history and was responsible for the deaths of an estimated more than 50 million people. There have been about three influenza pandemics in each century for the last 300 years. If a new outbreak occurs and is caused by a microorganism that spreads by the airborne route, fast action affecting building operations will be needed.

Some biological agents that may be used in terrorist attacks are addressed elsewhere (USDHHS 2002, 2003).

Engineers can support emergency planning by understanding the design, operations, and maintenance adequacy of buildings for which they are responsible and helping emergency planners mitigate vulnerabilities or develop interventions. For instance, there may be means to increase dilution ventilation, increase relative humidity, or quickly apply upper-room UVGI in an emergency room, transportation waiting area, shelter, jail, and crowded entries to buildings in an emergency, provided that this does not create either (1) flow of air to less contaminated areas or (2) conditions of extreme discomfort. In other situations, curtailing ventilation or creating pressure differentials may be the appropriate strategy. Actions should be thoughtfully undertaken in collaboration with infection control professionals and based on knowledge of the system and its operation and the nature and source of the threat.

[8] Respiratory hygiene includes behavior such as coughing into and disposing of facial tissue or putting masks on ill individuals to prevent dissemination of particles (CDC 2001; Siegel et al. 2007).

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

At the building level, engineers may provide support by (1) identifying vulnerabilities with air intake, wind direction, shielding, etc.; (2) identifying building systems and safe zones in the general building environment; (3) identifying approaches to interrupting air supply to designated "shelter-in-place" locations in general building environments; and 4) identifying cohorting possibilities for pandemic situations so that whole areas of a hospital may be placed under isolation and negative pressure. For guidance, see "Airborne Infectious Disease Management Manual: Methods for Temporary Negative Pressure Isolation" (MDH 2013).

Building operators and engineers should have information about how to contact public health authorities and other emergency planning support (BOMA 2012).

4. RECOMMENDATIONS

Some infectious diseases are transmitted through inhalation of airborne infectious particles, which can be disseminated through buildings by pathways that include ventilation systems. Airborne infectious disease transmission can be reduced using dilution ventilation; directional ventilation; in-room airflow regimes; room pressure differentials; personalized ventilation;[9] and source capture ventilation, filtration, and UVGI.

Engineers play a key role in reducing disease transmission that occurs in buildings. Goal 11 of the ASHRAE Research Strategic Plan for 2010–2015, "Understand Influences of HVAC&R on Airborne Pathogen Transmission in Public Spaces and Develop Effective Control Strategies," recognizes the key role that ASHRAE plays (ASHRAE 2010).

Societal disruption from epidemics and the unexpected transmission of disease in workplaces, public access facilities, and transportation warrants further research on the effectiveness of engineering controls.

ASHRAE recommends the following:

- All facility designs should follow the latest practice standards, including but not limited to ASHRAE Standard 55 for thermal conditions (ASHRAE 2013a); ventilation Standards 62.1 (ASHRAE 2013b), 62.2 (ASHRAE 2013c), and 170 (ASHRAE 2008; and FGI *Guidelines for Design and Construction of Health Care Facilities* (FGI 2010).
- Commissioning, maintenance, and proper operation of buildings, and, in particular, systems intended to control airborne infectious disease, are necessary for buildings and systems to be effective.
- Building designers, owners, and operators should give high priority to enhancing well-designed, installed, commissioned, and maintained HVAC systems with supplemental filtration, UVGI, and, in some cases, to additional or more effective ventilation to the breathing zone. Filtration and UVGI can be applied in new buildings at moderate additional cost and can be applied quickly in existing building systems to decrease the severity of acute disease outbreaks. *Indoor Air Quality Guide* (ASHRAE 2009) contains information about the benefits of and techniques for accomplishing these enhancements.
- New health-care facilities, including key points of entry such as emergency, admission, and waiting rooms; crowded shelters; and similar facilities should incorporate the infrastructure to quickly respond to a pandemic. Such infrastructure might include, for

[9] For the purpose of this PD, personalized ventilation is a mechanical ventilation strategy of supplying air directly to the occupant's breathing zone without mixing it with contaminated room air.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

example, HVAC systems that separate high-risk areas; physical space and HVAC system capacity to upgrade filtration; the ability to increase ventilation even as high as 100% outdoor air; the ability to humidify air; and receptacles at the upper room and ceiling heights of at least 2.4 m (8 ft) to enable effective upper-room UVGI. Once the building is in operation, rapid availability of filter elements and upper-room UV fixtures should be arranged for rapid deployment in an emergency.

- Infection control strategies should always include a bundle of multiple interventions and strategies (not just ventilation).
- Multidisciplinary teams of engineers, building operators, scientists, infection prevention specialists, and epidemiologists should collaborate to identify and implement interventions aimed at mitigation of risk from airborne infectious disease and understand the uncertainty of the effectiveness of current practice recommendations.
- Building operators and engineers have a role to play in planning (BOMA 2012) for infectious disease transmission emergencies.
- Committees that write and maintain practice standards and guidelines for critical environments such as health-care facilities and crowded shelters should consider recent research and understanding of infectious disease control and consider adding or strengthening requirements for the following:
  - Improved particle filtration for central air handlers
  - Upper-room and possibly other UVGI interventions or at least the ceiling heights and electrical infrastructure to quickly deploy them
  - The ability to quickly and temporarily increase the outdoor air ventilation rate in the event of an infectious disease outbreak
  - Avoiding unintended adverse consequences in infectious disease transmission resulting from lower ventilation levels motivated solely by reduced energy consumption
- Airborne infectious disease researchers should receive input on study design, methodology, and execution from many discipline experts (including engineers, infection prevention specialists, health-care epidemiologists, public health officials, and others) to provide a better picture of the interplay between building systems and disease transmission.
- Controlled intervention studies should be conducted to quantify increases or decreases in disease propagation resulting from various ventilation rates.
- Controlled intervention studies should be conducted to quantify the relative airborne infection control performance and cost-effectiveness of specific engineering controls individually and in combination in field applications. Table 1 summarizes the research priority and applicable occupancy categories for each strategy. Studies should include occupancies at high-risk (such as jails, homeless shelters, schools, nursing homes, and health-care facilities).
- Research should quantify rates of airborne removal by filtration and inactivation by UVGI strategies specific to individual microorganisms and should field validate in real facilities the effectiveness of these interventions in preventing transmission.
- Research should be conducted to better characterize the particle size distributions of coughed materials, which are thought to encompass a broad range of diameters.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Table 1 Airborne Infectious Disease Engineering Control Strategies: Occupancy Interventions and Their Priority for Application and Research

Strategy	Occupancy Categories Applicable for Consideration*	Application Priority	Research Priority
Dilution ventilation	All	High	Medium
Temperature and humidity	All except 7 and 11	Medium	High
Personalized ventilation	1, 4, 6, 9, 10, 14	Medium	High
Local exhaust	1, 2, 8, 14	Medium	Medium
Central system filtration	All	High	High
Local air filtration	1, 4, 6, 7, 8 10	Medium	High
Upper-room UVGI	1, 2, 3, 5, 6, 8, 9, 14	High	Highest
Duct and air-handler UVGI	1, 2, 3, 4, 5, 6, 8, 9, 14	Medium	Highest
In-room flow regimes	1, 6, 8, 9, 10, 14	High	High
Differential pressurization	1, 2, 7, 8 11, 14	High	High

Note: In practical application, a combination of the individual interventions will be more effective than any single one in isolation.
*Occupancy Categories:

1. Health care (residential and outpatient)
2. Correctional facilities
3. Educational < age 8
4. Educational > age 8
5. Food and beverage
6. Internet café/game rooms
7. Hotel, motel, dormitory
8. Residential shelters
9. Public assembly and waiting
10. Transportation conveyances
11. Residential multifamily
12. Retail
13. Sports
14. Laboratories where infectious diseases vectors are handled

5. REFERENCES

Aliabadi, A.A., S.N. Rogak, K.H. Bartlett, and S.I. Green. 2011. Preventing airborne disease transmission: Review of methods for ventilation design in health care facilities. *Advances in Preventive Medicine*. Article ID 12406.

Anderson, D.J., M.F. Gergen, E. Smathers, D.J. Sexton, L.F. Chen, D.J. Weber, W.A. Rutala. 2013. Decontamination of targeted pathogens from patient rooms using an automated ultraviolet-C-emitting device. *Infection Control and Hospital Epidemiology* 34(5):466–71.

Apisarnthanarak, A., P. Apisarnthanarak, B. Cheevakumjorn, and L. M. Mundy. 2009. Intervention with an infection control bundle to reduce transmission of influenza-like illnesses in a Thai preschool. *Infection Control and Hospital Epidemiology* September 30(9):817–22. doi: 10.1086/599773.

Apisarnthanarak, A., P. Apisarnthanarak, B. Cheevakumjorn, and L. M. Mundy. 2010a. Implementation of an infection control bundle in a school to reduce transmission of influenza-like illness during the novel influenza A 2009 H1N1 pandemic. *Infection Control and Hospital Epidemiology* March, 31(3):310–1. doi: 10.1086/651063.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Apisarnthanarak, A., T.M. Uyeki, P. Puthavathana, R. Kitphati, and L.M. Mundy. 2010b. Reduction of seasonal influenza transmission among healthcare workers in an intensive care unit: A 4-year intervention study in Thailand. *Infection Control and Hospital Epidemiology* October, 31(10):996–1003. doi: 10.1086/656565.

ASHRAE. 2000. ASHRAE Guideline 12-2000, *Minimizing the Risk of Legionellosis Associated With Building Water Systems*. Atlanta: ASHRAE.

ASHRAE. 2008. ANSI/ASHRAE/ASHE Standard 170-2008*, Ventilation of Health-Care Facilities*. Atlanta: ASHRAE.

ASHRAE. 2009. *Indoor Air Quality Guide: Best Practices for Design, Construction and Commissioning*. Atlanta: ASHRAE.

ASHRAE. 2010. ASHRAE 2010–2015 Research Strategic Plan. www.ashrae.org/standards-research--technology/research. Atlanta: ASHRAE.

ASHRAE. 2012a. *Legionellosis*, Position Document. Atlanta: ASHRAE.

ASHRAE. 2012b. ASHRAE Standard 52.2-2012, *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*. Atlanta: ASHRAE.

ASHRAE. 2013a. ASHRAE Standard 55-2013, *Thermal Environmental Conditions for Human Occupancy*. Atlanta: ASHRAE.

ASHRAE. 2013b. ANSI/ASHRAE Standard 62.1-2013, *Ventilation for Acceptable Indoor Air Quality*. Atlanta: ASHRAE.

ASHRAE. 2013c. ANSI/ASHRAE Standard 62.2-2013, *Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings*. Atlanta: ASHRAE.

ASHRAE. 2013d. *Minimizing Indoor Mold Problems through Management of Moisture in Building Systems*, Position Document. Atlanta: ASHRAE.

Azimi, P. and B. Stephens. 2013. HVAC filtration for controlling infectious airborne disease transmission in indoor environments: Predicting risk reductions and operational costs. *Building and Environment* 70:150e160.

Belongia, E.A., B.A. Kieke, J.G. Donahue, R.T. Greenlee, A. Balish, A. Foust, S. Lindstrom, D.K. Shay. 2009. Marshfield Influenza Study Group. Effectiveness of inactivated influenza vaccines varied substantially with antigenic match from the 2004–2005 season to the 2006–2007 season. *Journal of Infectious Diseases*, January, 15;199(2):159–67. doi: 10.1086/595861.

Bischoff, W.E., K. Swett, I. Leng, T.R. Peters. 2013.Exposure to influenza virus aerosols during routine patient care. *Journal of Infectious Diseases* 207(7):1037–46. doi: 10.1093/infdis/jis773. Epub 2013, Jan 30.

BOMA. 2012. *Emergency Preparedness Guidebook: The Property Professional's Resource for Developing Emergency Plans for Natural and Human-Based Threats*. Washington, DC: Building Owners and Managers Association International.

Brankston, G., L. Gitterman, Z. Hirji, C. Lemieux, and M. Gardam. 2007. Transmission of influenza A in human beings. *Lancet Infectious Disease* 7:257–65.

Catanzaro, A. 1982. Nosocomial Tuberculosis. *American Review of Respiratory Diseases.* 125:559–62.

CDC. 2001. Recognition of illness associated with the intentional release of a biologic agent. *Journal of the American Medical Association* 286:2088–90. Centers for Disease Control and Prevention.

CDC. 2003. *Guidelines for Environmental Infection Control in Health-Care Facilities*. Atlanta: Center for Disease Control and Prevention.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

CDC. 2005. Guidelines for Preventing the Transmission of *Mycobacterium Tuberculosis* in Health-Care Settings. *Morbidity and Mortality Weekly Report* (MMWR), 54 (No. RR-17):1–140. Atlanta: Centers for Disease Control and Prevention.

CDC. 2014. NIOSH-approved N95 particulate filtering facepiece respirators. www.cdc.gov /niosh/npptl/topics/respirators/disp_part/n95list1.html.

Cermak, R., A.K. Melikov, Lubos Forejt, and Oldrich Kovar. 2006. Performance of personalized ventilation in conjunction with mixing and displacement ventilation. *HVAC&R Research* 12(2):295–311.

Cheng, V.C., J.W. Tai, L.M. Wong, J.F. Chan, I.W. Li, K.K. To, I.F. Hung, K.H. Chan, P.L. Ho, and K.Y. Yuen. 2010. Prevention of nosocomial transmission of swine-origin pandemic influenza virus A/H1N1 by infection control bundle. *Journal of Hospital Infection* March, 74(3):271–7. doi: 10.1016/j.jhin.2009.09.009. Epub 2010 Jan 12.

Chu, C.M., V.C. Cheng, I.F. Hung, K.S. Chan, B.S. Tang, T.H. Tsang, K.H. Chan, and K.Y. Yuen. 2005. Viral load distribution in SARS outbreak. *Emerging Infectious Diseases* December, 11(12):1882–6.

Cole, E.C., and C.E. Cook. 1998. Characterization of infectious aerosols in health care facilities: an aid to effective engineering controls and preventive strategies. *American Journal of Infection Control* 26(4):453–64.

D'Alessio, D.J., C.K. Meschievitz, J.A. Peterson, C.R. Dick, and E.C. Dick. 1984. Short-duration exposure and the transmission of rhinoviral colds. *Journal of Infectious Diseases* August 150(2):189–94.

Dick, E.C., C.R. Blumer, and A.S. Evans. 1967. Epidemiology of infections with rhinovirus types 43 and 55 in a group of University of Wisconsin student families. *American Journal of Epidemiology* September, 86(2):386–400.

Dick, E.C., L.C. Jennings, K.A. Mink, C.D. Wartgow, and S.L. Inhorn. 1987. Aerosol transmission of rhinovirus colds. *Journal of Infectious Diseases* 156:442–8.

Duguid, J.P. 1946. The size and duration of air-carriage of respiratory droplets and droplet nucleii. *The Journal of Hygiene* (London) 44:471–79.

Fennelly, K.P., J.W. Martyny, K.E. Fulton, I.M. Orme, D.M. Cave, and L.B. Heifets. 2004. Cough-generated aerosols of *Mycobacterium Tuberculosis*: A new method to study infectiousness. *American Journal of Respiratory and Critical Care Medicine* 169:604–609.

FGI. 2010. *2010 Guidelines for Design and Construction of Health Care Facilities*. Dallas: Facility Guidelines Institute.

Fusco, F.M., S. Schilling, G. De Iaco, H.R. Brodt, P. Brouqui, H.C. Maltezou, B. Bannister, R. Gottschalk, G. Thomson, V. Puro, and G. Ippolito. 2012. Infection control management of patients with suspected highly infectious diseases in emergency departments: Data from a survey in 41 facilities in 14 European countries. *BMC Infectious Diseases* January 28:12:27.

Gao, X., Y. Li, P. Xu, and B.J. Cowling. 2012. Evaluation of intervention strategies in schools including ventilation for influenza transmission control. *Building Simulation* 5(1):29, 37.

Gwaltney, J., and J.O. Hendley. 1978. Rhinovirus transmission: One if by air, two if by hand. *American Journal of Epidemiology* May,107(5):357–61.

Han, K., X. Zhu, F. He, L. Liu, L. Zhang, H. Ma, X. Tang, T. Huang, G. Zeng, and B.P. Zhu. 2009. Lack of airborne transmission during outbreak of pandemic (H1N1) 2009 among tour group members, China, June 2009. *Emerging Infectious Diseases* October, 15(10):1578–81.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Hoge, C.W., M.R. Reichler, E.A. Dominguez, J.C. Bremer, T.D. Mastro, K.A. Hendricks, D.M. Musher, J.A. Elliott, R.R. Facklam, and R.F. Breiman. 1994. An epidemic of pneumococcal disease in an overcrowded, inadequately ventilated jail. *New England Journal of Medicine* 331(10):643–8.

Klontz, K.C., N.A. Hynes, R.A. Gunn, M.H. Wilder, M.W. Harmon, and A.P. Kendal. 1989. An outbreak of influenza A/Taiwan/1/86 (H1N1) infections at a naval base and its association with airplane travel. *American Journal of Epidemiology* 129:341–48.

Ko, G., M.W. First, and H.A. Burge. 2002. The Characterization of upper-room ultraviolet germicidal irradiation in inactivating airborne microorganisms. *Environmental Health Perspectives* 110:95–101.

Kujundzic, E., F. Matalkah, D.J. Howard, M. Hernandez, and S.L. Miller. 2006. Air cleaners and upper-room air UV germicidal irradiation for controlling airborne bacteria and fungal spores. *Journal of Occupational and Environmental Hygiene* 3:536–46.

Kujundzic, E., M. Hernandez, and S.L. Miller. 2007. Ultraviolet germicidal irradiation inactivation of airborne fungal spores and bacteria in upper-room air and in-duct configurations. *Journal of Environmental Engineering and Science* 6:1–9.

Li, Y., H. Qian, I.T.S. Yu, and T.W. Wong. 2005a. Probable roles of bio-aerosol dispersion in the SARS outbreak in Amoy Gardens, Hong Kong. Chapter 16. *Population Dynamics and Infectious Disease in the Asia-Pacific*. Singapore: World Scientific Publishing.

Li, Y., X. Huang, I.T.S. Yu, T.W. Wong and H. Qian. 2005b. Role of air distribution in SARS transmission during the largest nosocomial outbreak in Hong Kong. *Indoor Air* 15:83–95.

Li, Y., G.M. Leung, J.W. Tang, X. Yang, C.Y.H. Chao, J.Z. Lin, J.W. Lu, P.V. Nielsen, J. Niu, H. Qian, A.C. Sleigh, H-J. J. Su, J. Sundell, T.W. Wong, and P.L. Yuen. 2007. Role of ventilation in airborne transmission of infectious agents in the built environment—A multidisciplinary systematic review. *Indoor Air* 17(1):2–18.

Li, Y. 2011. The secret behind the mask. (Editorial.) *Indoor Air* 21(2):89–91.

Lowen, A.C., S. Mubareka, J. Steel, and P. Palese. 2007. Influenza virus transmission is dependent on relative humidity and temperature. *PLOS Pathogens* 3:1470–6.

Mahida, N., N. Vaughan, and T. Boswell. 2013. First UK evaluation of an automated ultraviolet-C room decontamination device (Tru-D™), *Journal of Hospital Infection*. http://dx.doi.org/10.1016/j.jhin.2013.05.005.

Mandell, G. 2010. *Mandell, Douglas, and Bennett's Principles and Practice of Infectious Diseases E-Book,* 7th Edition, Churchill Livingstone Elsevier.

McLean, R.L. 1961. The effect of ultraviolet radiation upon the transmission of epidemic influenza in long-term hospital patients. *American Review of Respiratory Diseases* 83(2): 36–8.

MDH. 2013. Airborne infectious disease management manual: Methods for temporary negative pressure isolation. Minnesota Department of Health. Available at www.health.state.mn.us/oep/training/bhpp/airbornenegative.pdf. Accessed September 13, 2013.

Memarzadeh, Farhad, Russell N. Olmsted, and Judene M. Bartley. 2010. Applications of ultraviolet germicidal irradiation disinfection in health care facilities: Effective adjunct, but not stand-alone technology. *American Journal of Infection Control* 38:S13–24.

Memarzadeh, Farhad. 2011. Literature review of the effect of temperature and humidity on viruses. *ASHRAE Transactions* 117(2).

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Miller, S.L., J. Linnes, and J. Luongo. 2013. Ultraviolet germicidal irradiation: Future directions for air disinfection and building applications. *Photochemistry and Photobiology* 89:777–81.

Miller-Leiden, S., C. Lobascio, J.M. Macher, and W.W. Nazaroff. 1996. Effectiveness of in-room air filtration for tuberculosis control in healthcare settings. *Journal of the Air & Waste Management Association* 46:869–82.

Moser, M.R., T.R. Bender, H.S. Margolis, G.R. Noble, A.P. Kendal and D.G. Ritter. 1979. An outbreak of influenza aboard a commercial airliner. *American Journal of Epidemiology* 110(1):1–6.

Myatt, T.A., S.L. Johnston, Z. Zuo, M. Wand, T. Kebadze, S. Rudnick, and D.K. Milton. 2004. Detection of airborne rhinovirus and its relation to outdoor air supply in office environments. *American Journal of Respiratory and Critical Care Medicine* 169:1187–90.

Nardell, E.A., S.J. Bucher, P.W. Brickner, C. Wang, R.L. Vincent, K. Becan-McBride, M.A. James, M. Michael, and J.D. Wright. 2008. Safety of Upper-Room Ultraviolet Germicidal Air Disinfection for Room Occupants: Results from the Tuberculosis Ultraviolet Shelter Study. *Public Health Reports Volume* 123:52-60.

S.J. Bucher, P.W. Brickner, C. Wang, R.L. Vincent, K. Becan-McBride, M.A. James, M. Michael, and J.D. Wright. 2008. Safety of upper-room ultraviolet germicidal air disinfection for room occupants: Results from the tuberculosis ultraviolet shelter study. *Public Health Reports* 123:52–60.

Nicas M, W.W. Nazaroff, and A. Hubbard. 2005. Toward understanding the risk of secondary airborne infection: Emission of respirable pathogens. *Journal of Occupational and Environmental Hygiene* 2:143–54.

Nicas, M., and R.M. Jones. 2009. Relative contributions of four exposure pathways to influenza infection risk. *Risk Analysis* 29:1292–303.

NIOSH. 2009a. *Environmental Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings*. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

NIOSH. 2009b. Health hazard evaluation report: UV-C exposure and health effects in surgical suite personnel, Boston, MA. By D. Sylvain, and L. Tapp. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, NIOSH HETA No. 2007-0257-3082.

Noti J.D., F.M. Blachere, C.M. McMillen, W.G. Lindsley, M.L. Kashon, D.R. Slaughter, and D.H. Beezhold. 2013. High humidity leads to loss of infectious influenza virus from simulated coughs. *PLOS ONE* 8(2):e57485.

OSHA. 1999. *OSHA Technical Manual*. Washington, DC: Occupational Safety & Health Administration.

Osterholm M.T., N.S. Kelley, A. Sommer, and E.A. Belongia. 2012. Efficacy and effectiveness of influenza vaccines: A systematic review and meta-analysis. *Lancet Infectious Diseases* January, 12(1):36–44. doi: 10.1016/S1473-3099(11)70295-X. Epub 2011 October 25.

Peccia, J., H. Werth, S. L. Miller, and M. Hernandez. 2001. Effects of relative humidity on the ultraviolet-induced inactivation of airborne bacteria. *Aerosol Science & Technology* 35:728–40.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

Reed, N.G. 2010. The history of ultraviolet germicidal irradiation for air disinfection. *Public Health Reports* January–February, 125(1):15–27.

Riley, R.L., C.C. Mills, F. O'Grady, L.U. Sultan, F. Wittestadt, and D.N. Shivpuri. 1962. Infectiousness of air from a tuberculosis ward—Ultraviolet irradiation of infected air: Comparative infectiousness of different patients. *American Review of Respiratory Diseases* 85:511–25.

Riley, R.L., and E.A. Nardell. 1989. Clearing the air: The theory and application of ultraviolet air disinfection. *American Review of Respiratory Diseases* 139(5):1286–94.

Riley, E.C., G. Murphy, and R.L. Riley. 1978. Airborne spread of measles in a suburban elementary school. *American Journal of Epidemiology* 107:421–32.

Roy, C.J., and D.K. Milton. 2004. Airborne transmission of communicable infection—The elusive pathway. *New England Journal of Medicine* 350:17.

SA Health. 2013. *Guidelines for Control of Legionella in Manufactured Water Systems in South Australia*. Rundle Mall, South Australia: SA Health.

Schaffer, F.L., M.E. Soergel, and D.C. Straube. 1976. Survival of airborne influenza virus: Effects of propagating host, relative humidity, and composition of spray fluids. *Archives of Virology* 51:263–73.

Sekhar, S.C., N. Gong, K.W. Tham, K.W. Cheong, A.K. Melikov, D.P. Wyon, and P.O. Fanger. 2005. Findings of personalised ventilation studies in a hot and humid climate. *HVAC&R Research* 11(4):603–20.

Shaman, J., and M. Kohn. 2009. Absolute humidity modulates influenza survival, transmission, and seasonality. *Proceedings of the National Academy of Sciences* 106(0):3243–48.

Siegel J.D., E. Rhinehart, M. Jackson, and L. Chiarello. 2007. *2007 Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Healthcare Settings.* Atlanta: Centers for Disease Control and Prevention, The Healthcare Infection Control Practices Advisory Committee.

Subhash, S.S., G. Baracco, K.P. Fennelly, M. Hodgson, and L.J. Radonovich, Jr. 2013. Isolation anterooms: Important components of airborne infection control. *American Journal of Infection Control* May, 41(5):452–5. doi: 10.1016/j.ajic.2012.06.004. Epub 2012, October 2.

Sun Y., Z. Wang, Y. Zhang, and J. Sundell. 2011. In China, students in crowded dormitories with a low ventilation rate have more common colds: Evidence for airborne transmission. *PLOS ONE* 6(11):e27140.

Tang J.W., Y. Li, I. Eames, P.K.S. Chan, and G.L. Ridgway. 2006. Factors involved in the aerosol transmission of infection and control of ventilation in healthcare premises. *Journal of Hospital Infection* 64(2):100–14.

Tang, J.W. 2009. The effect of environmental parameters on the survival of airborne infectious agents. *Journal of the Royal Society Interface* 6:S737–S746.

Tellier, R. 2006. Review of aerosol transmission of influenza a virus. *Emerging Infectious Disease*12(11):1657–62.

USDHHS. 2002. *Guidance for Protecting Building Environments from Airborne Chemical, Biological, or Radiological Attacks*. NIOSH Publication No. 2002-139, May. Washington, DC: United States Department of Health and Human Services.

USDHHS. 2003. Guidance for Filtration and Air-Cleaning Systems to Protect Building Environments from Airborne Chemical, Biological, or Radiological Attacks NIOSH Publication No. 2003-136. Washington, DC: United States Department of Health and Human Services.

© 2014 ASHRAE (www.ashrae.org). For personal use only. Additional reproduction, distribution, or transmission in either print or digital form is not permitted without ASHRAE's prior written permission.

VanOsdell, D., and K. Foarde. 2002. *Defining the Effectiveness of UV Lamps Installed in Circulating Air Ductwork—Final Report*. Air-Conditioning and Refrigeration Technology Institute, Arlington, Virginia.

Wainwright, C.E., M.W. Frances, P. O'Rourke, S. Anuj, T.J. Kidd, M.D. Nissen, T.P. Sloots, C. Coulter, Z. Ristovski, M. Hargreaves, B.R. Rose, C. Harbour, S.C, Bell, and K.P. Fennelly. 2009. Cough-generated aerosols of *Pseudomonas aeruginosa* and other Gram-negative bacteria from patients with cystic fibrosis. *Thorax* 64:926–31.

Wang, B., A. Zhang, J.L. Sun, H. Liu, J. Hu, and L.X. Xu. 2005. Study of SARS transmission via liquid droplets in air. *Journal of Biomechanical Engineering* 127:32–8.

Wat, D. 2004. The common cold: A review of the literature. *European Journal of Internal Medicine* 15:79– 88.

Wells, W.F. 1955. *Airborne Contagion and Air Hygiene*. Cambridge: Harvard University Press, 191.

WHO. 2007. *Legionella and the prevention of Legionellosis*. Geneva: World Health Organization 2007. Available at www.who.int/water_sanitation_health/emerging/legionella/en/.

WHO. 2009. *Natural ventilation for infection control in health-care settings*. World Health Organization: Geneva, Switzerland.

WHO. 2014. Influenza: Public health preparedness. www.who.int/influenza/preparedness/en/.

Wong, B.X., N. Lee, Y. Li, P.X. Chan, H. Qiu, Z. Luo, R.X. Lai, K.X. Ngai, D.X. Hui, K.X. Choi, I.X. Yu. 2010. Possible role of aerosol transmission in a hospital outbreak of influenza. *Clinical Infectious Diseases* 51(10):1176–83.

Xie, X., Y. Li, A.T.Y. Chwang, P.L. Ho, and H. Seto. 2007. How far droplets can move in indoor environments—Revisiting the Wells evaporation-falling curve. *Indoor Air* 17:211–25.

Xie, X.J., Y.G. Li, H.Q. Sun, and L. Liu. 2009. Exhaled droplets due to talking and coughing. *Journal of The Royal Society Interface* 6:S703–S714.

Xu, P., J. Peccia, P. Fabian, J.W. Martyny, K. Fennelly, M. Hernandez, and S.L. Miller. 2003. Efficacy of ultraviolet germicidal irradiation of upper-room air in inactivating bacterial spores and mycobacteria in full-scale studies. *Atmospheric Environment* 37:405–19.

Xu, P., E. Kujundzic, J. Peccia, M.P. Schafer, G. Moss, M. Hernandez, and S.L. Miller. 2005. Impact of environmental factors on efficacy of upper-room air ultraviolet germicidal irradiation for inactivating airborne mycobacteria. *Environmental Science & Technology* 39:9656–64.

Xu, P., N. Fisher, and S.L. Miller. 2013. Using computational fluid dynamics modeling to evaluate the design of hospital ultraviolet germicidal irradiation systems for inactivating airborne mycobacteria. *Photochemistry and Photobiology* 89(4):792–8.

Yang, J., C. Sekhar, D. Cheong Kok Wai, and B. Raphael. 2013. CFD study and evaluation of different personalized exhaust devices. *HVAC&R Research*.

Yang, W., S. Elankumaran, and L.C. Marr. 2012a. Relationship between humidity and influenza a viability in droplets and implications for influenza's seasonality. *PLOS ONE* 7(10):e46789. doi:10.1371/journal.pone.0046789.

Yang, W., and L. Marr. 2012b. Mechanisms by which ambient humidity may affect viruses in aerosols. *Applied and Environmental Microbiology* 78(19):6781. DOI: 10.1128/AEM.01658-12.

Yu, I.T., Y. Li, T.W. Wong, W. Tam, A.T. Chan, J.H. Lee, D.Y. Leung, and T. Ho. 2004. Evidence of Airborne Transmission of the Severe Acute Respiratory.