ASHE Monograph

The Environment of Care and Health Care-Associated Infections

An Engineering Perspective

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1 Introduction

Indoor air quality (IAQ) is one of the most important environmental health problems, according to the U.S. Environmental Protection Agency (EPA). Unhealthy IAQ is caused by poor or inadequate ventilation and exposure to one or more contaminant sources in a building. Because of the population they serve, health care facilities pose a unique set of conditions related to indoor air quality that require particular attention from those responsible for infection prevention efforts, both clinical and engineering.

A significant portion of the occupants in a health care facility are patients who have preexisting health problems and are more likely than the general population to have depressed immune systems. This fact increases the susceptibility of these patients to building-related illnesses and exposure to airborne microorganisms. Complicating a patient's vulnerability is direct and indirect exposure to communicable disease agents, which can result if visitors, family, or health care personnel do not take proper precautions such as hand or respiratory hygiene when in contact with the susceptible patient. People with a potentially infectious illness in a facility who talk, sneeze, cough, or touch surfaces with contaminated hands may be a source of these disease agents, especially if they are in direct contact with patients or produce short-range aerosols within 6 feet of a susceptible patient or coworker. Health care personnel are periodically evaluated for obligate airborne-transmitted

disease (e.g., TB) to mitigate transmission from personnel to patient. For other obligate or preferential airborne microbes (e.g., measles and chicken pox), immunizations can largely prevent health care personnel from serving as a source of exposure.

Building ventilation systems help prevent building-associated illness by diluting and removing unknown airborne microbial contaminants from indoor air. In a health care facility, ventilation systems are also used to isolate patients who may have airborne or droplet-transmissible infectious diseases (e.g., pneumonia and influenza) if these diseases are suspected or confirmed. Early identification of such illness is critical but often missed or delayed. As a result, the patient with a potentially communicable disease may be transported through hospital corridors or to diagnostic procedure labs before being placed under isolation precautions.

Another significant source of patient exposure to communicable diseases is health care personnel. Health care personnel make multiple contacts with undiagnosed patients before they are recognized as infectious. Health care facilities train staff to use standard precautions with all patients, understanding that all are potentially infectious. Hand-washing is recognized by the Centers for Disease Control Prevention (CDC) as the single most important procedure in infection control, and health care personnel use hand hygiene and personal protective equipment (PPE) as appropriate for evident symptoms. Despite common acceptance and use of these procedures, studies and reports indicate that lack of or improper hand hygiene still contributes significantly to disease transmission (Global Consensus Conf. 1999). There are many reasons for this. One is hand-washing sinks or PPE that are not placed conveniently near the exits of patient rooms. Another is that, although most infections contracted in health care facilities are associated with insertion and care of medical devices that result in direct contact with mucous membranes or sterile tissue, more invasive procedures are being performed in non-sterile environments (e.g., imaging labs) not designed for performing sterile procedures.

Design features can be used to address the vulnerability of buildings that house ill patients and healthy staff in an environment where they may be exposed to many infectious agents.

Engineers and practitioners in the health care field are faced with a dilemma—to provide design features that address building vulnerability in the context of an unusually high concentration of people vulnerable to infectious disease alongside others who, though not as vulnerable, are exposed to many more infectious agents than are found in a non-health care setting. Although HVAC engineers are primarily concerned with problems that are "airborne" and thus carried with the building air currents and possibly as a result of the

ventilation system, other means of transmitting infectious agents can be controlled or reduced by other engineering and/or architectural considerations.

Traditionally, nosocomial infections have been referred to as those that develop 48 or more hours after admission to a health care facility. However, shorter hospital stays have suggested the more precise term is health care-associated infection (HAI), which means initial exposure likely occurred in a health care facility but the illness may manifest weeks or even months later. For the most part, this paper will refer to HAIs since the circumstances for transmission of contaminants in all health care settings, including hospitals, are generally analogous. Although most microorganisms are not harmful to humans (in fact, many are necessary in our bodies for our well-being, such as *E. coli*), risk factors may exist in an individual that make that person more vulnerable to contracting a disease. Risk factors for HAIs are not a direct cause of the disease, but appear to be associated in some way with infection. The presence of a risk factor for an HAI increases an individual's chances of contracting a condition, but does not always lead to an HAI. As well, the absence of any single risk factor or the presence of a protective factor does not necessarily guard against contracting an HAI.

The national initiative to prevent HAIs has evolved into a multidisciplinary science that requires a multidisciplinary approach. Successful application of preventive measures that will reduce transmission of infectious organisms to susceptible humans in a health care setting requires an in-depth understanding of causative agents, symptoms, particle dynamics, modes of transmission, the built environment, and engineering strategies. It also requires a close alliance and communication among infection preventionists, microbiologists, physicians, epidemiologists, engineers, industrial hygienists, architects, other planning and design professionals, members of the patient care team, and other health care personnel.

Three factors are important to consider in assessing infection control measures with respect to health care ventilation systems (Riley 2002):

1. **Presence of at-risk patients:** Health care facilities house many persons with heightened susceptibility to infections, respiratory distress, and other problems associated with airborne contaminants. Examples of populations at risk include:

    a. Induction therapy patients and others who are severely immunocompromised due to underlying diseases or medications that suppress immune function.

b. Surgical patients

c. Neonatal intensive care patients (e.g., neonates and premature infants)

d. Solid organ transplant and hemopoietic stem cell transplant (HSCT) patients (CDC 2003b)

e. Burn patients

f. Orthopedic surgery patients

g. Intensive care patients

2. **Occupant density of high-acuity patients:** The density of patients with acuity in a health care setting is relatively high; therefore, at-risk patients may be in close proximity to infectious individuals.

   a. Emergency rooms, particularly waiting room areas, present a risk of infection transmission to susceptible patients.

   b. Multiple patients per room increase the risk of disease transmission.

3. **Compromised condition of mechanical systems:** Health care facilities function around the clock every day of the year. This results in some of the most intense use of almost any building occupancy. In addition, many mechanical systems in hospitals are aging. Their ventilation systems are outdated and in serious need of maintenance and repair, making it possible for them to serve as reservoirs for microorganisms.

More research is needed to improve understanding of which parts of the built environment are most likely to transmit infectious disease.

Scientifically supported recommendations to improve the control of airborne infections in the design and construction of health care facilities are needed. In particular, more research is needed to improve understanding of areas of the built environment with the greatest potential for transmission of infectious disease. In the case of viruses, many infections can be prevented by immunization, leading to a significant change in the epidemiology of a virus. These include pathogens primarily transmitted via air (e.g., measles and varicella zoster virus, or chicken pox) as well as other viral and bacterial infections transmitted by large droplets (e.g., mumps, bacterial meningitis, and pertussis). Before the development of vaccines, very few controlled human-to-human viral transmission studies implicated specific organisms

under specific environmental conditions with results that could be universally applied across a range of areas in a health care facility. In most cases, observational and epidemiological human studies are difficult to interpret due to the many confounding factors inherent in the study design, including these:

- Differences in interpretations of definitions;
- Design parameter variability;
- Artificial conditions that may or may not be applicable to infectious transmission in a real-life setting;
- Lack of controls;
- Inability to identify an index case; and
- Incomplete or unavailable data.

Most studies do not account for the time patients spent in the space in relation to the environmental conditions or the exposure quantity (dose) necessary to cause infection. Added to all the unknowns is that not every exposure necessarily results in a symptomatic infection or an asymptomatic infection that could result in a "carrier" situation (one leading to later infections of other susceptible individuals). As well, the data from uncontrolled observational studies have the potential for observation bias, confounding, co-intervention, or chance variation (Brankston et al. 2007).

A significant body of data is available on the transmission of tuberculosis (TB). In general, the results of studies on the survival of bacteria are more difficult to interpret than those for viruses because bacteria tend to be more sensitive to the methods of aerosolization, collection, and culture, making it difficult to assess the viability of airborne bacteria in response to different environmental conditions (Cox 1989, 1998).

Factors that affect the viability and infectivity of a microorganism include its composition, the effects of aerosol particle dynamics, and the variables inherent in the host.

It is easy to see the complexity of disease transmission from the variety of factors that affect the viability and infectivity of a microorganism. An understanding of the basic composition of microorganisms, the role aerosol particle dynamics plays, and the variables inherent in the host is important to put the effect of biological, environmental, and physical parameters in context.

As shall be noted further in this paper, the evidence clearly shows that no single factor is responsible for the spread of infectious disease, regardless

The variety of factors that can affect the spread of infectious disease makes risk assessment important when planning a health care facility project.

of which offending microorganism is being considered. Among the many factors involved in the spread of infectious disease are aerosol and droplet transmission dynamics; the nature of dust levels; the health and condition of an individual's nasopharyngeal mucosal linings; patient susceptibility; the population density in a particular location; the ventilation, temperature, and humidity of the area in the health care facility; and the geographic location of the facility.

Because of the variety of factors that can affect the spread of infectious disease, it is important to perform a risk assessment and develop a risk management plan when planning new health care facility construction or renovation of portions of an existing facility or when reviewing existing infrastructure. The risk assessment and the risk management plan should take into account the type of facility or areas of the facility being assessed (e.g., building, room, suite of rooms, floor, etc.) in making recommendations to alter any single variable—whether physical, environmental, or epidemiologic—to accommodate the function of that designated space. It is not always cost-effective to provide enhanced physical measures to reduce HAIs or to plan a response to the possible health effects of a bioweapons attack. This is particularly true in an existing facility or a small community facility where the age or design of the infrastructure may not be suited to major updates or where the patient traffic and census are low. However, in the design of a new facility or in a densely populated region that may be at higher risk of person-to-person contact, it is worth considering design options in which first costs might provide a variety of long-term savings.

2 The Importance of Risk Management

A risk management guidance report from the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2003) defines *risk assessment and management* as "a systematic approach to the discovery and treatment of risks facing an organization or facility. The goal is to help objectively state, document, and rank risk and prepare a plan for implementation." Risk management techniques are used to identify appropriate countermeasures, options, or alternatives to counteract identified risks for a particular actual or anticipated situation.

Although much information is available on how to conduct a risk assessment, certain general steps should be part of any risk assessment (ASHRAE 2003):

1. Identify the risk.
2. Estimate the level of exposure.
3. Estimate the probability that the identified risks will occur.
4. Determine the value of the loss.
5. Rank the identified risks.
6. Identify vulnerabilities.

The approach to risk assessment outlined in the Facility Guideline Institute's *Guidelines for Design and Construction of Health Care Facilities* is required by states that adopt or adapt the *Guidelines* for regulatory purposes as well as by the Joint Commission for states that do not have codes governing health care design and construction. This approach to infection prevention and environmental control, which requires performance of an infection control risk assessment (ICRA), considers both the susceptibility of patients and health care personnel and the degree of environmental contamination. An ICRA supports communication between clinical and facility staff and includes both design and remediation issues to protect patients and staff in both the long and the short term. Design strategies that respond to *infection prevention and control* risks include consideration of the patient population served, the range and complexity of services provided, and the settings in which care is provided. Other variables include patient status (e.g., infectious or susceptible), area under consideration (e.g., isolation or protective environment), type of filtration, ventilation and pressurization, and operations and maintenance procedures and management in place. Design strategies that respond to risks from *environmental controls* include the use of personal protective equipment for health care personnel, the type of isolation necessary (e.g., protective or containment), and the ventilation standards that apply to the type of facility being assessed. (Kosar 2002)

In an infection control risk assessment, the degree of environmental contamination and the susceptibility of patients and health care personnel are considered.

Involvement of professionals from the medical and building sciences, including architects, engineers, epidemiologists, and industrial hygienists and infection preventionists, is required to provide effective IAQ practices in health care facilities. Acceptable IAQ can be achieved by using ventilation in conjunction with air filtration of recirculated and fresh air, mechanical arrestance media to clean air of microbial and other particulate matter, and ultraviolet germicidal irradiation (UVGI) in targeted applications to alter airborne and surface-borne microbes and limit the proliferation of infectious agents.

Multidisciplinary professional involvement is needed to achieve effective IAQ practices.

The role that environmental factors, such as air temperature and relative humidity (RH), play in surface survival of infectious agents is important for risk assessment and the development of infection prevention measures. In an attempt to control environmental factors in the health care environment, a balance must be found between reducing infectious disease transmissibility and maintaining occupant comfort.

3 Emerging Diseases

As long as microorganisms are capable of rapid replication, mutation, and adaptation to their environment, the human community will be plagued by emerging diseases. An emerging infectious disease is one that has newly appeared in the population, or has existed in the past and is rapidly increasing in incidence or geographic range. Although occurrences of these diseases may appear without explanation, they rarely appear without reason (Morse 1995). Emerging infections and antibiotic-resistant strains of common bacterial pathogens usually spread from a geographic location of origin to a new location (Soares 1993). The infectious agent may be carried by environmental, physical, or mechanical mechanisms. In recent years, air travel has caused previously isolated organisms to appear globally. As well, most emerging human, domestic animal, and wildlife diseases infect multiple hosts.

Six factors have been identified as responsible for the emergence or reemergence of infectious diseases (The Institute of Medicine 1992):

1. Ecological changes, including those due to economic development and land use
2. Human demographics and behavior
3. International travel and commerce
4. Technology and industry
5. Microbial adaptation and change
6. Breakdown in public health measures

The implications of emerging and reemerging infectious diseases for HAIs are enormous. In the last two decades alone, newly identified diseases, viruses, and antibiotic-resistant, disease-causing bacteria have changed the face of medical science and caused us to rethink the design of our health

care facilities. Among these are severe acute respiratory syndrome-associated coronavirus (SARS-CoV), hanta virus, multi-drug resistant tuberculosis, methicillin-resistant staphylococcus aureus (MRSA), and vancomycin-resistant staphylococcus aureus (VRSA). Other drug-resistant organisms are emerging as pathogens in immunocompromised patients, transplant and implant recipients, and patients undergoing hemo/peritoneal dialysis.

In the last two decades, newly identified diseases, viruses, and antibiotic-resistant, disease-causing bacteria have changed the face of medical science and caused us to rethink the design of our health care facilities.

A new gene has been identified in klebsiella pneumonia, Escherichia coli, salmonella, and more than a half-dozen other gram-negative bacteria that enables microbes to destroy the class of antibiotics usually used in last-ditch efforts to save patients whose infections have failed to respond to standard antibiotics. New Delhi metallo-B-lactamase 1 (NDM-1) has been identified in three U.S. patients who received treatment in India, where the gene appears to have originated. The highly resistant gene has not yet affected microbes that are spread by coughing or sneezing, but the microbes can spread via contaminated sewage, water, medical equipment, and ineffective personal hygiene like inadequate hand-washing. NDM-1, which has been involved primarily in urinary tract infections and pneumonia, is but one example of a serious health problem disseminated as a result of extensive travel (CDC 2010).

Emerging viral strains are of particular concern because some strains appear capable of jumping species. Influenza is an example. Although its natural reservoirs are birds and pigs, certain strains of influenza virus periodically jump species.

Each of the more recently identified viral influenza strains H1N1, H5N1, and SARS-CoV has its own unique characteristics (WHO fact sheets 2006, 2008). Coronaviruses in humans are responsible for respiratory tract infections and have been linked to gastroenteritis (Lai and Holmes 2001). Microbiologists believe that SARS-CoV is a mutated form of a coronavirus found in an animal that has contact with humans (Sharma and Khuller 2001). First identified in Guangdong Province in Southern China (Guan et al. 2003), SARS (severe acute respiratory syndrome) raised concerns because of its severity and seeming ease of transmission.

The 2009 influenza A pandemic (H1N1) flu has two genes from flu viruses found in pigs in Europe and Asia, along with avian genes and human genes (Rambaut 2008). Since the 2009 emergence of H1N1 virus in Mexico, H1N1 flu has spread to 156 countries, with at least 140,000 cases confirmed and 850 deaths (Dawood et al. 2009, Ginocchio et al. 2009).

The H5N1 flu virus is an influenza A virus subtype that is highly contagious and deadly among birds. Avian influenza strains are generally transmitted between birds via the fecal-oral route, yet transmission of avian strains to human beings is believed to occur mostly via direct contact between infected bird secretions and human respiratory mucosa (CDC 2005). The H5N1 flu virus does not usually infect people. Nearly all human cases have appeared in people who had direct or close contact with H5N1-infected poultry or H5N1 contaminated surfaces. There have been very few cases of human-to-human transmission.

Surveillance studies indicate that due diligence by hospital professional staff could have a profound effect on the reduction of health care-associated infections.

Surveillance studies indicate that due diligence by hospital professional staff could have a profound effect on the reduction of health care-associated infections. HAIs are caused by a wide variety of common and unusual bacteria, fungi, and viruses introduced during the course of medical care. With shorter hospital stays becoming the norm, a percentage of the vast majority of HAIs occur in patients after discharge.

Disease surveillance strategies are of utmost importance in determining which therapies and design features could help reduce or prevent the spread of emerging infectious diseases. Health care facilities should collect at least three types of data in their surveillance efforts (Jain and Singh, 2007):

- Predominant organisms in the hospital and its ICU
- Current resistance patterns of these predominant organisms
- Outbreaks of HAIs involving one or more prevalent organisms

Effective global disease surveillance strategies are needed and should be backed by an appropriate rapid response system that can provide early warning of emerging infections. The success of such surveillance strategies will depend on their ability to identify unusual events early. Knowledge of the factors underlying the emergence of a disease can help focus resources on the situations and areas the disease is most likely to affect worldwide and facilitate development of effective prevention strategies (Morse 1990, 1991).

4 HAI Statistics

Ninety percent of all HAIs are caused by bacteria, whereas mycobacterial, viral, fungal, or protozoal agents are less commonly implicated (Jain and Singh 2007). HAIs occur primarily in people whose immune system is already compromised from a preexisting condition and who reside in a health care facility for a time. However, HAIs also occur in health care personnel attending patients, which requires employee health programs and policies to ensure patients are not exposed to ill health care providers. Previously compromised persons who contract an HAI may require a longer stay in the initial facility or a long-term care facility and are at increased risk of death.

Five to 10 percent of patients admitted to acute care hospitals and long-term care facilities in the United States—more than one million people annually—develop an HAI. The CDC indicates that about 36 percent of these infections could be prevented by health care workers' adherence to strict guidelines when caring for patients. Although many HAIs are associated with person-to-person contact, the evidence clearly suggests that some infections are transmitted by the airborne route; these may account for as much as 10 to 20 percent of all endemic HAIs (Brachman 1970).

Five to 10 percent of patients admitted to acute care hospitals and long-term care facilities in the United States—more than one million people annually—develop an HAI. Those who contract an HAI are primarily those with compromised immune systems who reside in a health care facility for a time.

The 10 most common pathogens, which account for 84 percent of all HAIs are these (Hidron 2008):

1. Coagulase-negative staphylococci (15 percent)
2. Staphylococcus aureus (15 percent)
3. Enterococcus species (12 percent)
4. Candida species (11 percent)
5. Escherichia coli (10 percent)
6. Pseudomonas aeruginosa (8 percent)
7. Klebsiella pneumoniae (6 percent)
8. Enterobacter species (5 percent)
9. Acinetobacter baumannii (3 percent)
10. Klebsiella oxytoca (2 percent)

Hospital-acquired infections result in significant economic consequences for the U.S. health care system.

Mortality rates reported from aspergillosis due to construction activities in health care facilities have been reported as high as 95 percent in bone marrow transplant patients; 13–80 percent in leukemia patients; and 8–30 percent in kidney transplant patients (Riley et al. 2004). The CDC estimates that 40 percent of those who acquire Legionnaires' disease in a hospital will die from the disease, while only 20 percent of those who acquire the disease outside of a hospital will die. Some outbreaks have claimed more than 50 percent of infected patients.

Hospital-acquired infections result in significant economic consequences for the U.S. health care system. The most comprehensive national estimate of the annual direct medical costs due to HAIs was published in 1992 (Martone). With an incidence of approximately 4.5 HAIs for every 100 hospital admissions, the annual direct costs to the health care system were estimated to be $4.5 billion in 1992 dollars. Adjusting for the rate of inflation using the Consumer Price Index (CPI) for all urban consumers, this estimate is approximately $6.65 billion in 2007 dollars. Recent published evidence indicates that the underlying epidemiology of HAIs in hospitals has changed, along with the costs of treating HAIs (Haas 2006, Stone 2005, Scott 2009).

It has been estimated that building-influenced communicable respiratory infections (influenza, the common cold, TB) amount to $10 billion in health care costs, $19 billion in costs arising from absenteeism due to illness, and $3 billion in other performance losses. In addition, it has been estimated that 5–7 million cases of influenza and the common cold could be prevented each year (10–14 percent of the 52 million cases/year), resulting in savings of $3 to 4 billion. (Morawska 2006)

The data collected by the CDC's National Nosocomial Infection Surveillance (NNIS) system—now known as the National Healthcare Safety Network or NHSN—is the most reliable source for infectious disease data from the past 30 years. In 2007 the CDC reviewed and published the distribution and mortality rates for the period 1990–2002 to provide a national estimate of the prevalence of HAIs. The most common sites for non-ICU HAIs were found to be the urinary tract (UTIs—32 percent), the respiratory tract (RTIs and pneumonia—15 percent), the bloodstream (BSIs—14 percent), and surgical sites (SSIs—22 percent). (Klevens 2007)

An estimated 2.6 percent of nearly 30 million operations are complicated by SSIs annually. In the surgical patient subset, SSIs are the most common HAI (Mangram 1999). As with other HAIs, SSIs have a significant impact on

length of hospital stay, cost of care, and—most important—morbidity and mortality. The NHSN system provides this data regarding SSIs:

- 38 percent of all HAIs in surgical patients are SSIs
- 4–16 percent of all HAIs among all hospitalized patients are SSIs
- 2–5 percent of surgery patients will develop an SSI
- Patients developing an SSI are:
  - 60 percent more likely to be admitted to an ICU
  - More than five times more likely to be readmitted to the hospital
  - Hospitalized an average of 7.5 days longer than a patient who does not contract an SSI
  - Twice as likely to die as similar patients without SSIs

The overall annual direct medical costs of HAIs to U.S. hospitals range from $35.7 to $45 billion (adjusted to 2007 dollars using the Consumer Price Index for inpatient hospital services).

Douglas Scott applied two different Consumer Price Index (CPI) adjustments to account for the rate of inflation in hospital resource prices. The overall annual direct medical costs of HAIs to U.S. hospitals ranges from $28.4 to $33.8 billion (after adjusting to 2007 dollars using the CPI for all urban consumers) and $35.7 billion to $45 billion (after adjusting to 2007 dollars using the CPI for inpatient hospital services). After adjusting for the range of effectiveness of possible infection control interventions, the benefits of prevention range from a low of $5.7 to $6.8 billion (20 percent of infections preventable, CPI for all urban consumers) to a high of $25 to $31.5 billion (70 percent of infections preventable, CPI for inpatient hospital services). (Scott R. D., 2009)

In 2002 the estimated number of HAIs in U.S. hospitals, adjusted to include federal facilities, was approximately 1.7 million: 33,269 HAIs among newborns in high-risk nurseries, 19,059 among newborns in well-baby nurseries, 417,946 among adults and children in ICUs, and 1,266,851 among adults and children outside ICUs. The estimated deaths associated with HAIs in U.S. hospitals were 98,987; of these, 35,967 were from pneumonia, 30,665 from bloodstream infections, 13,088 from urinary tract infections, 8,205 from surgical site infections, and 11,062 from infections of other sites. (Klevens 2007)

5 Surgical Site Infections

Infections following surgery in the United States occur in approximately 3 to 5 percent of all cases and in more than 10 percent of certain types of operations. A surgical site infection (SSI) is an infection that occurs after surgery in the part of the body where the surgery took place. Some surgical site infections are superficial infections involving the skin only; others are more serious and can involve tissues under the skin, organs, or implanted material. Despite the frightening statistics, SSIs are less prevalent than they used to be as a result of the trend toward shorter hospital stays. However, in complicated cardiac, vascular, orthopedic, prosthetic, and transplant surgeries that require longer hospital stays, there still is a high risk of post-operative surgical site infection.

Currently in the United States alone, more than 27 million surgical procedures are performed each year. The CDC's National Nosocomial Infections Surveillance (NNIS) system, established in 1970, monitors reported trends in nosocomial infections in U.S. acute care hospitals. According to data from the NNIS system, the types of pathogens isolated from SSIs have not changed markedly during the last decade. (Nooyen et al. 1994)

Staphylococcus aureus, coagulase-negative staphylococci, Enterococcus spp., and Escherichia coli remain the most frequently isolated pathogens. An increasing proportion of SSIs are caused by antimicrobial-resistant pathogens, such as methicillin-resistant S. aureus (MRSA), or by Candida albicans (CDC 1996, Jarvis 1995, Hidron 2009). Most SSIs are caused by antimicrobial-resistant pathogens. Although fungi are widely present in the environment, they rarely cause SSIs although the incidence of fungal SSIs has risen significantly in the last decade. Most fungal infections arise from the patient's own flora or as a complication of medications and therapies. Viruses are not implicated in SSIs, although they may be responsible for other HAIs. (CDC 1999)

The source of SSI pathogens is usually the patient's skin, mucous membranes, or bowel and rarely another infected site in the body (endogenous sources). Organisms associated with SSIs vary with the type of procedure and the anatomic location of the operation. Exogenous sources of SSI pathogens (e.g., aerobic staphylococci or streptococci species) can come from members of the surgical team (e.g., from hands, nose, or other body parts); contaminated surfaces in the operating room or the air; and contaminated instruments, surgical gloves, or other items used in the surgery.

HAIs are also prevalent in intensive care units (ICUs), where they usually manifest as pneumonia from antibiotic-resistant Acinetobacter and Staphylococcus. Other risk factors include the insertion of catheters, the number of people in the operating room during surgery, increased duration of surgery, and inappropriate use of antimicrobial prophylaxis (Horan et al. 1992).

Of course, not all patients colonized with a potentially disease-causing organism will develop an SSI or other HAI. An infection is more likely to occur in a patient who is physically weakened and immunocompromised than in a relatively healthy individual undergoing a procedure. The potential for infection depends on the number of microorganisms entering the wound; the type and virulence of the microorganisms, the effectiveness of the host's inflammatory response, the status of the patient's immune system, and the length of the hospital stay.

Most preventive measures to reduce surgical site infections involve actions of the clinical team and the length of time the patient is exposed. Less obvious preventive measures involve the design and operation of a facility's ventilation and plumbing systems.

Most preventive measures to reduce SSIs involve actions of the clinical team (e.g., preoperative preparation of the patient's skin, appropriate timing of antibiotic prophylaxis, intraoperative maintenance of normothermia, compliance with asepsis in the operating room, and impeccable compliance with standards for clean equipment and procedures) and the length of time the patient is exposed (minimizing procedure length and reducing duration of hospital stay help prevent SSIs). Less obvious preventive measures involve the design and operation of a facility's ventilation and plumbing systems. For example, measures recommended by ANI-ASHRAE-ASHE Standard 170 include maintaining positive-pressure ventilation, 15–20 air exchanges per hour (ACH), "proper" temperature and humidity levels, and filtration of all fresh or recirculated air. However, it may not be feasible or cost-effective to follow these recommendations in all situations. When this is the case and it may be difficult or impossible to control the environmental conditions, it is even more important to closely follow sterile practices and procedures.

6 HAI Reservoirs

Some of the more commonly implicated organisms and the need for surveillance of HAIs and SSIs have been elucidated in the previous sections in this paper. In the case of HAIs, however, there are many other causative agents and reservoirs for infectious disease-causing organisms.

Humans are the natural reservoir for most contagious pathogens. Human reservoirs are classified as symptomatic, where the individual shows signs and

symptoms of the disease (such as in influenza or measles), or asymptomatic, where the individual does not show signs or symptoms of the disease. For example, the influenza virus infects the columnar epithelium lining of the respiratory tract, can cause infection in both the upper and lower airways, and has a typical incubation period of two days (Morris et al. 1966). Although approximately 50 percent of influenza infections may be asymptomatic, infected persons with few or no signs of illness may still shed the virus and be infectious to others (Foy 1987). Infected individuals can become contagious the day before symptoms begin and can shed the virus for an average of four days (Morris et al. 1966, Murphy et al. 1973).

Animal reservoirs that have been implicated in human disease include both wild and domestic animals that harbor microorganisms. Diseases that occur primarily in animals and can be transmitted to humans are called zoonotic. Examples include rabies and Rocky Mountain spotted fever. Coccidioides, Histoplasma, and Blastomyces grow in soil but may be carried by bats and birds or may be wind-borne and cause disease in humans.

An understanding of the infection dynamics of disease reservoirs is essential for implementing successful disease control measures. These measures must be directed at the disease reservoir as well as at the host.

Environmental reservoirs include primarily soil and water. For example, *Clostridium botulinum* is a bacteria commonly found in soil all over the world. Outdoor spore levels for both bacteria and fungi vary with season and climate and can reach very high levels when dry, windy conditions disturb the soil where fungi grow. Stagnant or slow-moving water that has been contaminated by human or animal feces is a reservoir for microorganisms responsible for gastrointestinal diseases, both bacterial and parasitic. Free-living amoebae like Acanthamoeba and *Naegleria fowleri* can be aerosolized from naturally and artificially heated waters and cause respiratory illness and meningoencephalitis. Actinomycetes such as streptomyces and algae cause allergic reactions, inflammation, and hypersensitivity pneumonitis. Moisture and temperature exacerbate the growth of allergenic fungi such as Stachybotrys, Ulocladium, and Chaetomium which produce toxins that are known to affect immune function and may be deadly to infants. An understanding of the infection dynamics of the many reservoirs described is essential for implementing successful disease control measures. These measures must be directed at the disease reservoir as well as at the host.

For a microorganism to infect a potential host requires three elements in a chain of transmission:

1. Portal of entry
2. Host

3. Portal of exit

Transmission of a microorganism can occur by more than one route. Numerous variables can impinge on each of the elements in the list above and affect the ability of the microorganism to move to the next level of infection. In the chain of transmission, a microorganism must leave one host or reservoir to be transmitted to another. That fact suggests there is a spatial component to the chain of transmission, whether it is direct or indirect contact transmission or transmission via an airborne route. A chain of transmission can involve a single reservoir and a single host or a complex combination of reservoirs and hosts. The infectious or lethal dose (ID_x or LD_x) of the infectious agent is important to consider when discussing the pathogenicity of an organism. An infectious dose (ID) is the minimum number of microbes required to cause infection in the host. For example:

- ID_1 indicates that exposure to only a single rickettsial cell can cause Q fever or a single cell of *Francisella tularensis* causes tularemia.
- ID_{10}^{9} of *Vibrio cholera* bacteria are required to cause cholera.

A lethal dose (LD_{50}) represents a dose at which a given percentage of subjects will die. LD_{50} indicates that 50 percent of exposures will be fatal. Once disease is established, and if the disease process is prolonged, the individual becomes further immunocompromised and prone to other opportunistic infections.

Equally important in the transmission of infection are the virulence of the organism and the site of its deposition in the individual. Infectivity may be lost when the infectious agent dries, particularly for those microorganisms not protected by a capsule. Therefore, hand or surface contact may require the exchange of moisture as well as an infectious dose (Kowalski 1997).

The portals of exit from the reservoir may include the respiratory tract and involve the expulsion of saliva as well as the fecal route, urogenital tract, skin, or blood, either through a wound or accidental exposure during a procedure. Reservoir causative agents can be transmitted to a susceptible host by direct or indirect contact transmission via a vehicle such as food, water, biological products, or fomites.

An animate or inanimate object that carries a pathogen from one host to another is called a disease vector. Vectors may be biological (e.g., an animal or insect that spreads a disease via a bite or its feces) or mechanical (e.g., the offending organism is transported as a contaminant on shoes or cloth-

It behooves the engineering community to work in conjunction with infection preventionists to develop targeted ventilation strategies that might reduce pathogenic agents' access to the host.

ing). The airborne route requires a mechanical means of dispersing the agent, which might include wind, ventilation, human or animal movement, and the like.

After a pathogen has been transmitted from its reservoir to a host, it must either colonize a surface or enter the new host. When a pathogen gains entry into a host, it attaches to host tissue by binding surface molecules on the pathogen to complementary surface receptors on the cells of certain host tissues. Once attached, the pathogen can invade a sterile body compartment and cause disease. Therefore, it behooves the engineering community—using risk assessments and available knowledge bases and working in conjunction with infection preventionists—to develop targeted ventilation strategies that might reduce pathogenic agents' access to the host. Infection preventionists know the pathogens likely to require the attention of engineers since many airborne pathogens can be prevented by vaccines and do not present the high level of risk or concern they did even 20 years ago.

The portals of entry in a host are much the same as the portals of exit from the reservoir and include microorganism or toxin contact with the skin or a mucous membrane in the gastrointestinal tract, respiratory tract, urogenital tract, puncture wound, or conjunctiva of the eye. The respiratory tract is the easiest and most frequently traveled portal of entry for infectious microbes such as the common cold, pneumonia, influenza, measles, and smallpox. Microorganisms can gain access to the gastrointestinal tract in food and water. Most microbes that enter the body via the digestive tract are destroyed by high concentrations of hydrochloric acid (HCl) and enzymes in the stomach, but those that survive can cause disease. Gastrointestinal organisms include hepatitis A, poliomyelitis, typhoid fever, and cholera. Microbes that can gain access to the body through openings in the skin, hair follicles, and sweat gland ducts include some fungi and hookworms, but these are generally transmitted via direct physical contact with the organism. Parenteral routes established via punctures, injections, bites, cuts, or surgery are the result of penetration or injury to the skin or connective tissue.

Other factors interact with the route of entry and may have an indirect effect on infectivity and degree of illness. For example, studies have shown that there is an inverse correlation between serum 25-hydroxyvitamin D (25-h D) levels and upper respiratory tract infection (URTI) (Cannell et al. 2006, 2008, 2009; Ginde and Mansbach 2009).

Activities that disturb spores or particle nuclei may play a role in the chain of transmission. These include bed-making, which can release large quantities of microorganisms into the air (e.g., microorganisms released on skin squames (Rhame 1998, Greene et al. 1960).

Any surface that is not regularly cleaned or possibly disinfected can harbor some pathogenic microorganisms. Areas of a health care facility that could potentially harbor pathogens include the ductwork, particularly if there has been a buildup of dust or moist residues on the inside surface of the duct. "Touch" surfaces in hospitals, including sink taps, computer keyboards, instrument handles, equipment trolleys, intravenous poles, push plates, grab bars, panic bars, trays, pans, bedrails, walkers, handrails, and stair rails are probable sources of contaminants that may transfer HAIs, particularly MRSA infections.

The three main ways infections are transmitted in health care facilities are via contact, droplet, and airborne transmission.

7 Modes of Transmission

The three main routes of infection transmission in health care facilities are contact, droplet, and airborne. An infectious agent, however, can be transmitted by more than one of these routes. For example, some microorganisms are transmitted by both airborne and contact routes at different stages of the disease.

1. *Contact*, both direct and indirect, is the most common mode of transmission in health care facilities and other indoor environments. HVAC has little impact on this mode of transmission.

2. *Droplet transmission* is characterized by dispersion of microorganisms from an infected person over short ranges (3–6 feet). The aerodynamics of this results in microbes contained in fluids that fall out of the air in rapid fashion.

3. *Airborne transmission* involves dissemination of microbes via droplet nuclei beyond short ranges, such as via an HVAC system.

Recent work by Xie and colleagues (2007) indicates that large droplets are those larger than 5–100 μm at the original time of release. Nicas and colleagues (2005) show by modeling that emitted large droplets will evaporate to 50 percent of their initial size and that if the initial diameter is < 20 μm this process will happen instantaneously. However, the release of large droplets in short-range aerosols is sometimes confused with airborne trans-

mission, although short-range aerosols typically do not transmit over long distances. A concept or classification of airborne disease introduced during the SARS epidemic may be more useful since some infectious agents (like SARS) that transmit primarily by large droplets may under some conditions be transmitted through the air (Roy and Milton 2004). Based on the capacity of the agent to be transmitted and to induce disease through fine-particle aerosols and other routes, Roy and Milton classified aerosol transmission of diseases in three categories:

1. *Obligate inhalational airborne transmission:* transmission of infection that is, under natural conditions, initiated only through aerosols deposited in the distal lung. TB may be the only such disease;

2. *Preferential inhalational airborne transmission:* transmission caused by agents that can naturally initiate infection through multiple routes but are predominantly transmitted by aerosols deposited in distal airways. Infection initiated through another route (e.g., viral exanthems like measles) usually causes modified disease.

3. *Opportunistic inhalational transmission:* transmission via short-range aerosols but also by routes that are not airborne (e.g., ingestion into the gastrointestinal tract). Examples of microorganisms transmitted in this manner are SARS-CoV and norovirus (the most common cause of viral gastroenteritis), which have been transmitted under unique circumstances. For instance, a dramatic outbreak of SARS-CoV in an apartment complex was due to failure of a sanitary sewer system, key atmospheric conditions, and resultant dissemination via short distances. Transmission over short ranges to those in the same room without face protection from a person with infection who is actively vomiting is another example of an opportunistic situation. Fine-particle aerosols may provide the organism with an efficient means of propagating in favorable environments.

The heart of the CDC guideline for preventing transmission of infections in health care facilities is establishing barriers that can break the chain of infection.

Regardless of classification scheme, these three primary routes each require different control strategies. Many years of infectious disease practice have generated standards of practice for infectious disease and hospital epidemiology. The primary and current standard of practice is the CDC's *Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Healthcare Settings*, published in 2007. The heart of the guideline is setting barriers to break the chain of infection.

It is well established that influenza is transmitted primarily through close contact, such as during exposure to large respiratory droplets, direct contact, short-range exposure to infectious aerosols, or perhaps a combination of these routes. However, the relative contribution and clinical importance of each of these modes of transmission has not been established.

A frequently cited aircraft study by Moser and colleagues (1979) describes an influenza outbreak that occurred on an Alaska Airlines flight during a stopover. The ventilation on the plane was shut down for three hours during which time passengers became restless and moved about the plane. The supposed index case on the flight became acutely ill with laboratory-confirmed influenza A, and 72 percent of the other passengers confined to the aircraft subsequently became infected with influenza. The occurrence of infection increased with time spent on the aircraft. In this case study, there is no clear evidence for a single mode of transmission. The passengers were moving around and probably touching surfaces that contaminated their hands, and there was no air circulation. Thus, the passengers who became ill may have been infected by any of the common modes of transmission.

Numerous studies have suggested that the mode of transmission in a disease outbreak is dependent on the setting and environmental conditions. This hypothesis has led to the belief that implementing engineering control methods in health care facilities could reduce the incidence of HAIs.

The results from numerous studies related to modes of transmission suggest that the mode of transmission in each disease outbreak probably differs according to the setting and the environmental conditions. This hypothesis has led to the belief that implementing engineering control methods in health care facilities could reduce HAIs (Tellier 2009).

However, a review of the same evidence by Brankston and colleagues reinforced that a hierarchy of controls—administrative, environmental, and PPE—is effective in mitigating cross-transmission of influenza. This review also concluded that "airborne transmission is unlikely to be of significance in most clinical settings." (Brankston et al. 2007)

8 Causative HAI Agents

Long-term care facilities such as nursing homes, chronic disease hospitals, rehabilitation centers, foster and group homes, and mental institutions may be perceived as reservoirs of HAIs because of the higher density of population and longer lengths of stay of the patients. A diverse variety of organisms known to cause HAIs—*K. pneumoniae, Staphylococcus aureus,* E. coli, Proteus spp, and *Pseudomonas aeruginosa*—are among the most common causative

Some HAI agents are serious human pathogens, while others are opportunistic pathogens that present minimal risk to healthy individuals but may cause serious infections in immunocompromised patients.

agents of HAI (Jain and Singh 2007). These common pathogens are carried by everyone, but if adherence to basic infection control techniques is low, patients may acquire them from another patient at which point they are termed HAIs.

In lower respiratory tract infections, *P. aeruginosa* and *S. aureus* are the leading pathogens. In urinary tract infections, *E. coli,* Klebsiella spp., Proteus spp. and *Streptococcus faecalis* predominate. In bacteremia, surgical wounds and burns, Staphylococci spp. and Enterococci spp. are primary pathogens respectively. Some of these are serious human pathogens, while others are opportunistic pathogens that present minimal risk to healthy individuals but may cause serious infections in immunocompromised patients (Fletcher et al. 2004). Fungi and some bacteria form large spores that are more resistant to environmental factors and disinfection strategies than most viruses and bacteria.

Airborne diseases. Sufficient evidence to demonstrate (Fennelly et al. 2004, Fitzgerald and Haas 2005) airborne transfer exists for only a handful of microorganisms. TB, caused by *Mycobacterium tuberculosis* and *M. africanum*, is perhaps the most studied disease agent in hospitals. It is known to be transmitted via the airborne route and is a major cause of infections in nursing homes. The emergence of multi-drug resistant strains of TB has increased concern regarding this disease. The only other truly airborne diseases are measles (rubeola virus) and chicken pox (varicella zoster). As noted earlier, these are vaccine-preventable diseases.

Smallpox. Although smallpox has been eradicated, it is noted here as a causative agent because of its potential to be used as a biological weapon. Smallpox is transmitted from person to person by infected aerosols and air droplets spread by face-to-face contact with an infected person after fever has begun, especially if symptoms include coughing. The disease can also be transmitted by contaminated clothes and bedding, although the risk of infection from this source is much lower. Patients diagnosed with smallpox must be physically isolated to break the chain of transmission. According to the World Health Organization (WHO), hospitals have proven to be sites of epidemic magnification during smallpox outbreaks, probably because of a lack of negative pressure isolation facilities. In the case of a smallpox epidemic, the limited isolation resources in medical facilities would be overwhelmed. Routine prophylaxis in the form of vaccination was terminated in 1980 after the WHO certified the eradication of smallpox in December 1979.

Methicillin-resistant staphylococcus aureus (MRSA). Sometimes termed a "super bug" because it has developed a resistance to most antibiotics, MRSA accounts for 52 percent of all *S. aureus* HAIs, one of the most prevalent health care-associated infections. MRSA infection is highly correlated with prolonged hospital stays, use of broad-spectrum antibiotics, duration of antibiotic use, presence of surgical wounds, and proximity to other patients infected by the organism. Although theoretically *S. aureus*—both sensitive and resistant—can be transmitted via an airborne route, most outbreaks are associated with direct contact via the hands, particularly between health care workers and patients. In the October 2007 issue of the *Journal of the American Medical Association*, the CDC estimated 94,000 serious, invasive, drug-resistant Staph aureus infections (MRSA) occurred in the United States in 2005 with MRSA deaths estimated at more than 18,000. This study established the first national baseline by which to assess future trends in invasive MRSA. In health care settings, MRSA occurs most frequently among patients who undergo invasive medical procedures or who have weakened immune systems and are being treated in hospitals and health care facilities such as nursing homes and dialysis centers. (Klevens et al. 2007)

MRSA infection is highly correlated with prolonged hospital stays, presence of surgical wounds, and proximity to other patients infected by the organism.

Water-associated Legionnaire's disease. The epidemiology of Legionnaire's disease, caused by Legionella spp., in health care facilities is not well characterized. The disease is thought to originate in water cooling towers and then to reside in water sources in a facility; if preventive controls are not maintained, it can spread as aerosols. The dose-response relationship is not known since its presence in water does not necessarily result in disease.

Water-associated *P. aeruginosa*. Pseudomonas aeruginosa (Psa) and Stenotrophomonas maltophilia (Smalto) are major opportunistic waterborne pathogens. These bacteria, which live in wet drains, have long been of concern as a normal water contaminant. Recent studies describe release of the planktonic bacteria Paeruginosa from hand-washing stations in single-occupancy intensive care unit (ICU) rooms as a cause of an outbreak of life-threatening infections (Hota et al. 2009). This evidence demonstrates that water can also directly contaminate the patient, equipment, and surfaces in an area and result in cross-transmission of disease.

***Aspergillus spp.*-environmental source.** Aspergillus is the major source of fungal infections in health care facilities. It has been identified in both indoor and outdoor construction sites as well as in construction materials such as ceiling tiles, porous insulation, and ductwork exposed to bird droppings and in equipment such as air-conditioning units, cooling coils, and

the like. Pulmonary aspergillosis is caused by inhalation of the fungal spores of *Aspergillus* spp. that enter hospital buildings through ventilation ducts with inadequate filtration. High concentrations of aspergillus spores are commonly associated with building work, which can liberate spores into the atmosphere. Immunocompromised individuals are particularly vulnerable to infection from aspergillus and mortality rates are significant, especially in bone marrow transplant patients.

Serratia marcescens *is* another water-associated opportunistic pathogenic and is believed to be responsible for 4 percent of hospital-acquired pneumonias. Multi-drug resistant forms are common, and some strains develop resistance during therapy (Fletcher et al. 2004).

Clostridium difficile **infection (CDI).** This frequently occurring HAI is responsible for significant morbidity and mortality among elderly patients in health care facilities and appears to be increasing in prevalence. CDI is spread via environmental contamination and possibly by airborne dissemination of *C. difficile* spores over short ranges, for example, three to six feet (Best et al. 2010). The spores, which are relatively resistant to disinfectants, can survive on inanimate surfaces for months.

Sporulation may be enhanced by exposure of cells to some types of cleaning agent, making this HAI difficult to eradicate (Wilcox and Fawley 2000). However, studies have shown that the use of sporocidal disinfectants can greatly reduce the number of *C. difficile* infections (Gerding, Donske, Duberkke; CID). The studies of Best et al. provide evidence of airborne dispersal of spores, but further studies will be needed to determine whether this is an important route of transmission; it is possible this is an interesting observation with limited clinical relevance. Most of the contaminated sites were frequently touched surfaces, suggesting that the source of contamination may have been the hands of health care personnel. Even if spores are disseminated via air, it would not change current medical practices. High-touch surfaces in CDI rooms will be targeted for sporicidal disinfection regardless of the mechanism of contamination. Airborne dispersal to infrequently touched surfaces may be irrelevant.

Viruses. Viruses of concern in HAIs include influenza, SARS-CoV and other coronaviruses, respiratory syncytial virus (RSV), parainfluenza viruses, and febrile rash infections caused by measles, rubella, and varicella zoster, the virus that causes chicken pox. As noted earlier, influenza, measles (rubeola), rubella, and chicken pox are all vaccine-preventable.

9 Airborne Particle Transmission

Respiratory flows from infected patients are one of the main sources of infectious airborne pathogens in hospitals, and the risk of infection for health care personnel can be very high during an outbreak of disease transmitted by airborne or droplet contact means. During the 2003 SARS epidemic, 20 percent of the infected individuals worldwide were health care workers. Despite this, the hospital engineering control community has paid very little attention to this topic compared to the abundance of research on ventilation and indoor air distribution in non-hospital buildings such as schools, offices, and homes.

The risk of infection for health care personnel can be very high during an outbreak of disease transmitted in respiratory flows from infected patients.

There is a great need to study how ventilation affects disease transmission in areas of health care facilities likely to have a higher frequency of infectious particle transmission. Some recent progress has been made in the study of isolation rooms, but this work has not included research into the ventilation of other hospital areas where potentially infectious patients might be encountered (e.g., emergency rooms, neonatal intensive care units, critical care units, etc.).

Room airflow is governed by a combination of air movements caused by ventilation, differences in temperature, moving bodies, and location and operation of equipment.

Aerosol transmission of microorganisms is affected by combinations of many interrelated factors. Some of these include:

- Humidity
- Temperature
- Population density
- Number of susceptible hosts
- Length of exposure
- Number of infected people producing contaminated aerosols
- Ventilation rate
- Room airflow
- Infectious particle settling rate

- Microorganism envelope composition
- Presence of surrounding organic material
- Exposure to UV light or antiviral or antimicrobial or antifungal chemicals
- Microorganism resistance to antibiotics
- Antiviral or antifungal therapy
- Type and degree of invasive procedures
- Spatial considerations such as seating or sleeping arrangements
- Contact with a carrier
- Persistence of pathogens within hosts
- Role of host genetic factors

Infectious airborne droplets are generated when an infected person undergoes procedures such as suctioning, endotracheal intubation, and cough induction as well as when the patient coughs, sneezes or talks.

Droplet nuclei were first described as the primary mode of airborne infection in the mid-1930s (Wells). It is well established that airborne respiratory droplets are generated when an infected person coughs, sneezes, or talks. Droplets are also generated when an infected person undergoes procedures such as suctioning, endotracheal intubation, cough induction by chest physiotherapy, and the like.

A process often overlooked in expulsion of viruses is vomiting. Infected individuals can shed up to 10^7 virus particles per ml of vomit (Barker et al. 2001). Vomit is a significant route of infection in diseases that cause frequent vomiting. For example, vomiting by a SARS-infected person in a hotel in Hong Kong in 2003 is believed to have caused a series of infections. It is not, however, clear whether the pathway of infection was primary airborne droplets, droplet residue, or re-entrained infected dust. (Morawska et al. 1999, Morawska 2006)

Infected individuals can shed up to 10^{12} virus particles per gram of feces (Barker et al. 2001). Feces are atomized via sewage aerosolization from toilets during flushing and during transport in building downpipe systems. Atomized droplets can be directly inhaled or deposited on the surfaces in a bathroom, which can lead to contamination of hands (Rusin et al. 1998).

The sizes of different types of biological aerosols can be broadly classified as viruses from 0.02 to 0.3 μm, bacteria from 0.5 to 10μ m, and fungi from 0.5

to 30 µm. The actual size of a particle is a consequence of the process that led to its generation, and therefore dependent on its source. The content of an infectious agent expelled by an infected person depends, among other factors, on the location within the respiratory tract where the droplets originate. Pathogenic organisms usually reside in the tonsils and the larynx and seldom at the front of the mouth. Thus, to assess the potential for infection via airborne droplets, it is important to develop an understanding of the locations where droplets originate during various expiratory activities and the numbers of droplets that arise from each site (Morawska 2006).

To assess the potential for infection via airborne droplets, determine where and during which activities droplets originate.

Pathogen-laden droplets expelled by an infected patient subsequently dry out in the room air environment and produce fine particles and droplet nuclei that can remain suspended in the air. Although the liquid evaporates, the residual droplet nuclei may remain in the air for long periods of time depending on particle size, velocity, and density; force of expulsion; humidity; and rate of airflow. Such airborne particles can contain bacteria or other disease-causing organisms. Air currents, aided by the ventilation system, help spread these organisms over a wide area. If the disease-causing organisms are inhaled by or come to rest near a susceptible person, that individual can be infected through mucous membrane contact by contaminated hands or materials. Droplet nuclei are so small that they bypass the potential host's innate upper respiratory tract defense mechanisms and are deposited in the alveoli in the lungs (Fletcher et al. 2004).

Clinically applicable distinctions are made between short-range airborne infection routes (between individuals, generally less than 1 m [3.28 ft] apart) and long-range routes (within a room, between rooms, or between distant locations, generally distances greater than 1 m [3.28 ft]). Small droplets may be transmitted at short range, but they are more likely than larger droplets to evaporate and become droplet nuclei, which then are considered to have the potential for long-range airborne transmission. Droplet nuclei of 2 µm will take 4.2 hours to fall six feet and can remain suspended in the air for several hours. Droplet nuclei can travel over long distances. Particles larger than droplet nuclei may settle and then be resuspended after evaporating to a smaller size. True long-range aerosol transmission becomes possible when droplets of infectious material are sufficiently small to remain airborne almost indefinitely, allowing them to be transmitted over long distances.

Experimental studies with smallpox conducted by Downie and colleagues (1965) and investigations during the global SARS outbreaks of 2003 by Wong and colleagues (2004) suggest that droplets from patients could reach persons located at a distance of 1.83 m (6 ft) or more.

Droplet Size Definitions

Although some investigators, including Fennelly and colleagues (2004) and Bjorn and Nielsen (2002), identify a large droplet diameter as greater than 60 µm, a small droplet diameter as less than 60 µm, and a droplet nuclei diameter as less than 10 µm, these parameters are not universally accepted. There is, however, essential agreement that particles with an aerodynamic diameter of 5 µm or less are aerosols, whereas particles of approximately 20 µm are large droplets. Studies show that 80 to 90 percent of particles from human expiratory activities are smaller than 1 µm (Papineni and Rosenthal 1997).

When reviewing the literature, it is important to verify the size of the particles being studied and the investigators' definitions. The author of this monograph supports and agrees with the universally accepted diameter measurements. All values used here refer to the aerodynamic diameter; for bioaerosols, they refer to the aerodynamic diameter after evaporation.

Larger droplets with more mass are more strongly influenced by gravity and less by airflows, causing them to fall to the ground more quickly. Smaller droplets with less mass are less influenced by gravity and can be transported as a cloud over greater distances by airflows. Particle movement in air is determined by Stokes's settling law, which governs how quickly a sphere falls under the opposing forces of gravity (downward) and air friction (upward). The resulting complex air movements of infectious particles make the route and suspension time very difficult to determine once the particles have left the infectious host.

Sneezing can introduce as many as 40,000 droplets, which can evaporate to produce droplets of 0.5 to 12 µm (Cole and Cook 1998, Wells 1955). In a patient with active TB who is coughing naturally, the infectious particle size has been found to be 2.1–3.3 µm (Fennelly et al. 2004). These particles can be expelled at a velocity of 100 m/s (≈20 000 FPM), reaching distances of several meters. A cough can generate about 3,000 droplet nuclei (Fitzgerald and Haas 2005), the same number as talking for five minutes, and a single sneeze can generate 100,000 floating bioaerosol particles, many containing viable microorganisms (Duguid 1945). Although a single cough typically produces a small percent of this amount, coughs occur about 10 times more frequently than sneezes. Some studies have shown that a TB-infected patient can produce 1 to 249 bacilli an hour, while a person in the infectious stage of a cold may produce 6,200 droplet nuclei per hour containing viable viruses that remain airborne longer than 10 minutes (Fitzgerald and Haas 2005).

Most pathogens have the potential to be transmitted by large droplets.

Droplet transmission is a form of contact transmission, and some infectious agents transmitted by the droplet route also may be transmitted by direct and indirect contact routes. However, in contrast to contact transmission, respiratory droplets carrying infectious pathogens transmit infection directly from the respiratory tract of the infectious individual to susceptible mucosal surfaces of the recipient, generally over short distances. Thus, mucous membrane protection is needed to prevent infection of the potential recipient.

Most pathogens have the potential to be transmitted by large droplets. Examples of pathogens that can be transmitted by large droplets but are not considered to be true airborne infections include SARS coronavirus (SARS CoV), whooping cough (*Bordetella pertussis)*, influenza virus, adenovirus, rhinovirus, *Mycoplasma pneumoniae*, group A streptococcus, and bacterial meningitis (*Neisseria meningitidis*).

Microorganisms are also hygroscopic (taken up and maintained under certain humidity and temperature conditions). A 1.5 µm hygroscopic particle may increase to 2.0 µm in diameter when passing through the nose and to 4.0 µm in the saturated air of the nasopharynx and the lung (Knight 1993), and this increased size may affect retention in the lung. Thus, the relative humidity (RH) of a space can have a profound effect on the transport of infectious particles as a result of changes in their size, viability, and airborne duration. Gravitational, thermal, and electrostatic fields profoundly affect the aerodynamic behavior of infectious particles (Cook and Cole 1998).

The use of aerosol-generating procedures in hospitals may amplify transmission of SARS (Yu et al. 2004). Many cases of SARS have occurred in hospitals, with infections traveling between patients and health care workers, in some cases apparently assisted by oxygen delivery and other respiratory support devices (Fowler et al. 2003). Detection of SARS-CoV RNA in air has also been reported (Booth et al. 2005), and in some cases airborne SARS CoV grown in culture has demonstrated viability (Xiao et al. 2004).

Clinical Laboratories

An area of concern for infection acquisition in a hospital is the clinical laboratory where health care workers are exposed to bioaerosols generated from patient body fluid samples during testing procedures. Bioaerosols from body fluids and tissues are generated when the sample container is initially opened and manipulated as required for mixing, pipetting, centrifuging, or mechanically aspirating the sample. Although many modern clinical testing equipment models are self-contained to protect the user from aerosol exposure, smaller hospitals may still have older pieces of equipment or perform manual tests that require pipetting and dispensing a body fluid sample on the lab bench top.

Generally, laboratory personnel follow universal precautions, such as donning gloves, masks, or face shields and gowns when handling specimens. However, consideration should be given to providing protective IAQ strategies when feasible.

Biological safety cabinets and fume hoods may be appropriate for handling large volumes of specimens. A bench exhaust system may be beneficial in certain circumstances to control removal of local contaminants. The computational fluid dynamics (CFD) methodology used to study bench exhaust system technology looked specifically at removal of chemical contaminants (Memarzadeh 2009). Further investigations are needed to determine the effectiveness of using bench-top exhaust to remove localized bioaerosol contaminants.

10 Effect of Temperature and Humidity on Transmission of Viruses

An extensive literature review of more than 120 papers on the effect of humidity and temperature on the transmission of infectious viruses was conducted in 2011 (Memarzadeh 2011). The review targeted infectious viruses known to be transmitted through the air as well as through direct and indirect contact. Each paper's data and assumptions were examined in their totality, rather than reviewing just the abstract and conclusion.

Despite the fact that animals (mice, ferrets, squirrel monkeys, and others) generally do not accurately display human symptoms, most studies have been performed on animal models. Thus, the results of these studies are difficult to extrapolate to an understanding of natural transmission of viral disease to and between humans via exhalation and surface contact routes. (Lowen et al. 2006-08, Lowen and Palese 2009, Andrewes and Glover 1941, Maines et al. 2009, Wells 1936, Frankova 1975, Ehrlich and Miller 1971, Elazhary and Derbyshire 1979) Results from observational and epidemiological human studies are often equally difficult to interpret because of confounding factors inherent in the design of each study (e.g., lack of controls, inability to identify an index case, and incomplete or unavailable data).

Numerous factors make comparison of the results of different studies difficult. Hermann (2007) states, "Inconsistent replication of airborne transmission under experimental conditions suggests that we do not understand the conditions required for its occurrence." Evidence in the literature as far back as 1943 (Loosli et al.) shows it is not easy to quantify the amount of virus inhaled. Nor has anyone closely examined the specific mucosal lining conditions (including duration of exposure) necessary for viral infectivity to occur. Airborne viruses may also have indirect effects on human health, such as triggering immune-mediated illnesses like asthma (Arundel et al. 1986; Hersoug 2005). A further complication is the lack of references to scientifically determined demarcations for the low, medium, and high ranges of RH and temperature in the literature.

Other factors that make definitive interpretation of study data questionable include the use of reverse transcriptase-polymerase chain reaction (RT-PCR) to detect naturally produced influenza bioaerosols in a hospital setting. Detection by RT–PCR alone does not necessarily imply infectivity (Blachere 2009). The literature suggests that the amount of time different symptoms

take to reach the point at which the effects of low humidity are negligible varies (Nagda and Hodgson 2001).

Most of the available evidence for airborne viral transmission is based on poorly controlled viability studies related to the effects of artificially aerosolized viral particles on animal susceptibility. Many studies have shown that influenza viruses can survive in an artificially generated airborne aerosol for varying amounts of time and at varying temperature and humidity ranges and that these experimental aerosols may cause infection in people and animals. (Hemmes et al. 1960; Harper 1961; Schaffer et al. 1976; Ijaz et al. 1985, 1987; Karim et al. 1985; Ehrlich and Miller 1971; Lowen 2007, 2008; Lowen and Palese 2009). However, Brankston and colleagues (2007) note, "we question whether these studies are relevant to the natural route of human transmission. The artificial aerosols studied were quite different from natural aerosols generated by coughing."

Despite a significant body of work investigating the survival characteristics of influenza in air and on surfaces, the evidence is insufficient to say that maintaining an enclosed environment at a certain temperature and a certain RH is likely to reduce the airborne survival and, therefore, the transmission of influenza virus when compared with a similar environment that does not adhere to such a tight control of indoor temperature and RH (Tang 2009). Most studies do not account for the duration of time a virus has been in a space in relation to the environmental conditions of that space; thus, no conclusive evidence exists to suggest a minimum or maximum RH that can make it more difficult for a virus to survive or affect its ability to cause an infection. There is data in support of every hypothesis for viral transmission, yet none of the hypotheses has been subjected to tests rigorous enough to reject it (Popper 1958).

In addition to the variable ranges used for low, medium, and high RH and temperature, the literature shows opposing conditions for transmission of viruses ranging from low RH and high RH with temperature a secondary factor (Knight 1980, Harper 1961, Hemmes et al. 1960), making it difficult to interpret the full complement of results. Generally, as temperature rises, virus survival decreases. Maintaining temperatures above 60°C for more than 60 minutes usually inactivates most viruses, although this can vary depending on the presence of organic material (e.g., blood, feces, mucus, saliva, etc.), which may surround exhaled viral particles and insulate the virus from extreme environmental changes, preserving its viability.

Humidity Definitions

Absolute humidity: the amount of water vapor present in a unit volume of air, usually expressed in kilograms per cubic meter. Absolute humidity does not fluctuate with the temperature of the air.

Relative humidity: the ratio of the actual amount of water vapor present in a volume of air at a given temperature to the maximum amount of water vapor the air could hold at that temperature, expressed as a percentage. Warm air can hold more water vapor than cool air, so a particular amount of water vapor will yield a lower relative humidity in warm air than it does in cool air.

Another key factor in virus spread is the characteristics of the droplet carrying the virus (Tang 2009). As the material surrounding an infectious particle evaporates, the droplet becomes smaller and the infectious particle is less protected and may become damaged. Numerous studies have looked at airborne virus survival under different RH, absolute humidity (Shaman and Kohn 2009), and temperature conditions. A study of airborne human coronavirus at two different temperatures with low, medium, or high RH demonstrated that high RH is deleterious to the survival of aerosolized virus, while low temperature improved the survival ability of the virus at a high RH. It was proposed that under conditions of high humidity, the fluidity of the lipid-containing envelopes stabilized at low temperature and protected the virion (Ijaz et al. 1985, 1987). It has been demonstrated that rhinovirus survives better in high humidity when it is at a low temperature, but at low and medium RH the infectivity of the airborne virus was rapidly lost (Karim et al. 1985). At 24°C the survival of the Japanese B encephalitis virus as an aerosol is inversely related to RH. From these and other studies, it is generally accepted that viruses with lower lipid content have greater stability at high RH than lipid-containing viruses (Pillai and Ricke 2002). Viruses that possess a lipid envelope are more stable in dry air, whereas viruses without a protective envelope are more stable in moist air (Roe 1992). Examples of viruses that are protected by a lipid envelope include influenza, parainfluenza, respiratory syncytial, and corona viruses, and thus they are expected to be more stable under drier conditions. Viruses without protective envelopes such as rhino-, entero-, and adenoviruses are more stable under humid conditions.

It is interesting that although RH and temperature are usually referred to in the literature as high, medium, or low, each researcher defines the actual RH or temperature ranges a bit differently. As mentioned earlier, there are no scientifically determined demarcations for these ranges. This is significant in that microorganisms behave differently at different combinations of temperature and RH. This variability not only makes interpretation of study results difficult, but the results may be contradictory and in some cases not meaningful when other variables are considered.

Aerosolized virus particles remain infective for longer periods during cold weather than during warmer weather, suggesting they are more stable at low

ambient air temperatures. This explains the occurrence of influenza epidemics during the cold winter season when low humidity is more prevalent. However, modern air-conditioned buildings also create cold, dry conditions, potentially lengthening the flu season.

Since influenza is a major pandemic concern, much of the research surrounding aerosol transmission revolves around the effects of the environment on the influenza virus. Influenza is transmitted primarily through close contact during exposure to large respiratory droplets, direct contact from hands to mouth, and short-range exposure to infectious aerosols. However, the relative contribution and clinical importance of each of these modes is unknown. The fact that significant outbreaks are relatively uncommon in acute care settings suggests that most influenza transmission occurs via large droplets.

Three mechanisms have been put forward to explain the observed influence of RH on viral transmission (Schaffer et.al. 1976, Shephard and Shek 1998, Harper 1961, Hemmes et al. 1960). First, RH may act at the level of the host. Breathing dry air could cause desiccation of the nasal mucosa, leading to epithelial damage and/or reduced mucociliary clearance, which would in turn render the host more susceptible to respiratory virus infections. Long-term exposure to dry air is likely to affect influenza virus growth in the upper respiratory tract, and may indeed play a role in influenza seasonality. The mucociliary clearance apparatus is an important defense mechanism for clearing the lung of foreign particulate matter. Secretory cells produce mucus that lines airway passages and affords protection from disease. (Bennett 2002). Pollutant exposure and viral or bacterial infections may cause disruption of mucociliary clearance (Waffaa et al. 2006) and likewise affect natural rheological properties (e.g., adhesiveness of nasal mucus and slowing of ciliary beating) (Salah et.al. 1988).

Microorganisms behave differently at different combinations of temperature and RH. This variability can interfere with study results. For more reliable data, the survival of airborne viruses should be examined in a standardized laboratory model with a repeatable methodology.

Viral diagnosis samples suggest that another virus infection may interfere with the spread of influenza. The H1N1 virus began to appear less frequently in the samples when a prevalence of rhinovirus appeared in about a third of them (Linde et al. 2009). In the United States, Rhinovirus epidemics typically occur soon after school has started. The virus is spread mainly by contaminated hands and has not been reported to be climate-dependent. A possible explanation for the sudden interruption of the spread of influenza could be the increase in the spread of rhinoviruses, which may have a selective advantage over influenza due to the mild and moist climate.

To achieve more reliable results, the survival of airborne viruses should be examined in a standardized laboratory model with a repeatable methodology.

It is encouraging that more experiments are being performed with human volunteers or taking place in real health care environments, where humans are the main sources of such potentially infectious aerosols (Xiao et al. 2004, Fabian et al. 2008, Huynh et al. 2008, Blachere et al. 2009, Stelzer-Braid et al. 2009). However, the exhaled or airborne viruses were collected in a different way in each study, so the collection method will need to be standardized to yield air-sampling results that can result in useful and reliable infection control recommendations.

11 Effect of Temperature and Humidity on Transmission of Bacteria and Fungi

The results of studies of the survival of airborne bacteria are more difficult to interpret than the results of similar studies on viruses. Even bacteria within the same structural classification (e.g., gram-negative or gram positive) may vary in how they respond to temperature and RH. The structural variation of potentially airborne bacteria may preclude useful generalization, and the airborne survivability of individual bacteria may need to be investigated separately (Tang 2009).

Like viruses, bacteria have different types of outer coats that are affected by local environmental conditions, which in turn affect their viability. Some bacteria are partially or completely sensitive to oxygen. Bacteria tend to be sensitive to methods of aerosolization, collection, and culture, so their responses have to be accounted for when assessing the viability of airborne bacteria under different environmental conditions (Cox 1989, 1998).

Studies have shown that the survival of some aerosolized gram-negative bacteria (including *Pseudomonas*, *Enterobacter*, and *Klebsiella* spp.) is greater in high RH, low temperature environments when the bacteria were contained in small droplets. This was thought to be because this condition caused more rapid droplet evaporation, resulting in bacterial desiccation (Marthi et al. 1990, Walter et al. 1990).

Generally, studies have shown that temperatures above about 24°C decrease survival of all airborne bacterial species. The effects of relative humidity are more complex.

Generally, studies have shown that temperatures above about 24°C decrease survival of all airborne bacterial species. In contrast, the effects of RH are more complex. Studies on numerous bacterial species have found increased death rates at intermediate to high RH environments (Webb 1959, Won and Ross 1966), while studies on other bacterial species have demonstrated relative stability at an intermediate RH (Bolister et al. 1992) and high RH levels (Jericho et al. 1977; Dinter and Muller 1984). Other studies have shown

that airborne stability is time dependent, with a higher initial survival rate at high RH after 5 minutes (69 at 79 percent RH compared with 22 at 28 percent RH), but a lower survival rate after 45 minutes (just 2 at 79 percent RH compared with 8 at 28 percent RH (Thomson et al. 1992).

The initial state of the organisms to be aerosolized may also affect their airborne survival duration (Cox et al. 1989, 1998). In studies where bacteria were aerosolized from a liquid suspension that mimicked human mucus or saliva, the organisms became desiccated. In studies where bacteria were aerosolized from a dry dust, they were partially rehydrated. The changes in water content affected the final survival of the airborne organisms in different ways.

Fungi are yet another organism of concern in HAIs. Fungi and their spores have a greater potential than bacteria and viruses to be blown into a building that uses natural ventilation. Unlike viruses and bacteria, the natural life cycle of most fungi involves long distance dissemination of spores, mainly in outdoor environments. Evolution and natural selection over millions of years have designed fungal spores to be capable of withstanding most environmental insults, including extremes of temperature, humidity, and ultraviolet light. Some fungi that are hazardous to immunocompromised patients include *Blastomyces*, *Coccidioides*, *Cryptococcus*, and *Histoplasma* spp. (Hardin et al. 2003). Like bacteria and viruses, fungi and their spores can trigger hypersensitivity reactions such as rhinitis, sinusitis, or asthma in healthy people.

Ventilation systems have been shown to have a significant effect on indoor levels of airborne fungi. Air-handling units reduce concentrations of airborne fungi, while natural ventilation and fan-coil units increase concentrations (Burge et al. 2000; Wu et al. 2005; MacIntosh et al. 2006). Dehumidification and high-efficiency particulate arrestance (HEPA) filtration have also been used to improve indoor air quality (Bernstein et al. 2005, Ramachandran et al. 2005).

Generally, fungi and their spores are more resilient than viruses and bacteria and can withstand the stress of dehydration, rehydration, and UV radiation.

Few experimental studies have specifically examined the effects of varying temperature and RH on airborne fungi and their spores in the indoor environment. However, studies have shown that airborne fungi and spore concentrations vary with seasonal environmental factors such as temperature, RH, rainfall, and wind speed. Generally, fungi and their spores are more resilient than viruses and bacteria and can withstand the stress of dehydration, rehydration, and UV radiation (Cox, 1989, 1998; Karra and Katsivela 2007). More pathogenic fungi (e.g., Aspergillus and Penicillium) can be hazardous to humans in high concentrations owing to their ability to pro-

duce mycotoxins. However, studies have shown that they are present in air at much lower concentrations than Cladosporium and Alternaria (Khan and Wilson 2003, Basilico et al. 2007).

Given the natural resistance of fungi and their spores to environmental extremes, infection control efforts in health care facilities should focus on physical means of dealing with fungal spores.

From an infection control viewpoint, it is well known that the most common urban source of fungi and their spores is nearby building construction, which can pose daily risks to immuno-compromised patients. Given the natural resistance of fungi and their spores to environmental extremes, infection control efforts in health care facilities should focus more on physical means of dealing with them. Suitable methods include physical barriers to reduce their intrusion (e.g., installation of permanently sealed windows—that is, windows that cannot be opened by patients—in the rooms of immuno-compromised patients) or physical removal of the fungal spores by circulating indoor air through HEPA filters in the vicinity of such patients.

An extensive review of the literature provides little if any evidence that a *marginally* lower RH limit has any impact on the frequency of surgical site infections. For example; the minimum humidity level of 30 percent RH in short-term patient care areas like operating rooms was set when flammable anesthesia was used, which required 50 percent RH. The conclusion from this review of the literature is that there is little if any evidence that lowering the lower limit of RH in short-term patient care areas, as accepted by the ANSI/ASHRAE/ASHE Standard 170: *Ventilation of Health Care Facilities* standing subcommittee, has any impact on the frequency of surgical site infections. RH and temperature do impact environmental survival and transmissibility of select microorganisms (e.g., M. tuberculosis and influenza virus), but these microorganisms are found predominantly in settings far removed from an operating room or other anesthetizing location. (For more information, see the paper titled "Literature Review of the Effect of Temperature and Humidity on Viruses" [Memarzadeh 2011], which was accepted for publication in *ASHRAE Transactions* at the 2011 ASHRAE Annual Meeting in Montreal.)

12 Deposition on Surfaces

As noted in the discussion of particle dynamics, bioaerosols can fall to the surface because of gravity if the droplets are large enough or they can travel a distance suspended in the air as droplet nuclei before being deposited on a surface or mucous membrane. The survival potential on a surface depends on the nature of the surface and its moisture content as well as on the type

of microorganism, particularly whether it has a protective outer coat and what its tolerance is for dry conditions. Whether the surfaces are porous or non-porous and the quantity of microorganisms present both affect transmission. Although temperature and RH may affect microorganism survival on surfaces, well-controlled studies have yet to make a direct link between infection resulting from contact with contaminated surfaces in the environment and HAIs. As well, one of the major confounding variables—removal of contaminants or pathogens by cleaning alone, without considering chemical agents—has not been included as a measurable factor in many studies until recently.

Human influenza viruses can survive on a variety of surfaces at 35–49 percent RH and a temperature of 28°C (Bean et al. 1982, Boone and Gerba 2005). Both influenza A and B viruses were cultured from experimentally contaminated nonporous surfaces (e.g., steel and plastic) up to 24 to 48 hours after inoculation and from cloth, paper, and tissues up to 8 to 12 hours after inoculation. However, viruses could be recovered from hands for only five minutes and only if the hands were contaminated with a high viral titer. Viable viruses could be transferred from nonporous surfaces to hands for 24 hours and from tissues to hands for 15 minutes. These data support the feasibility of spreading influenza by indirect contact. The SARS virus may survive on surfaces for days at temperature and humidity levels common to indoor environments.

The SARS virus may be able to survive on surfaces for days at temperature and humidity levels common to indoor environments.

13 Strategies to Reduce HAIs

Protecting patients and health care workers from contracting health care-acquired infections via the airborne route requires reduction of microbial, viral, and fungal contaminants to safe levels. Hospital rooms are connected by doorways, corridors, stairwells, and elevator shafts. Small pressure differences, induced by natural forces such as thermal buoyancy due to air temperature differences, wind, or mechanical fans, can generate airflows that move air from one room to another. Besides increasing the number of air changes per hour, airflows can be manipulated in other ways to reduce the spread of airborne infection in an indoor environment. Advanced mathematical (numerical) modeling can provide information to help develop new methodologies for the design and construction of isolation facilities to improve the control of and reduce the risk from aerosol-transmitted infections. (Memarzadeh 2000) These methodologies can later be adapted to assess conditions in other health care areas where infectious patients are treated.

Before any strategy selected to improve indoor air quality is implemented, a thorough risk assessment should be conducted that emphasizes infection and environmental control.

Numerous strategies, some more cost-effective than others, have been employed to various degrees to improve indoor air quality. Preventive strategies include, but are not limited to, use of the following techniques (Castle and Ajemian 1987):

- Pressurization control, including to create isolation rooms
- Purging with outside air
- Improved ventilation
- HEPA and other filtration
- Ultraviolet germicidal irradiation (UVGI)
- Strict hygiene procedures

Any strategy that is selected should be preceded by a thorough risk assessment that emphasizes infection and environmental control. This assessment should be periodically revisited to assess whether the system is being properly maintained.

Ventilation Techniques

Ventilation is used to establish proper pressurization or differential airflows, which can protect against the spread of infectious diseases.

To protect against the spread of infectious diseases, ventilation is used to establish proper pressurization or differential airflows. Isolation rooms are generally designed for negative pressurization and 100 percent exhausted air. In contrast, to protect immunocompromised patients from infection, an oversupply of makeup air is used to support a positive pressure environment. Typically, exhaust air fans for isolation areas are dedicated to this use, but most supply air systems are not. Hence, due to demands elsewhere in the health care facility, the ventilation air supply may be subject to variation and the pressurization compromised in isolation rooms (Cali et al. 2000).

A methodology has been identified by Memarzadeh (2010) to calculate how much air displacement and contaminant leakage might occur during a power outage, when doors are opened and closed, and when people move about in a room. The methodology can also be used to calculate how much of such displacement and leakage may result in a momentary positive pressure reversal in areas that use sustained differential air pressure as one means to prevent infectious particle transmission (e.g., airborne infection isolation rooms and patient protective environment rooms). The assessment compares the degree of contaminant leakage that would occur through closed door gaps during momentary pressure reversal versus the contaminant leakage that

would occur when the door is opened to exit the area. This methodology can also be used to quantify contaminant migration across a boundary for other room types. The methodology provides a scientific approach that quantifies particle leakage across a barrier and includes a visual smoke test.

Filtration

Options for increasing the ability of filters to prevent spores from entering a building include the use of biocidal filters, electrostatic filters, carbon adsorbers that remove volatile organic compunds (VOCs) produced by some fungi and bacteria, low-level ozonation, negative air ionization, and photocatalytic oxidation microbial filters (Kowalski 2003, 2006).

Natural decay mechanisms operate too slowly inside most buildings to prevent secondary infections (Kowalski 1997). Pressurization control is commonly used in biohazard facilities and isolation rooms to prevent migration of microbes from one area to another. Full outside air systems are often used in health care facilities, particularly in airborne infection isolation (AII) rooms. The recirculation of HEPA-filtered air carries a lower total energy penalty (Burroughs 1997) in hot or cold climates, but in mild or dry climates using high percentages of outside air can prove economical, especially in applications involving evaporative coolers (Kowalski, 1997). Each technology has advantages and limitations, but optimization for any application is always possible if microbial IAQ goals are clearly defined.

Each filtration technology used to prevent spores from entering a building has advantages and limitations, but optimization for any application is always possible if microbial IAQ goals are clearly defined.

Filters help to intercept spores, but moisture may cause them to "grow through" the filter media. Although cooling coils can have a pronounced filtering effect on spores (Godish 1995, Samson 1994), the presence of condensation may also cause microbial growth and amplification (Woods, 1997) downstream of the coils, negating the effect. Boosting outside airflow may help reduce the infectious particle level only if the ventilation system is not the source of microbial contamination; if that is the case, increasing airflow may exacerbate the problem (Godish 1995). A fungus problem that is not caused by the ventilation system (e.g., a leaky roof or wall) requires separate remedial action such as removal of the damaged material (Kemp et al. 1995).

Physical size is the single most important characteristic by which to assess filtration efficiency (Burroughs 1998). According to ASHRAE's Minimum Efficiency Reporting Value (MERV) rating system for filters in Standard 52.2-1999: *Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size*, preventing infiltration of fungi spores requires filters with a MERV rating of 9 to 12 with up to 90 percent efficiency in

Choosing a filter that matches the health care space use and contaminant control requirements is an essential step in proper filtration application.

the 3 to 10 micron range. Preventing infiltration of bacteria requires filters with MERV ratings of 13 to 16 (with up to 95 percent efficiency in the 0.3 to 1.0 micron range). Preventing infiltration of high percentages of viruses requires high-efficiency particulate filtration, beyond the range and outside the scope of the ASHRAE MERV rating tests. Lower MERV-rated filters can be effectively applied as prefilters to reduce the larger particle loading on HEPA filters and extend the service life of the more expensive HEPA media. An essential aspect of proper filtration application is choosing a filter that matches the health care space use and contaminant control requirements (Burroughs 1998).

Filter bypass and maintenance problems can be a major source of fungal contamination in hospitals.

A major potential source of fungal contamination in hospitals is filter bypass and maintenance problems (Kowalski 2008). Because they are used to filter large quantities of outside air, MERV 7 to MERV 13 filters are likely to accumulate spores. Filters should be checked for areas where outside air is bypassing the filters, and maintenance procedures requiring shutdown of fans should be followed diligently. Otherwise, spores may enter ventilation systems and accumulate in carpeting and furnishings. Periodic surface sampling of cooling coils and drain pans can help identify potential problems.

HEPA filters are not the only choice for controlling microbial IAQ issues. Medium- or high-efficiency filters are capable of removing airborne pathogens, especially spores, without high operation or replacement costs (Burroughs 1997, Kowalski 1997, Kowalski and Bahnfleth 1998). Overall, particle removal efficiency might be improved by locating medium-efficiency filters in the recirculation loop rather than in the outside air intakes or even downstream of the cooling coils. But this choice will depend on the system's operating parameters of the individual system.

HEPA filtration is effective only when used in combination with other control measures.

It has been suggested that using HEPA filters to control airborne microbes might be an example of overkill (Luciano 1977). Currently, the only HEPA application directly linked to reduction of HAIs from fungi is their use in protective environments. Although HEPA filtration is effective, it is only so if used in combination with tightly sealed rooms, higher air change rates, positive pressure (airflow out of the room), and other control measures. Therefore, the ASHRAE 170 ventilation standard does not require HEPA filters for any other locations.

The combination of UVGI and high-efficiency filters in the MERV 13 to 15 range may be able to provide performance virtually equivalent to HEPA filtration, thus offering health care facilities reduced energy costs when such

a high level of filtration is perceived to be desirable. Even so, little published evidence is available to demonstrate the efficacy of using HEPA filtration in the HVAC system of an entire building to prevent HAIs. Using this level of filtration dramatically increases energy consumption, a factor that needs to be considered before adopting this approach as a strategy to reduce HAIs.

Ultraviolet Germicidal Irradiation

UVGI is a recognized method of inactivating a wide variety of biological agents, particularly airborne microorganisms (Rice and Ewell 2001). The literature indicates that the efficacy of ultraviolet irradiation is a function of many factors, including the intensity of the ultraviolet light, exposure time, air velocity, local airflow patterns, degree of maintenance of the ultraviolet lamp, characteristic resistance of the microbes, humidity, and lamp placement (Memarzadeh 2001, Memarzadeh et al. 2010, Lin and Li 2002; Ko et al. 2000).

Although UVGI is generally effective in reducing transmission of airborne bacterial and viral infections in hospitals, it has only a minimal effect on fungal and bacterial spores.

Use of UVGI as a supplemental air-cleaning measure requires much more research (Memarzadeh et al. 2010). Although it is generally effective in reducing transmission of airborne bacterial and viral infections in hospitals, it has only a minimal effect on inactivating fungal and bacterial spores (Banfleth and Kowalski 2000). Microorganisms are particularly vulnerable to UV light at wavelengths close to 254nm since this represents the maximum absorption wavelength of their DNA molecule. Research performed at the University of Leeds in the U.K. showed that all airborne bacterial pathogens are susceptible to the effects of ultraviolet rays, but the magnitude of the effect is extremely species-specific. For instance, two studies using S. *marcescens* showed an increase in survival of the microorganisms in the presence of UV light at higher RH levels. Bean and colleagues (1982) and Boone and Gerba (2005) showed that this may be due to the protective effect of larger particle sizes as evaporation would be less at these higher RH levels, indicating a thicker water coat offers protection from UV radiation (Riley and Kaufman 1972, Ko et al. 2000).

UVGI can be an efficient method for decontamination in the right applications (e.g., controlling microbial growth in cooling coils).

UVGI can be an efficient method for decontamination in the right applications, such as controlling microbial growth in cooling coils (Bjorn and Nielsen 2002). Continuous UV exposure appears to inhibit fungal growth and may kill the spores as well in applications involving disinfection of airstreams. A single pass through a UVGI system may have a limited effect, but recirculation, whether through stand-alone units or ventilation systems, will result in multiple exposures or chronic dosing.

Three UVGI strategies are commonly used today:

- Installation of UV lamps in ventilation ducts
- Irradiation of the upper zones of occupied spaces
- In-room irradiation after one occupant leaves and before the next arrives

Each of these strategies depends on inactivation of viable agents carried in droplet nuclei (Memarzadeh et al. 2010). In isolation rooms and some common areas (e.g., waiting rooms), UVGI is applied to upper air zones. In air-handling units UVGI is applied in close proximity to filter banks and cooling coils. To function properly, the UV emitters must have a line of sight to targeted microbial amplification sites such as wet coils, drain pans, and moisture-exposed filters (Kosar 2002).

When duct-mounted UVGI is effectively applied, it functions similarly to filtration.

In both duct and in-room UVGI applications, the amount of radiation applied can be much higher than that used for upper-zone UVGI equipment, resulting in higher exposures and quicker inactivation of microorganisms. When effectively applied, duct-mounted UVGI functions similarly to filtration. Upper-zone UVGI, when *effectively applied*, inactivates infectious agents locally and can be considered for public access and high-traffic areas such as cafeterias, waiting rooms, and other public spaces. Since exposure to UV light is particularly harmful, such devices are fitted with a number of louvers to prevent the UV light from penetrating the lower room. The goal of upper room UVGI is to inactivate infectious airborne microorganisms, primarily *M. tuberculosis* in the upper room, in order to supply the lower room with disinfected upper room air. Upper room installations rely on natural convection currents, rather than fans, to carry airborne microorganisms through the UV field.

In-room UVGI can be used to disinfect a room between occupations by successive patients. Recent research (Ko et al. 2002, Kujundzic et al. 2007, Xu et al. 2003, 2005) shows that UVGI in both upper room and in-duct configurations can inactivate some disease-transmitting organisms and thus can affect disease transmission rates (McLean 1961).

Upper air UVGI systems have been used to control respiratory infections. One study showed that UVGI can reduce airborne microbial concentrations to below 10 cfu per cubic meter in an OR. UV lamps have also been used in TB wards to control the spread of infection (Memarzadeh 2001, Lidwell 1994).

14 Managing HAI Risk

Source management, activity management, design intervention, dilution intervention, and cleaning should all be considered when determining what means are best suited to reduce the HAI risks in a particular location (Cole and Cook, 1998).

Source Management

The source of a health care-associated infection is the location where infectious organisms originate, such as the reservoirs discussed earlier. To manage potential sources of infection, consideration should be given to implementing the following activities:

- Reducing moisture in places where mold (*Aspergillosis* spp. etc.) can form
- Purging hot water systems to eliminate water and airborne infectious organisms such as Legionella
- Isolating infectious patients in negative pressure rooms or using personal protective devices such as removable clothing and respirators for health care workers
- Conducting routine inspection and maintenance of air intakes; filter banks; heating, ventilation, and air-conditioning unit components; air ducts; cooling towers; and hot water systems

Environmental sources of infections such as mold spores and dried droplet nuclei can be greatly reduced by removing and capturing both routine dust and construction dust by HEPA vacuuming or wiping down surfaces with cloths that are made of microfiber or are damp so they will not just redistribute the dust.

Activity Management

Activity management ensures that a facility is being used as intended. For example, when a lab is converted for use as an office space, contaminants may linger in the area if it is not properly decontaminated before construction. Whenever a space in a health care facility is renovated, the previous and subsequent use must be carefully analyzed and a rigorous decommissioning of the existing space appropriate to its next use must be performed. (ANSI/AIHA Z9.11-2008: *Laboratory Decommissioning*)

Design Intervention

Design approaches can be used to address infection prevention in health care facilities in a variety of ways.

Whenever possible and financially feasible, design elements for health care facilities should be mold- and bacteria-retardant and easy to clean, service, and maintain. Use of building materials and products that are less likely to harbor microorganisms should be considered. For example, ceiling tiles and carpeting are not the best choice for surfaces in certain areas in a health care facility because they are difficult to clean.

In a new design, project planners might consider including anterooms for a small proportion of AII rooms to provide a place for donning protective clothing. In many facilities, though, placing wall-mounted caddies inside or outside the AII room has been found to minimize clutter and facilitate standard precautionary procedures.

Some facilities are leaning toward a greater proportion of single-patient rooms, citing the health benefits of privacy and noise reduction. In existing hospitals with 30 patients per ward, an average of approximately five patients each week are transferred, although some wards see more than 20 moves per week (Chaudhury et al., 2003). The most frequently cited reason for these transfers is a request for privacy (greater than 50 percent), followed by patient (mis)behavior and infection control issues. Other reasons include extended stays in hospital, visitor considerations, and a needed move to an ICU setting (Chaudhury et al. 2003, 2005).

Some studies have shown that single-patient rooms reduce HAI rates as long as other basic elements of infection control are in place.

According to some studies, single-patient rooms reduce nosocomial infection rates provided that other basic elements of infection control are in place. A review of 16 studies showed reductions in both airborne-related and contact-related nosocomial infections. The evidence is more compelling for reducing airborne infections, however, and some studies show no effect from single-room isolation on nosocomial methicillin-resistant *Staphylococcus aureus* colonization transmitted by contact. (Ulrich et al. 2004, Vietri et al. 2004, Cooper et al. 2004, Cepeda et al. 2005)

Dilution Intervention

The concentration of airborne pollutants in the indoor environment can be reduced by using a number of HVAC strategies that replace pollutant-laden air with clean air. One such method is in-room filtration with ventilation control. Design engineers use ASHRAE Standard 62.1-2004 to calculate the

exact amount of outside air a system should provide. This standard attempts to balance the cost of conditioning outside air with the amount of conditioned air needed to properly dilute pollutants, providing metrics for outdoor air based on cubic feet per minute (cfm) per person and cfm per square foot, depending on the space.

Cleaning

Cleaning is the purposeful and routine process of identifying, containing, removing, and disposing of possible contaminants (e.g., dust, chemicals, droplet nuclei) from surfaces or the environment. Cleaning is best accomplished using high-efficiency filtered vacuum cleaners, damp dustcloths, and disinfectants targeted to a specific microorganism or broad spectrum organisms that might be of concern in a specific location. Studies have shown that regular cleaning reduces the concentration of fungi and bacteria in carpets and the environment.

It has now been well-documented that pathogens such as methicillin-susceptible S. aureus, MRSA, and VRE are readily transmitted from environmental surfaces to health care workers' hands (Bhalla 2004, Hayden et al. 2008, Duckro et al. 2005). Recently, the link between environmental contamination and patient acquisition of infection has been more convincingly demonstrated. Epidemiological studies have shown that patients admitted to rooms previously occupied by individuals infected or colonized with MRSA, VRE, or Acinetobacter baumanii are at significant risk of acquiring these organisms from previously contaminated environmental sites. (Dancer et al. 2006, Boyce et al. 1997, Huang et al. 2006, Denton et al. 2005)

The CDC recommends that environmental services personnel pay close attention to cleaning and disinfection of high-touch surfaces in patient care areas.

Recent studies have focused on evaluating cleaning protocols, actually measuring the thoroughness of cleaning to assess the effectiveness of its use as a basic step in ensuring the removal of potential pathogens (Carling et al. 2006a, b). The CDC recommends that environmental services personnel pay close attention to cleaning and disinfection of high-touch surfaces in patient care areas and that hospitals support compliance by housekeeping staff with cleaning and disinfecting procedures (CDC 2003a).

15 Facility Design and Operation

Building design, engineering, operations, and maintenance can play a key role in controlling HAIs. For example, the dose a patient, staff member, or visitor receives from an airborne concentration of microbes could be con-

Studies have shown that if moisture is removed within 24 to 48 hours, mold abatement is usually not necessary.

sidered a factor that is under engineering control since it is affected by the local air change rate and degree of mixing as well as the generation rate of the organism (Kowalski and Bahnfleth 1998). RH and temperature must be controlled to reduce the growth of mold and mildew. Studies have shown that if moisture is removed within 24 to 48 hours, mold abatement is usually not necessary. This is because fungal spores require about that much time to germinate, after which they can be spread and cause allergic reactions or infections. Under extended moist conditions, spore germination can be high enough to make indoor spore levels exceed outdoor levels. Control of environmental factors is also necessary to reduce or inhibit the proliferation of other microorganisms that can cause disease in immunocompromised patients. Microbes decay naturally at different rates under different environmental conditions. For example, direct sunlight contains lethal levels of UV radiation. Dehydration inactivates most microbes except those with spores. High temperatures and freezing eventually inactivate all pathogens with the exception of some spores. Oxygen kills most airborne microorganisms through oxidation. Pollution can be fatal to microorganisms.

Although humans are almost exclusively the source of contagious viruses and bacteria in the indoor environment, spores and environmental bacteria may enter a health care facility from the outdoors by inlet air, or infiltration. They may also be brought in with building materials, carpets, clothes, food, pets, or potting soil. Once spores germinate and growth occurs in an air-handling unit or anywhere inside a building, new spores may be generated. Such spores as well as viable microorganisms may be disseminated in the return air of the ventilation system. In a normal, dry building, the return air will have lower levels of spores than the outdoor air, except when snow covers the ground and outdoor spore levels approach zero. But once growth occurs indoors, spores may appear in the return air at higher levels than in the outdoor air.

The optimal mix of technologies for reducing the spread of HAIs is not known and varies by geographic location. Life cycle costs of MERV 7/14 filtration of recirculated air tend to be more cost-effective in hot and humid or cold climates, while in mild or dry climates large volumes of outside air can more economically be used for ventilation. In mild or dry climates, then, combining ventilation air with filtration results in overall performance that is essentially additive, making cost optimization straightforward (Dragan 2000a, b). When ventilation is not considered sufficient in specific areas, filtration can be used to remove fungi (spores) from incoming outdoor air and the bulk of bacteria and viruses from recirculated air, while ventilation delivers dilution air from outdoors to further decrease concentrations of all

airborne microbes proliferating indoors (Kosar 2002). UVGI can be added to target vulnerable bacteria (excluding spores) and viruses in AHU (air-handling unit) microbial amplification sites.

A review of the applicability and relative contribution of UVGI to disinfection of air in health care facilities has led to the conclusion that UVGI should be considered as a disinfection application in a health care setting only in conjunction with other well-established strategies, such as appropriate heating, ventilation, and air-conditioning (HVAC) systems; dynamic removal of contaminants from the air; and preventive maintenance combined with thorough cleaning of the care environment (Memarzadeh et al. 2010). UVGI is not efficacious as a primary intervention to kill or inactivate infectious microorganisms or to meet indoor air quality requirements for health care facilities. More targeted, multi-parameter studies are needed to evaluate the efficacy, safety, and incremental benefit of using UVGI to mitigate reservoirs of microorganisms and ultimately prevent cross-transmission of pathogens, which leads to health care-associated infections.

More research is needed to evaluate the efficacy, safety, and incremental benefit of using UVGI to mitigate reservoirs of microorganisms and ultimately prevent cross-transmission of pathogens.

At present, the use of air-cleaning technologies such as UVGI or photocatalytic oxidation to inactivate biological agents is viewed as insufficiently reliable and lacking in proof of efficacy. Both full-flow and side-stream filtration are options that an owner or engineer might consider instead. (Kowalski and Bahnfleth 2003).

Three air-cleaning technologies are successfully being used today. Air-purging is a ventilation system function that uses outdoor air. Systems that employ 100 percent outdoor air have an advantage against internal releases of pathogens, depending on the number of air changes per hour (ACH). Microorganisms are removed or purged from the building by dilution ventilation at the same rate as the ACH. Filtration is a highly effective method for removing most particulate contaminant agents. The efficacy of filtration depends on the medium used to filter the particles, the location of the filter, and the condition of the filter. UVGI exposure is characterized by UVGI rating values (URVs). A UVGI system consisting of 20 gradations of average UV intensity has been proposed (Kowalski and Bahnfleth 2003). URV ratings parallel MERV ratings and provide a convenient way to match filters and UVGI systems for aerobiological applications. The two rating approaches show that, for any given building, there is only one appropriate air-cleaning-system size and that size is independent of the agent tested. The size of a MERV/URV-rated system is a function of ventilation flow rate and building volume. Microorganism removal rates can be boosted further by increasing either the total airflow rate or the outside airflow rate.

HVAC design features intended to inhibit the spread of airborne hazards include the use of ducted returns (NIOSH 2002) and compartmentalized zoning (USACE 2001, ASHRAE 2003). Positive pressurization of buildings relative to the outdoors is beneficial as a means of limiting vulnerability to infiltration of pathogens from outdoors. Zoned pressurization, when feasible, may assist in the containment of an indoor release of pathogens and protection of egress paths. Envelope tightness is important for preventing entry of airborne hazards and for helping to control them using pressurization strategies (NIOSH 2002, ASHRAE 2003).

Various current or experimental technologies have the potential to reduce airborne disease transmission or indoor amplification. Biocidal filters can limit or prevent fungal growth on the filter media. Electrostatic filters (i.e., electrically stimulated filters) are available but are not widely used. Carbon adsorbers have pore sizes too small to remove viruses, but they are effective at removing VOCs produced by some fungi and bacteria. Other technologies currently being researched include low-level ozonation, negative air ionization, and photocatalytic oxidation, a technology that may one day result in a type of light-powered, self-cleaning microbial filter.

Current guidance that applies to both disease transmission and building security recommends layering of multiple modes of protection. An HVAC system's capability and gas phase filtration should be considered when a risk of attacks with chemical agents is perceived.

Standard operating procedures should be developed to accompany any strategy a health care organization chooses to manage infection prevention.

Standard operating procedures (SOPs) should be developed to accompany any strategy a health care organization chooses to manage infection prevention. When new strategies are adopted for an existing facility, SOPs currently in use must be updated. Consideration should be given to reducing and preventing HAIs during the earliest stages of project planning and for every aspect of design, construction, operations, and maintenance of a health care facility.

16 Implications of Bioweapons for HAIs

Hospital bio-preparedness and hazardous infectious disease planning is mandated by the Joint Commission and the CDC. Hospitals need to be ready to care for patients with avian influenza, severe acute respiratory syndrome (SARS), or other as yet unidentified infectious diseases while assuring staff safety. Given recent government mandates, hospitals are better prepared to convert, dedicate, or staff a ward to handle a potentially hazardous airborne

infectious disease crisis. Even now, a hospital might have to provide care for an occupational exposure to a highly contagious illness (Rusnak et al. 2004).

The challenge to professionals who design, construct, and operate HVAC systems is to adopt security as a design parameter in addition to comfort, health, energy conservation, and other more routine considerations.

The ever-present threat of exposure to a bioweapon agent has greatly affected how we look at prevention control measures. The challenge to professionals who design, construct, and operate HVAC systems is to adopt security as a design parameter in addition to comfort, health, energy conservation, and other more routine considerations. The National Institute for Occupational Safety and Health (NIOSH) notes that measures used for air-cleaning "also provide the side benefits of improved HVAC efficiency, increased building cleanliness, limited effects from accidental releases, and generally improved air quality."

The World Health Organization (World Health Assembly 1967) defines a biological agent as one that produces its effect through multiplication within a target host and is intended for use in war to cause disease or death in human beings, animals, or plants. The public health threat of deadly infectious diseases from a deliberately released biological agent touched the United States with the release of *Bacillus anthracis* (anthrax) spores in letters mailed to public officials in 2001. The airborne and contact contamination from *B. anthraces* resulted in five deaths and 17 infections, leading to as yet uncalculated millions of dollars in costs to decontaminate entire buildings, intensified security surveillance, and a criminal investigation that was not formally closed until February 19, 2010 (various Internet resources; search "anthrax timeline").

For a biological weapons agent to be efficacious, it must be mass produced in a viable, communicable form; be highly lethal and stabile in an aerosol form of 17μm to 5 μm particle size for dispersal and infectivity (Kortpeter and Parker 1999); and be virulent, pathogenic, and contagious and have an incubation time compatible with the existing environmental conditions and the target host (Venkatesh and Memish 2003). It may or may not produce a toxin that can be inhaled or absorbed through membranes. Such aerosolized agents are generally susceptible to weather conditions, however. Some microorganisms of concern for HAIs (i.e., bacteria, rickettsia, viruses, and fungi capable of entering the human body by inhalation or ingestion and multiplying and causing illness and death) are the same microorganisms that could be effective as biological weapons (Venkatesh and Memish 2003).

The organisms and toxins commonly associated with bioweapons are *B. anthracis,* variola (smallpox), *Yersinia pestis* (plague), staphylococcal enterotoxin B, Botulinum toxin, Venezuelan equine encephalitis (VEE) virus, *F.*

tularensis (tularemia), *Brucella suis, Coxiella burnetti* (Q fever), the genetically unique animal-borne RNA virus of the filovirus family that causes Marburg Hemorrhagic fever, Ebola virus, *Burkholderia pseudomallei* (found in soil and water and causes melioidosis), and the rickettsia bacteria that cause typhus.

Brucella suis is of particular interest because, although infections are treatable, the course of antibiotics can last nine months or more and the infection is difficult to eliminate entirely. A widespread outbreak of brucellosis could result in an economic disruption due to the expense and availability of long-term antibiotics.

An aerosolized exposure to smallpox virus, unlike exposure to other agents such as anthrax, plague, or botulinum toxin, could cause a public health catastrophe because of its communicability by aerosol and the potential lack of treatment for the disease. The virus is relatively stable in the natural environment and, if aerosolized, retains its infectivity for at least several hours if not exposed to sunlight or ultraviolet light.

Plague, like smallpox and anthrax, can decimate a population. Both plague and tularemia are potentially lethal without proper treatment, and are infectious at low doses. The person-to-person communicability and untreated case fatality rate of pneumonic plague is at least twice that of tularemia. However, effective treatments and prophylaxis are available for both diseases, which may reduce possible damage to a population.

The hemorrhagic fevers—Marburg, Ebola, and Lassa fever from the Arenaviridae family; Rift Valley fever and Crimean Congo hemorrhagic fever from the Bunyaviridae family; and the recently recognized Lujo virus, which is capable of causing hemorrhagic fever—are classified as potential biological agents because of their lethality and high aerosol infectivity shown in animal models (Franz et al. 1997). None of these hemorrhagic fevers has a known successful cure, and treatments are palliative at best.

An attack on an office building might include an outside air release of pathogens, a release in the outside air intakes, a release in the air-handling unit (AHU), or a release in a general area of the building (Kowalski and Bahnfleth 2003). A release into outside air intakes would pose the greatest threat to occupants because the agent would enter the ventilation system and be distributed throughout the zones served by the system. If an AHU contains air-cleaning devices such as filters or UVGI, concentrations of the pathogen could be reduced dramatically. In both an outdoor release and an air-intake

release, a large fraction of the bioweapon agent may be removed on the first pass through a filter unit, with the remaining concentration reduced through purging and recirculation over time. If a bioweapon agent were released in a general area of a building, such as a lobby or atrium, concentrations would be high in the vicinity of the release, but considerably lower elsewhere. Although the agent would circulate, it also would be ex-filtrated or purged at the normal building outside-airflow rate. Concentrations in the release area would remain high until the agent was purged, while the concentrations in other areas would not reach levels as high as those in the air-intake release scenario. This may not always hold true for large internal auditoriums and atria or where stack effects play a major role in redistributing airflows. In general, a release inside an AHU downstream of the filters would produce the highest overall airborne concentrations in a building, which is good reason to lock equipment rooms and restrict access (USACE 2001).

As unlikely as a bioweapon threat may be, the implications of the release of a biological agent either inside or outside a building are profound. For one thing, exposure to a lethal infectious agent has the potential to lead to a pandemic.

Design features that might protect against the release of a causative agent inside a building, or that might protect building occupants from an external release, can also be used to mitigate everyday exposure to organisms that might cause infection.

Design features that might protect against the inadvertent release of a causative agent into the environment from inside a building, or that might protect the building population from an external release, can also be employed to mitigate everyday exposure to organisms that might cause infection. "Immune building technologies" have been proposed to suppress or resist harmful microbial contamination. For airborne pathogens that might be used as bioweapons, these include dilution ventilation, filtration, and UVGI (Kowalski and Bahnfleth 2003).

Many pathogens other than those described above can cause illness and death. Again, recognition of the importance of an appropriate surveillance system and laboratory capability to identify new pathogens will help to improve public health and the ability of medical practitioners to respond to the most dangerous naturally occurring biological pathogens that could be used as bioweapon weapons (Kortpeter and Parker 1999).

In general, anthrax spores are relatively easy to filter, but are resistant to UVGI; smallpox is able to penetrate filters, but is highly susceptible to UVGI; TB bacilli are removable by either filtration or UVGI. In its weaponized form, botulinum toxin is typically a powder consisting of particles measuring 0.9 to 5.8 microns. Although particles of this size are usually 100 percent removed by MERV 13 to 15 filters, there is insufficient data to suggest that UVGI can

break down botulinum toxin. Botulinum toxin is therefore assumed to be completely resistant to breakdown under UVGI exposure.

It is good engineering practice to locate air intakes at a second-story level or higher. For roof top or ground-level intakes that cannot be modified, NIOSH (2002) recommends establishment of a security zone to limit access. Secure access to HVAC and other building system controls is recommended by Lawrence Berkeley National Laboratory (2003) and ASHRAE (2003). This is important because of the potential for manipulation of HVAC controls by unqualified persons and terrorists. Shelter in-place responses to attacks and other hazardous releases require that buildings have areas that can be isolated, at least for a time, from surrounding contaminated spaces.

Other measures include securing mechanical rooms, securing return air grilles, restricting roof access, and similar tactics. Restricting access to building information that could aid in planning an attack is also recommended. The ASHRAE report (2003) titled "Risk Management Guidance for Health, Safety, and Environmental Security under Extraordinary Incidents" provides a particularly thorough list of security vulnerabilities that should be evaluated and eliminated.

The ASHRAE report (2003) notes that "sensors, monitors, and other means of forewarning are not presently available or reliable for many contaminants. Therefore, strategies other than feedback control are relied upon today and for the foreseeable future." ASHRAE recommends that a building system have "a control sequence continuum from normal operations to effective responsiveness during the occurrence of an extraordinary incident." Two possible responses to an extraordinary incident are distinguished by the presence or absence of protective features.

When protective measures are available during an internal release, HVAC controls should isolate the zone and start any special air-cleaning components. Controls should also operate intake and exhaust dampers to regulate building pressures. During an external release of a known agent, with protective measures in place for that agent, the system should continue to run. When there is doubt regarding either the agent or the efficacy of countermeasures, the system should be shut down. Shutdown may be most appropriate in response to outdoor releases. Interior pressurization may be useful in other circumstances to protect egress and prevent spreading of agents. Low-leakage, fast-acting outdoor air dampers are recommended to minimize the spread of agents through HVAC distribution systems whether they are operating or shut down.

When protective features are not available, shutting down the system is the only alternative to normal operation. However, because this may increase exposure to the agent if it is being released internally, conditions under which a shutdown would occur should be carefully reviewed. The need to design control responses in consultation with qualified professionals is emphasized, as is the importance of training staff responsible for carrying out a response plan that involves the HVAC system.

The need to design HVAC control responses in consultation with qualified professionals is emphasized, as is the importance of training staff responsible for carrying out a response plan that involves the HVAC system.

17 The Future is Now

Increasingly, hospitals appear to be incorporating infection control precautions under the guise of patient privacy and comfort, such as private rooms. Many acute care hospitals in the Washington, D.C., community, for example, are converting their patient rooms to single-patient spaces (*Washington Post*, October 9, 2010). Their justification is that consumers are demanding privacy and older rooms cannot accommodate the glut of new technologies and equipment needed to care for patients. Although these reasons may be valid, too, research supports adoption of single-patient rooms because of the health benefits of isolation.

Along with new vaccines that prevent many airborne viral infections, improved ventilation techniques are a significant reason for the reversal in the trend toward increased infection rates seen in the past several years. Potentially infectious patients are placed in rooms that are negatively pressurized to prevent infectious microbes from spreading even before a diagnosis is confirmed. Immunosuppressed patients are placed in positively pressurized rooms to prevent them from coming into contact with infectious organisms. Immunosuppressed patients who are also infected are placed in rooms that have anterooms, when they are available, to remove the pathogenic particles (e.g., V zoster or TB) from the infected patient.

Single-patient rooms, new vaccines, and improved ventilation techniques have contributed to the recent reversal in the trend toward increased HAI rates.

A more unusual facility type is a biocontainment patient care unit (BPCU), which is designed and operated to maximize patient care with appropriate infection control practices and procedures. BPCUs are secure and physically separated from other patient care areas, have special air-handling systems, and accommodate advanced personal protective measures for staff (Smith 2006). BPCUs have been designed and built in several facilities across the United States. The first was built at the U.S. Army Medical Research Institute of Infectious Diseases (USAMRIID) at Fort Detrick, Maryland, to care for patients with possible laboratory-acquired infections caused by exotic, highly

hazardous pathogens (Marklund 2003). Until recently, only three other facilities in the United States have been designed to safely care for patients with serious communicable illnesses: Emory University Hospital in Atlanta; the University of Nebraska Medical Center in Omaha; and St. Patrick's Medical Center in Missoula, Montana.

18 Conclusions

The concentration of biological particles in indoor air is usually significantly lower than that of non-biological particles like dust. Thus, the behavior of biological particles in the air cannot be investigated in isolation. Viable infectious agents, inanimate materials, and air currents inevitably interact in a way that affects the biological agent, although to date, the nature of this interaction has not been well characterized.

Standardized, repeatable research into the transmission of disease and how pathogens react to differing environmental conditions is needed.

Observational human and animal studies suggest airborne transmission of infectious agents is conducted via small particle aerosols, but few data support airborne transmission over long distances or prolonged periods. The variability among strains of viruses and microorganisms also infers that their responses to specific environmental conditions may vary significantly, making it beneficial—if not practical—to conduct controlled studies for each strain.

Clearly, there is a need for additional research into the transmission of disease. This research needs to be standardized and repeatable and must closely examine the variability in bacteria, viruses, and fungi and how they react to differing environmental conditions. It will be crucial to establish specific airborne-contamination limits, increase the use of air sampling to identify nosocomial sources, use innovative technologies on a larger scale, and explore green technologies, energy-efficient methods of controlling airborne microorganisms, and the use of new antimicrobial materials.

Future recommendations for controlling environmental conditions to reduce infectious virus transmission will need to consider the comfort of patients and staff and, importantly, the length of patient stay.

Infection prevention using today's available resources is critical.

The optimal conditions for suppressing viruses, bacteria, and fungi are different. Therefore, health managers must decide which airborne pathogens pose the most risk to patients and staff and prioritize environmental remediation measures accordingly for their health care facility.

Prevention using today's available resources is critical. The most important infection prevention strategy is often overlooked—immunizations. Hospitals

today maintain a basic immunization history for all personnel and require that all employees keep critical vaccinations (Hepatitis B, Bordetella pertussis, and the basic airborne viral infections—chicken pox, measles, mumps, rubella, etc.) up-to-date. After vaccinations, management must be diligent in requiring personnel to wear personal protective equipment and properly discard contaminated needles, paper products, and invasive equipment such as catheters. Maintaining a training program in appropriate patient care, cleaning, and disinfection practices can have long-term benefits in reducing transmission of airborne disease and protecting staff and patients. Although it is known that a combination of methods is best for controlling the transmission of airborne infectious agents, research is still needed to obtain the data to identify more effective policies and practices. Major infectious disease and infection control organizations such as the Association for Professionals in Infection Control and Epidemiology (APIC), and the Society of Healthcare Epidemiologists of America (SHEA) in conjunction with the CDC and CDC/NIOSH are undertaking research to begin to answer some of the questions about how engineering controls and human behavior affect infection prevention.

Maintaining a training program in appropriate patient care, cleaning, and disinfection practices can have long-term benefits in reducing transmission of airborne disease and protecting staff and patients.

Of course, not all patients colonized with a potential disease-causing organism will develop an SSI or other HAI. An infection is more likely to occur in a patient who is immuno-compromised than in a relatively healthy individual undergoing a procedure. The potential for infection depends on the number of microorganisms entering the wound, the type and virulence of the microorganisms, and the effectiveness of the host's inflammatory response and immune system status as well as the duration of the hospital stay.

Research findings underscore the importance of improving risk management and infection control practices and the vital part that collaboration between HVAC engineers and facility managers should play in such efforts. Precautionary measures are needed to control the increasing number of antibiotic-resistant disease strains, particularly in locations like long-term care facilities, where resistant strains tend to persist and become endemic.

Research shows the importance of improved risk management and infection control practices and the vital part collaboration between HVAC engineers and facility managers plays in such efforts.

Security considerations must also be integrated with other design and operations criteria. Layering of multiple modes of protection should be considered. Access and information control, HVAC and building design, and occupant training can be combined with other measures to make buildings safer without making them less open or conducive to productivity.

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