Understanding the Role of Facility Design in the Acquisition and Prevention of Healthcare-Associated Infections

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The *Health Environments Research & Design Journal* (HERD) is an interdisciplinary, peer-reviewed journal whose mission is to enhance the knowledge and practice of evidence-based healthcare design by disseminating research findings, discussing issues and trends, and translating research into practice.

The vision of HERD is to improve measurable healthcare outcomes as a result of enhancing healthcare environments for those receiving and providing care.

HERD is the only journal featuring evidence-based articles on the design of health environments and the design-related outcomes associated with safety, clinical results, organizational performance, economics, and the human experience. The commitment to an interdisciplinary design process is reflected in HERD’s interdisciplinary Editorial Board, with representatives from healthcare (including nursing, medicine, and healthcare administration), the design industry (architecture, engineering, interiors, graphics), environmental and behavioral psychology, neurosciences, systems and organizational effectiveness, art, music, and other complementary fields. The journal centralizes knowledge about healthcare innovations and design while addressing significant industry challenges to improve patient outcomes, reduce errors, and enhance the work environments of healthcare professionals.

As a translational journal linking research to practice, HERD features both rigorous research from academic sources and applied research from practice. Submissions from both scholars and practitioners are welcome. All will be held to high standards.
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Creating a Healing Environment

Carolyn M. Clancy, MD

The realities of healthcare-associated infections, or HAIs, are as familiar as they are distressing. Suffice it to say that HAIs—such as infections caused by methicillin-resistant *Staphylococcus aureus* (MRSA), or infections of the surgical site, urinary tract, or bloodstream—are a major healthcare problem. These deadly, costly infections afflict 1 in 20 hospitalized patients in the United States at any one point in time. But they are also largely preventable. HAIs are not simply an unfortunate consequence of care, as clinicians once thought. Certain targeted interventions can be highly effective at preventing them.

Now the question before us is, what do we do with this knowledge? How committed are we, truly, to combatting HAIs? I believe that the answer is a promising one. The reduction and eventual eradication of HAIs is a high priority goal of the U.S. Department of Health and Human Services (HHS). HHS has explicitly demonstrated this commitment in its *National Action Plan to Prevent Healthcare-Associated Infections: Roadmap to Elimination* (2012). HHS and its Agencies, including the Agency for Healthcare Research and Quality (AHRQ), have been working closely with stakeholders, including providers and provider organizations, to discover and promote proven practices that will combat HAIs. Fortunately, the evidence base behind HAI elimination strategies is growing (Clancy, 2011). Because we now know that HAIs are largely avoidable, we must examine every aspect of the care environment to ensure that we are doing our best to minimize patients’ exposure to potential infection. The built environment is one such aspect that demands our attention.

The design of the healthcare facility environment (including layout, placement of equipment, and ease of access to materials) has the ability to improve patient safety, and more specifically, prevent the spread of HAIs (Ulrich et al., 2008) (Zimring et al., 2013). For instance, we’ve learned that single-bed rooms and
improved air filtration systems can reduce the transmission of pathogens causing HAIs. We also know that we can improve hand hygiene—a strategy long ago shown to prevent infections—by making it easier and more convenient for staff to wash their hands prior to care by carefully incorporating sinks and other hand sanitizing tools into building design (Ulrich, Zimring, Quan, Joseph, & Choudhary, 2004).

Since the movement to link design to patient safety emerged more than 10 years ago, AHRQ has gradually increased its support for research to expand the evidence base in this area (AHRQ, 2010). One of the first projects to come to fruition in 2007 was a DVD, “Transforming Hospitals: Designing for Quality and Safety,” promoting best practices in evidence-based design (EBD) (AHRQ, 2007). Since that time, the Agency has funded other projects that incorporate design and human factors into their research aims. The articles contained in this HERD Supplement are a result of that support, and they advance an overarching conclusion that will not surprise any architect: the built environment can affect patient safety. Healthcare workers can take steps to limit HAIs, and our buildings can either help them do so or erect barriers to keep them from doing so. Good design should make the right thing to do the easy thing to do.

We can conclude that it takes two kinds of science to fight HAIs. The first is traditional infection control science—i.e., the study of infections, how they can be prevented, and how they should be treated should those prevention efforts fail. The second kind of science has been less clear to us until recently but is no less important—behavioral and human factors science, including how design can affect our work. This systems science is of critical importance, because it directly affects how we spend billions of dollars on healthcare facility construction. EBD is a foundational aspect of this second kind of science. Ultimately, these two kinds of science should work together in multidisciplinary fashion, as evidenced throughout the articles found in this Supplement.

As healthcare leaders, we must look around our own physical environment with the goal of ensuring the healthcare building contributes to, rather than impedes, the process of healing. We have accomplished a great deal in the past decade to understand how our buildings impact the ability to heal. Every time a hospital needs to be built, every instance in which a nursing home needs an upgrade, is an opportunity to spend precious resources wisely. Every construction project offers the opportunity for a series of practical decisions to be made, based not only on what is best for patients but also on workflow, cost, and aesthetics. The patients’ needs must always come first and incorporating design elements that help to limit the potential for infection is critical to meeting those needs. I believe that the advancement of EBD can help us achieve both safety and value with the goal of creating and maintaining a healing environment.

CAROLYN M. CLANCY, MD, was at the time of this writing the Director of the Agency for Healthcare Research and Quality. She is currently Assistant Deputy Under Secretary for Health, Quality, Safety and Value at the U.S. Department of Veterans Affairs.
References


Healthcare-associated infections (HAIs) have been a concern of nurses since the time of Florence Nightingale, who first introduced the concept as important to patient outcomes with the soldiers in the Crimean war. Nightingale’s notations about the importance of clean air and ventilation, light, cleanliness, noise, variety, and sanitation are the foundations for the concept of “healing environments” today and the first recognition that infectious diseases could be transmitted from patient to patient, patient to caregiver, and caregiver to patient (Nightingale, 1992).

In *Notes on Hospitals* (Nightingale, 1863), Nightingale discussed her concerns about the sanitary conditions of hospitals and explained the definition of “infection” as compared to the notion of “contagion.” She suggested that there were four causes of healthcare- or hospital-associated diseases and/or infections: (1) the congregation of the sick under one roof, (2) the deficiencies in space per bed, (3) the deficiency of fresh air, and (4) the deficiency of light. Nightingale stated that the close proximity of numerous patients in the open with minimal space between patients was a cause for increased morbidity and mortality in city hospitals such as the Hotel Dieu in Paris as well as hospitals in London, India, and France. She was also very concerned about the lack of fresh air for patients, who often recovered in putrid-smelling open wards with a lack of sanitation, freshwater, or disposal of human wastes. This book outlined concerns of dumping wastes in open drainage systems that often contaminated the source of drinking water and subsequently spread gastrointestinal diseases among the patients and caregivers. Her book also outlined many recommendations for the design and construction of hospitals to prevent the spread of diseases and to provide a safer environment for patients. Nightingale suggested that the distance from the beds to the windows be minimized and suggested having windows on both sides of the open bed wards to provide improve ventilation for the patients. She was also
concerned about the types of materials that were used on the floors and walls and recommended that that the materials used be easy to wash and clean.

Nightingale was the first to be concerned not only about patient safety and hospitals but also about the safety of caregivers. In her book (1863), she mentioned that hospital nurses were particularly at risk for catching the diseases of their patients, and described cases where washer women would “catch” diseases from the hospital laundries. She gave instructions on how hospitals should be drained of sewage, how kitchens should be designed, how to dispose of linen, and how to ventilate open wards. Nightingale was not only the “mother of the nursing profession” but she was also a statistician, politician, and a woman of influence and affluence, able to support many of her recommendations with statistical evidence about the effect of poor hospital design, overcrowding in hospitals, and poor ventilation on the transmission of diseases among patients and caregivers. Because of her social influence, she made significant changes in hospital design that impacted hospitals for over a century. She was one of the first who kept statistical records comparing hospitals’ infection, mortality, and morbidity rates.

Nurses today are no less concerned about the “sanitary conditions” of hospitals. All nurses receive basic education in microbiology and infectious diseases, and on-the-job training and orientation regarding care of patients with transmittable infectious disease processes. Most other disciplines have similar orientation and training focused on reducing the cross-contamination of infectious diseases from one patient to another. In spite of hospitals’ efforts to inform and monitor nursing and other professionals’ practice, hospital-acquired infections continue to be a serious life-threatening risk to both patients and caregivers.

**Influence of Hospital Design on the Transmission of Infectious Diseases**

Not much changed in hospital design from Nightingale’s day until the 1970s, when hospital designers and healthcare leaders encouraged the move from multi-bed, open-ward designs to semi-private rooms. There were a few private rooms on most patient care units, but the influence of single rooms for maternity care with a homelike environment encouraged the design of single-patient rooms on other clinical units as well. In early 2000s, recommendations were made by design industry professionals and a few healthcare leaders for the design of single-patient rooms on all patient care units with the goal of decreasing nosocomial infections, improving patient satisfaction, and providing patient privacy. The new guidelines and recommendations for single room design in critical care settings and general acute care settings have demonstrated effectiveness in reducing the transmission of infectious processes and antibiotic use (Levin, Golovanevski, Moses, Sprung, & Benenson, 2011).

Although there is some emerging evidence that the physical environment can contribute to reducing the transmission of infections, it is widely recognized that design changes must be supported with patient safety initiatives to enculturate the belief among all healthcare providers that the most significant culprit in transmitting infections from one person to another is the human hand.
Any design initiative with the goal of decreasing healthcare-associated infections must recognize that hand washing sinks and gel dispensers must be visually obvious and convenient for the caregivers to ensure compliance with hand hygiene.

**Nurses Are Instrumental in Creating Safety Cultures**

Recent changes by the Centers for Medicare and Medicaid Services (CMS) to the inpatient prospective payment system and concern about preventable HAIs has captured the attention of nurse and other hospital leaders. There are strong financial disincentives and penalties for hospitals that are above benchmarked rates of healthcare-associated conditions including hospital-acquired infections. Recognizing that nursing has strong influence on the prevention of HAIs, the American Nurses Association (ANA) developed the National Database of Nursing Quality Indicators (NDNQI), outlining 14 indicators that are specific to nursing and forming the monitoring scorecard that compares more than 1,100 hospitals nationwide on each of the nurse-sensitive indicators. The indicators outline structures, processes, and outcomes that reflect the quality of nursing care of patients. It should be noted that one indicator, nosocomial infections, includes urinary catheter-associated urinary tract infections (UTIs), central line-associated bloodstream infections (CLABSIs), and ventilator-associated pneumonias (VAPs), which nurses can influence in their specific care processes. It should also be noted that the working conditions (staffing levels) and environment (unit design, availability of equipment and resources) in which nurses deliver patient care are also considered to be sensitive indicators that can influence patient outcomes (Patrician, Loan, McCarthy, Brosch, & Davey, 2010; Stone, Clarke, Cimiotti, & Correa-de-Araujo, 2004).

It has also been demonstrated that the nurses’ level of knowledge and judgment play a critical role in the prevention, mitigation, and creation of adverse events, and that nurses’ specialty certification and clinical expertise are important contributors to decreasing hospital-acquired UTIs (Kendall-Gallagher & Blegen, 2009; Ribby, 2006) and VAPs (Fox, 2006). With this in mind, a number of hospitals have developed mandatory education for all employees regarding their role in infection control and have created learning modules to ensure nurses’ competence in preventing healthcare-associated infections. With the financial penalties for HAIs, the data suggests that the greatest financial opportunity for hospitals is to prevent the infections from happening in the first place (Virkstis, Westheim, Boston-Fleischhauer, Matsui, & Jaggi, 2009).

Recognizing that hand washing is the single most effective way to prevent healthcare-associated infections, hospitals invest heavily on cultural change strategies and self-assessment to improve compliance with hand washing among all professionals. Safety campaigns are often launched to increase awareness about the causes of HAIs and the necessity of hand washing and to encourage patients and families to raise concerns when they observe professionals initiating care without washing their hands (Cam, 2004; Cole, 2009). The main barriers to hand washing compliance are high occupancy, poor staffing levels, inappropriately placed hand gels and hand washing sinks, and the failure of staff to see the consequenc-
es of their actions or inactions, since the actual infection appearing in patients may occur after discharge from the hospital. Safety campaigns, in-service education, and frequent discussions about the importance of hand hygiene, the use of gloves in care processes, and other interventions to reduce transmission of infectious diseases will improve the safety culture among all staff.

Over the past year, I have witnessed the nursing and medical care of a family member in two hospitals near my home. I have been amazed at the difference in how the nursing staff, physicians, and housekeeping staff approached infection control in the two hospitals. In both hospitals, hand gel dispensers were located immediately adjacent to the entry door of the patient room. Glove boxes were also located at the door and on the headwall in the patient room. The only sink for hand washing was located in the patient bathroom and in locations in the hallway. Therefore, the environmental conditions were the same in both hospitals.

While at one of the hospitals, I observed volunteers coming into the patient room each day with microcidal-infused cloths to wipe down all frequently touched surfaces including the hand gel dispenser lever, door handles and push plates, the patient's overbed table and bedside table, all medical equipment, the patient bed side rails, the trash and linen hampers, and the seating and sofa bed for visitors. I was amazed at this action and as a family member witnessing the cleaning process, I was reassured that this hospital was serious about their mission and vision to ensure patient safety by reducing the potential for HAIs. I began to think about all of the times that I, as a nurse, had pushed the lever for the hand gel to be dispensed without recognizing how contaminated the lever was from other previous users. Observing the daily wipe down of all frequently used and touched surfaces made me more conscious of surfaces that could potentially transmit infections and influenced my belief that this hospital provided a higher quality of care as compared to the other hospital.

Nurses' Exposure to Infectious Diseases

While this editorial, and this special supplemental issue of HERD, focuses on patients and healthcare-associated infections, nurses and other healthcare workers are also threatened by a wide range of potential work-acquired infectious diseases. Nurses are exposed to blood and body fluids and blood-borne pathogens in their work with most exposures involving needle sticks, splashes or sprays of fluid to the eyes or mouth, or direct contact with infected blood or non-intact skin. It is estimated that there are 600,000 to 800,000 work-related needle stick injuries each year in the United States, and studies indicate that high workloads and poor organizational climate are the major contributors to needle stick injuries or near misses among hospital nurses (Stone et al., 2004). The actual design of the patient room with the location of sharp boxes for the disposal of uncapped needles and other sharp devices and the location of contaminated supply disposal units would likely decrease the incidence of such injuries. Nurses’ perceptions of unsafe working conditions may negatively affect recruitment and retention of qualified staff. Nurses must be assured that their health and safety concerns are
also important as hospital leaders emphasize the importance of reducing hospital-acquired infections for patients and families.

Clinical nurses are a critical resource for decreasing the risk of healthcare-associated infections in the surveillance of care practices that could increase the transmission of infections and for the enculturation of safety practices that are essential for reducing healthcare-associated infections for patients and providers.

References


Understanding the Role of Facility Design in the Acquisition and Prevention of Healthcare-Associated Infections

Kendall K. Hall, MD, MS, and Douglas B. Kamerow, MD, MPH

Healthcare-associated infections (HAIs) are a serious and costly threat to public health in the United States, afflicting an estimated one in 20 hospitalized patients at any given time. Hospital-acquired infections alone were responsible for between $28 billion and $33 billion in excess health-care costs in 2002 (U.S. Department of Health & Human Services, 2012). Over the past decade, the importance of these infections as causes of preventable harm has gained increasing attention among both healthcare professionals and other groups, including consumer advocates, payers, and legislators. In part stimulated by legislative mandates and public reporting of HAI rates, there have been expanded efforts to eliminate preventable HAIs.

To date, work related to HAI prevention has predominantly focused on changing clinician behaviors and improving teamwork and the “safety culture.” Many of these efforts have targeted specific infection types and focused on standardizing best practices, including improving hand hygiene compliance and implementing evidence-based care strategies such as the way central venous catheters

KEYWORDS: Built environment, design process, evidence-based design, healthcare-associated infections, hospital

AUTHOR AFFILIATIONS: Kendall K. Hall is a Medical Officer with the Agency for Healthcare Research and Quality in Rockville, Maryland. Douglas B. Kamerow is a Chief Scientist in Health Services and Policy Research at RTI International in Washington, D.C.

ACKNOWLEDGMENTS: The authors would like to thank the entire project team, including participants from RTI, Georgia Tech, and Emory University, and all of the technical experts who contributed their knowledge and experience to this work. Financial Support: This HAI-Design project was funded under contract HHS290201000024I (ACTION II) to RTI International in collaboration with Emory University and the Georgia Institute of Technology from the Agency for Healthcare Research and Quality, U.S. Department of Health and Human Services. The opinions expressed in this article are those of the authors and do not reflect the official position of the Agency for Healthcare Research and Quality or the U.S. Department of Health and Human Services.

are inserted (Pronovost, 2008). The ability of some healthcare organizations to lower HAI rates by implementing these best practices establishes that environmental contamination can be reduced by optimizing clinical practices.

There is also growing evidence that the built environment plays a significant role in the transmission of pathogens in healthcare settings. Abundant data demonstrate widespread environmental contamination with major nosocomial pathogens (Hota, 2004), well-described outbreaks of HAIs with molecular epidemiologic linkage to an environmental source, and outbreaks that have been interrupted only after interventions to eliminate the environmental source of the pathogen (Weber, Rutala, Miller, Huslage, & Sickbert-Bennett, 2010).

While the hospital environment is often contaminated with microorganisms capable of causing disease, the frequency with which these organisms actually lead to HAIs is largely unknown. This uncertainty is due in part to the complexity of microbial transmission in the healthcare setting and the difficulty in directly linking an environmental source to a specific transmission event or infection, particularly in the absence of a cluster of infections.

Many design interventions have been touted as decreasing infection risk. These include structural changes, such as the use of single patient rooms and airborne protective isolation rooms; design improvements in sinks and toilet rooms; surface redesigns to employ antibacterial and cleanable surfaces; strategic relocation of hand alcohol rubs and sinks; the use of electronic reminder systems for clinician hand hygiene; and the use of improved air filtering, airflow, and ventilation systems (Bartley & Streifel, 2010; Memarzadeh, 2011; Ulrich et al., 2008). There are, however, few rigorous studies demonstrating the link between design and a subsequent reduction in HAIs. As a result, the field largely remains an idiosyncratic patchwork of best practices and inferential steps from lab or epidemiological research.

The project from which the articles discussed below were derived assessed the rigor of these claims, with the goal of identifying design strategies that appear to be effective in interrupting pathogen transmission and reducing HAIs. This project represents a multidisciplinary assessment of the current state of knowledge and identifies emerging trends in the fields of infection prevention and control within the context of the built environment. It expands on previous reviews of topics such as “environments of care” (Bartley & Streifel, 2010), evidence-based design (Ulrich et al., 2008), and reviews that focus on single modes of transmission (Memarzadeh, 2011, 2012).

The first HAI paper in the group, by Zimring et al., describes a general conceptual framework developed as part of the project (Zimring, Jacob, et al., 2013). The framework, which follows the chain of transmission of pathogens, displays the mechanisms by which HAIs occur and the points at which design could possibly be used to interrupt those pathways. Enhanced versions of the framework include the potential interventions and mechanisms for mitigating infections. These causal pathways are intended to be relevant to all stakeholders, from clinicians to architects and engineers to hospital administrators. They can be used
to ground future research and serve as a basis for discussions among multidisciplinary groups seeking to reduce HAIs.

The second paper, by Lenfestey et al., contains the results of interviews with a multidisciplinary group of experts involved in design decision making (Lenfestey, Denham, Hall, & Kamerow, 2013). Experts in the areas of infection prevention and control, hospital epidemiology, architecture, interior design, engineering, and hospital administration were consulted individually and in groups of three (“triads”). Discussion guides were created to guide the interviews and triads across topics that included general perceptions and their opinions on specific strategies. The authors also requested input on the conceptual framework and asked for recommendations on key references. The interviews and triads were used as a means to gain a better understanding of current practice, decision making, and areas for future development.

The major task of the HAI-Design project was an extensive review of the evidence for each of the three major modes of transmission: contact, air, and water, and these constitute the next three papers. In order to circumscribe the study scope and increase depth, the reviews focused on acute care hospitals, including the overall building design and components that are attached to the physical environment that workers, patients, and families touch or interact with as part of the healthcare process. In addition, only design interventions and strategies applicable to U.S. settings (as opposed to strategies from countries with different care processes and standards) were included. To assist in this undertaking, the team worked with experts in library science, who were able to cast a wide net to find both peer-reviewed and “gray” literature related to the topics under evaluation. Over 1,000 articles were selected for abstract review and 782 full papers were reviewed. The final reviews were based on the 204 most relevant papers.

Steinberg et al. reviewed the role of the hospital environment in the spread of pathogens by direct and indirect contact, as well as strategies for preventing transmission through interventions involving the built environment (Steinberg, Denham, Zimring, Kasali, Hall, & Jacob, 2013). This review covers topics that include cleaning strategies and disinfection techniques, the use of antimicrobial surfaces, ways to promote hand hygiene, and the use physical barriers to prevent infections.

Jacob et al. present the evidence for and opportunities to prevent airborne transmission of pathogens in hospitals through the built environment (Jacob, Kasali, Steinberg, Zimring, & Denham, 2013). After describing the role of air in the chain of transmission, their paper focuses on four approaches to prevent airborne transmission of infectious agents, including ventilation systems, filtration, decontamination, and isolation.

Denham et al. describe the role that water sources and reservoirs play in transmission of pathogens in hospitals, as well as opportunities for intervention through the built environment to eliminate or minimize the impact of water sources of infection (Denham, Kasali, Steinberg, Cowan, Zimring, & Jacob, 2013). The three major types of mitigation include safe plumbing practices, water source
decontamination, and the use of design elements that minimize the potential for contamination.

The final paper in this group, by Zimring et al., provides a summary of the project findings, including research opportunities that have emerged from each of the papers described above (Zimring, Denham, et al., 2013). The opportunities to further improve the information base include understanding the tradeoffs involved with each design decisions made when focusing on infection prevention.

The HAI-Design project and the resultant papers within this publication are meant to serve several purposes. The work highlights how the built environment can impact patient safety through the use of a specific and high-impact example: healthcare-associated infections. The work also illustrates the necessity of cross-discipline collaboration to develop solutions to these patient safety problems. When approaching a particular issue, each discipline brings with it a different perspective. The development of a common framework can serve to bridge those differences and provide a platform for meaningful discussion and, we hope, improved patient outcomes.

References

Bartley, J., & Streifel, A. J. (2010). Design of the environment of care for safety of patients and personnel: Does form follow function or vice versa in the intensive care unit? Critical Care Medicine, 38(8), S388–S398. doi:10.1097/CCM.0b013e3181e6d0c1


The Role of Facility Design in Preventing the Transmission of Healthcare-Associated Infections: Background and Conceptual Framework

Craig Zimring, PhD; Jesse T. Jacob, MD; Megan E. Denham, MAEd; Douglas B. Kamerow, MD, MPH; Kendall K. Hall, MD, MS; David Z. Cowan, MS; Altug Kasali, MArch, PhD; Nancy F. Lenfestey, MHA; Ellen Do, PhD; and James P. Steinberg, MD

ABSTRACT

OBJECTIVE: To describe the conceptual framework and methodology used to conduct a comprehensive literature review of current evidence evaluating the role of the built environment in the transmission of healthcare-associated infections.

BACKGROUND: A multidisciplinary approach to evaluating a vast and diverse dataset requires a conceptual framework to create a common understanding for interpretation. This common understanding is accomplished through the application of a “chain of transmission” model, depicting temporal and physical paths of pathogens that cause healthcare-associated infections. The chain of transmission interventions model argues that infection can potentially be reduced by interrupting any of several links in the chain.

TOPICAL HEADINGS: The key pathogens impacted by the built environment are identified. The chain of transmission and the conceptual framework are described. Opportunities for intervention through the built environment are presented, which in turn guide the subsequent methodology used to conduct the systematic literature review.

CONCLUSIONS: The chain of transmission interventions model is a multidisciplinary conceptualization of the interaction between pathogens and the built environment, and this model facilitated a systematic literature review of a very large amount of data.

KEYWORDS: Built environment, design, healthcare-associated infection, hospital

AUTHOR AFFILIATIONS: Craig Zimring is a Professor at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Jesse T. Jacob is an Assistant Professor in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia. Megan E. Denham is a Research Associate II at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Douglas B. Kamerow is a Chief Scientist in Health Services and Policy Research at RTI International in Washington, D.C. Kendall K. Hall is a Medical Officer in the Center for Quality Improvement and Patient Safety at the Agency for Healthcare Research and Quality in Rockville, Maryland. David Z. Cowan is a Senior Research Scientist for the Health Systems Institute at Georgia Institute of Technology in Atlanta, Georgia. Altug Kasali is a Research Assistant at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Nancy F. Lenfestey is a Public Health Policy Associate at RTI International in Research Triangle Park, North Carolina. Ellen Do is a Professor at the School of Industrial Design in the School of Interactive Computing at Georgia Institute of Technology in Atlanta, Georgia. James P. Steinberg is a Professor of Medicine in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia.

CORRESPONDING AUTHOR: Craig Zimring, PhD, Georgia Institute of Technology, 828 West Peachtree St., NW, Suite 334, Atlanta, GA 30332-0477; craig.zimring@coa.gatech.edu; (404) 385-8193; (404) 385-7452 (fax).

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Healthcare-associated infections (HAIs) affect hundreds of thousands of Americans each year, leading to unnecessary deaths, delayed recoveries, and increased costs. The realization of the economic and personal costs of HAIs has led to increased efforts at prevention, and HAI rates have decreased nationally over the last few years. These prevention efforts have focused primarily on improving clinical practices. Recently there has been growing recognition by both the infection prevention and design communities that the built environment plays a role in the transmission of pathogens (Bartley & Streifel, 2010). However, evidence linking the built environment to the transmission of pathogens causing HAIs is scattered among disciplines and has not recently been systematically evaluated.

This article reports on a large multidisciplinary literature review and industry scan exploring the impact of the built environment on HAIs. The multidisciplinary team, including researchers and clinicians from the Agency for Healthcare Research and Quality (AHRQ) (part of the U.S. Department of Health and Human Services), RTI International, Emory University, and the Georgia Institute of Technology, explored three key questions on this topic:

1. What conceptual framework best guides research and practice for using interventions in the built environment to control pathogens?
2. For existing and new hospitals, what are the key design strategies that should be considered or avoided in new construction and renovation?
3. What are important research directions to consider for the future?

This article primarily addresses the first key question. The second and third key questions are addressed by other articles in this special supplemental issue, articles which discuss in depth the interviews conducted with a multidisciplinary group of experts, findings about pathogens transmitted through contact, air, and water, and overall conclusions of the project (Denham, Kasali, Steinberg, Cowan, Zimring, & Jacob, 2013; Jacob, Kasali, Steinberg, Zimring, & Denham, 2013; Lenfestey, Denham, Hall, & Kamerow, 2013; Steinberg, Denham, Zimring, Kasali, Hall, & Jacob, 2013; Zimring, Denham, et al., 2013).

The first section of this article introduces the major pathogens whose transmission can be caused or influenced by the built environment. For this project, the “built environment” refers to the physical structure of the hospital, in addition to the fixed components within the facility, which healthcare workers, patients, and families touch or interact with as a part of the healthcare process. The second section proposes a conceptual model for organizing research and interventions. The final section of the article discusses the methodology used to conduct the interviews and systematic literature review.

The Role of the Built Environment in the Transmission of Common Pathogens

Organisms (pathogens) that cause HAIs can be endogenous (part of the patient’s own “community” of microbes) or exogenous (acquired after entry into the hospital). Pathogens can be acquired from human or environmental sources (e.g.,
contaminated surfaces, water supplies, or ventilation systems). Patients, healthcare workers, or visitors need not be infected to transmit a pathogen. Many otherwise healthy people or patients can be colonized with pathogens that cause an HAI (i.e., an organism is present on the skin or in the body without causing disease) and can transmit these pathogens to other people or can contaminate the environment.

There is growing evidence that environmental sources serve an important role in the transmission of pathogens. For example, molecular studies show that the same organisms that contaminate the environment can cause HAIs, studies show increased risk of a patient acquiring the same pathogen as the previous occupant of a room, and studies also demonstrate that enhanced environmental cleaning reduces the risk of acquiring an HAI. In a large retrospective cohort study, Huang and colleagues showed a 40% increased risk of acquiring the common pathogens methicillin-resistant Staphylococcus aureus (MRSA) and vancomycin-resistant Enterococcus (VRE) for patients admitted to intensive care rooms when the previous room occupant was known to harbor one of these pathogens, even though the rooms had been terminally cleaned (Huang, Datta, & Platt, 2006). In a retrospective study in an intensive care unit, there was more than a two-fold risk of acquiring another serious pathogen, Clostridium difficile, if the prior room occupant had this infection (Shaughnessy et al., 2011).

Organisms can persist on surfaces for as long as days or months, depending on the biologic properties of the organism, the presence of organic matter or moisture on surfaces, environmental conditions and the type of surface. Many common pathogens causing HAIs, such as Staphylococcus aureus (S. aureus), VRE, Acinetobacter spp., and Clostridium difficile (C. difficile), can survive for weeks to months on dry surfaces. Organisms such as C. difficile can form spores that allow for prolonged survival and are relatively resistant to disinfection. Organisms such as S. aureus, including antibiotic resistant strains such as MRSA and VRE, also frequently contaminate the environment. VRE is a normal inhabitant of the human colon and fecal incontinence can promote environmental contamination. Although bacteria are the most clinically important pathogens that contaminate inanimate surfaces in the hospital, viruses such as norovirus can also survive on dry surfaces for weeks or more. (Refer to Table 1 for a more comprehensive description of these pathogens, their ecological niche and clinical significance.)

While contamination of environmental surfaces can be transient, with organisms surviving for a variable periods of time, contaminated water sources can support ongoing replication for some pathogens. These water reservoirs can be difficult to eradicate. [For more information about water sources and reservoirs, see Denham et al. (2013), also appearing in this special supplement.] Airborne transmission of respiratory pathogens, such as Mycobacterium tuberculosis, occurs when smaller particles containing organisms are generated by coughing or sneezing, remain suspended in the air, and are inhaled by a susceptible host. Other pathogens such as Aspergillus spp. can become airborne when the local environment is disrupted, such as during construction projects. These airborne organisms can spread widely through ventilation systems. [For additional information
about airborne pathogens and strategies for intervention, see Jacob et al. (2013), also appearing in this special supplement to HERD.]

Table 1, below, provides an overview of organisms most commonly discussed in the literature, focusing on strategies for intervention through the built environment.

While the hospital environment is often contaminated with pathogenic microorganisms, the frequency with which these organisms lead to HAIs is not well established. This uncertainty is due in part to the complexity of microbial transmission in the healthcare setting and the difficulty in directly linking an environmental source to a specific transmission event or infection. It is also complicated by the fact that many studies of transmission of pathogens are based on investigation of outbreaks. Much less is known about the contribution of the built environment to endemic or non-outbreak transmission causing isolated infections occurring in the hospital.

**Conceptual Framework**

This work was organized around a “chain of transmission” model that depicts how pathogens move on temporal and physical paths to cause HAIs. The chain of transmission can be viewed as a map of the predicted route of pathogens. This framework (Figure 1) shows the distinction between *direct transmission* (contact between a colonized or infected person or an environmental source and a vulnerable host) and *indirect transmission* (a pathogen moves from a source to a patient by an intermediary such as the hands of healthcare worker or a contaminated piece of equipment).

Opportunities for intervention through the built environment can generally be divided into three categories: those that prevent transmission by direct or indirect contact with contaminated surfaces, those directed at eliminating transmission of pathogens through airborne routes, and those aimed at eliminating waterborne sources of infection.

The chain of transmission interventional model argues that interrupting any of several links in the chain can potentially prevent infections. Some environmental interventions can prevent a pathogen from entering the hospital or room, such as by the use of air filtering or isolation strategies. Other interventions seek to disinfect reservoirs or improve cleaning of surfaces.

Interrupting the chain of transmission requires changing behavior and care practices as well as physical measures that directly eliminate pathogens. For example, considerable attention has been given to the use of design to change behavior such as improving hand hygiene by healthcare workers or supporting better routine cleaning of healthcare spaces. Isolating patients who are infected can require complex changes in hospital procedures involving screening patients, procedures for gowning-and-gloving, and special visiting processes. Potential interventions in the chain of transmission are shown in Figure 2.
### TABLE 1. PATHOGENS, ECOLOGICAL NICHE, AND CLINICAL SIGNIFICANCE

<table>
<thead>
<tr>
<th>PATHOGEN</th>
<th>ECOLOGICAL NICHE IN HEALTHCARE</th>
<th>SURVIVAL ON INANIMATE SURFACE</th>
<th>MAJOR MODE OF TRANSMISSION</th>
<th>ROLE OF INANIMATE ENVIRONMENT AS SOURCE OF TRANSMISSION</th>
<th>EVIDENCE THAT TRANSMISSION CAN BE MITIGATED THROUGH THE ENVIRONMENT</th>
<th>OUTBREAKS ASSOCIATED WITH ENVIRONMENT</th>
<th>CLINICAL SIGNIFICANCE OF PATHOGEN IN HEALTHCARE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Staphylococcus aureus, including methicillin-resistant strains (MRSA)</td>
<td>Human skin and mucosal surfaces; inanimate surfaces</td>
<td>Days–Months</td>
<td>Contact</td>
<td>Modest</td>
<td>Some evidence for reduction with enhanced cleaning</td>
<td>Transmission with reusable medical equipment and built environment</td>
<td>Major healthcare-associated pathogen; causes a wide spectrum of mild to life-threatening infections, including surgical site infections and catheter-associated infections</td>
</tr>
<tr>
<td>2. Enterococcus spp., including vancomycin-resistant strains (VRE)</td>
<td>Human colon; inanimate surfaces</td>
<td>Days–Months</td>
<td>Contact</td>
<td>Moderate</td>
<td>Some evidence for reduction with enhanced cleaning</td>
<td>Transmission with reusable medical equipment and built environment</td>
<td>Can cause variety of healthcare-associated infections particularly in immunocompromised individuals</td>
</tr>
<tr>
<td>3. Pseudomonas aeruginosa</td>
<td>Water; human colon</td>
<td>Days–Months</td>
<td>Contact</td>
<td>Documented in outbreaks; role in endemic setting unknown</td>
<td>Yes, in outbreaks</td>
<td>Faucets; sink traps</td>
<td>Major healthcare-associated pathogen; often associated with ventilator-associated pneumonia</td>
</tr>
<tr>
<td>4. Legionella spp.</td>
<td>Standing water</td>
<td>Long-term contamination of water sources</td>
<td>Common source (inhalation of aerosol or aspiration of water)</td>
<td>Clear environmental source for almost all hospital-acquired infections</td>
<td>Yes, in both endemic and epidemic scenarios</td>
<td>Water systems; cooling towers</td>
<td>Less common cause of pneumonia acquired in hospitals, primarily in immunocompromised patients</td>
</tr>
<tr>
<td>5. Mycobacterium tuberculosis</td>
<td>HCWs; patients with active disease</td>
<td>Days–Months</td>
<td>Air</td>
<td>None to minimal</td>
<td>Yes, can be reduced with negative pressure ventilation, ultraviolet light irradiation</td>
<td>Transmission from source patient in settings without proper environmental controls</td>
<td>Uncommon healthcare-acquired pathogen causing pulmonary or extra-pulmonary disease</td>
</tr>
</tbody>
</table>

*continues…*
<table>
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<tr>
<th>PATHOGEN</th>
<th>ECOLOGICAL NICHE IN HEALTHCARE</th>
<th>MAJOR MODE OF TRANSMISSION</th>
<th>SURVIVABILITY ON SURFACE</th>
<th>CLINICAL SIGNIFICANCE IN HEALTHCARE</th>
<th>AS OUTBREAKS ASSOCIATED WITH ENVIRONMENT</th>
<th>ROLE OF EVIDENCE THAT TRANSMISSION CAN BE MITIGATED</th>
<th>CLINICAL SIGNIFICANCE</th>
<th>CLINICAL SIGNIFICANCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspergillus spp.</td>
<td>Soil</td>
<td>Days–Months</td>
<td>Minimal</td>
<td>Contact with contaminated surfaces; in outbreaks; role in endemic setting unknown</td>
<td>Contact with contaminated surfaces to hands; can be reduced with filtration</td>
<td>Yes, can be reduced with filtration</td>
<td>Less common but severe pulmonary or disseminated infections, particularly in immunocompromised patients</td>
<td>Construction; contaminated carpet (1 report)</td>
</tr>
<tr>
<td>Influenza</td>
<td>Human respiratory tract</td>
<td>24–48 hours</td>
<td>Moderate</td>
<td>Documented in outbreaks; role in endemic setting</td>
<td>Contact with contaminated surfaces to hands; can be reduced with filtration</td>
<td>Yes, in outbreaks</td>
<td>Primarily respiratory infections; especially among elderly and infirm</td>
<td>Contact with contaminated surfaces contributes to seasonal outbreaks</td>
</tr>
<tr>
<td>Acinetobacter spp.</td>
<td>Water sources; surfaces; can colonize human skin and mucosal surfaces</td>
<td>Days–Months</td>
<td>Contact</td>
<td>Documented in outbreaks; role in endemic setting</td>
<td>Curtains; faucet; ventilator circuits; documented in outbreaks</td>
<td>Yes, in outbreaks</td>
<td>Primarily respiratory pathogen in mechanically-ventilated patients</td>
<td>Curtains; faucet, ventilator circuits</td>
</tr>
<tr>
<td>Norovirus</td>
<td>Gastrointestinal tract; surfaces</td>
<td>Hours–Days</td>
<td>Contact</td>
<td>Documented in outbreaks; role in endemic setting</td>
<td>Surface contamination associated with outbreaks</td>
<td>Yes, in outbreaks</td>
<td>Uncommon diarrheal disease</td>
<td>Surface contamination associated with outbreaks</td>
</tr>
<tr>
<td>Clostridium difficile</td>
<td>Colon; multiple surfaces</td>
<td>Months</td>
<td>Contact</td>
<td>Documented in outbreaks; role in endemic setting</td>
<td>Contact; Common source</td>
<td>Yes, decreased with appropriate cleaning</td>
<td>Common diarrheal disease with potential for relapse</td>
<td>Contact; Common source</td>
</tr>
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</table>
Figure 1. Conceptual framework for the chain of transmission.

**Reservoir**: Place (human or environmental) where organisms reside and multiply.

**Source**: Place from which an organism is transmitted to the host. Source may be the same as the reservoir or become contaminated from the reservoir (e.g., a surface or instrument).
In reality, transmission of pathogens may not be a linear chain, as there may be multiple routes for a pathogen to get to the patient, with the presence of unrecognized environmental contamination being one of several possible intermediate steps. Consequently, there can be ongoing transmission events despite efforts to “break” a link in the chain. Discerning the role of the hospital environment is complicated further by the fact that pathogens can remain on surfaces or in reservoirs for weeks or months. For further reading on the acquisition and prevention of HAIs through the built environment, see the topical articles appearing in this supplemental edition (Denham et al., 2013; Jacob et al., 2013; Steinberg et al., 2013).

**Methods**

This investigation was conducted by a multidisciplinary team that included physicians specializing in infection prevention and hospital epidemiology, clinical specialists, architects, evidence-based design researchers and others. The methodology used to evaluate the current state of evidence, and to develop the topical articles featured in this special issue (Denham et al., 2013; Jacob et al., 2013; Steinberg et al., 2013) followed a systematic review process, guided by a set of key questions.

**Types of Studies Included**

The literature review includes articles with various methodologies evaluating the relationship between HAIs and the built environment. In order to provide a focused set of literature, the dataset is limited to studies applicable to acute care hospital settings. In addition, only papers published in English are included.

**Search Methods**

The literature scan for this study used a range of databases across several disciplines, including, but not limited to, medicine, health, and design. It included an initial comprehensive database search that was augmented by literature from review articles and expert recommendations published between January 1, 1970, and March 1, 2012. This search strategy was developed in consultation with a clinical information specialist and was conducted using PubMed, EMBASE, Web of Science, Compendex, IEEE Xplore, ACM Digital Library, ACS Digital Library, Avery Index of Architectural Periodicals, and the National Technical Information Service (NITS).

The research team generated three sets of keywords, based on the key questions and the conceptual model (see Appendix A for list of keywords). Set A includes a list of terms describing healthcare settings and Set B includes words or phrases for infection-related outcomes of interest. Set B1, a subset to Set B, includes mediator concepts in the field. Mediator concepts are higher-level interventions or strategies, such as “surveillance,” that can be impacted by design but are not design elements in themselves. Set C covers the set of facility elements and related interventions or exposures.
Figure 2. Chain of transmission interventions model.

**Reservoir:** Place (human or environmental) where organisms reside and multiply.

**Source:** Place from which an organism is transmitted to the host. Source may be the same as the reservoir or become contaminated from the reservoir (e.g., a surface or instrument).

- **Human Reservoirs**
- **Environmental sources and reservoirs of pathogens**
- **Transmission Event**
  - direct or indirect contact including transient carriage (e.g., hands of healthcare workers)
  - airborne/droplet
- **Opportunities for interventions through the built environment**
Selection and Sorting of Studies

The initial electronic database searches yielded 2,999 citations matching the established inclusion criteria. A secondary scan was conducted after reviewing the literature to include additional relevant references through March 2013. A manual search of the bibliographies of selected research articles and major reviews yielded an additional 118 articles not captured in the preliminary electronic search. Bibliographic management software (EndNote X5) was used to pool and store articles generated from these searches.

An initial abstract review, followed by further refinement of inclusion and exclusion criteria and a second round of abstract reviews, was conducted to identify and eliminate studies that were not specific to the relationship between the HAIs and the built environment. A full-paper review was conducted for the remaining 782 articles to further refine the dataset. Based on the full-text evaluation, 190 articles addressing the key questions and the proposed conceptual framework were included for further review and were used as resources for the secondary scan. After a final full-text review, 203 articles remained, and these were sorted into three sub-groups. The articles within these sub-groups were used to create the contact, air, and water articles featured in this special edition (Denham et al., 2013; Jacob et al., 2013; Steinberg et al., 2013).

Conclusions

There is a growing body of evidence suggesting that the built environment plays a significant role in the transmission of pathogens in hospitals and that interventions involving the built environment can mitigate the risk of infection. However, the research linking the built environment to infection is scattered among a wide range of disciplines.

This multidisciplinary effort developed a conceptual framework to organize research and practice that links interventions involving the built environment to the prevention of infection and that guided the literature review and industry scan and was refined by those tasks. It conveys the complexity of the chain of transmission and the difficulty of designing interventions to interrupt transmission of pathogens. More detail about these interventions is provided in other articles in this special issue. However, what is clear is that this requires a focus on understanding how interventions impact the complex system of a hospital: its physical environment but also the culture and behaviors that lead to effective cleaning and hand hygiene. Addressing this problem at the systems level necessitates the engagement of designers, clinicians, quality improvement, staff from hospital facility department, infection control, environmental control, and purchasing—those who specify and design clinical processes, materials and equipment, and heating, ventilation, and air condition systems.

Implications for Practice

- The “chain of transmission” intervention model helps highlight the various ways in which the built environment can be used to reduce trans-
mission: preventing transmission by direct or indirect contact with contaminated surfaces eliminating transmission of pathogens through airborne routes, and eliminating waterborne sources of infection.

- Organisms can persist on surfaces for as long as days or months.
- A literature review of more than 3,800 references in the design and medical fields found good evidence that design affects HAI, but the exact cause is often hard to establish because an intervention often requires a system of solutions.
### APPENDIX: KEYWORDS FOR DATABASE SCAN

#### SET A (SETTINGS)
- Critical care unit
- Emergency department
- Hemodialysis
- Hospital
- Hospital wards
- Inpatient acute care
- Patients’ rooms [MeSH]
- Inpatient rehabilitation facility
- Intensive care unit
- Long term acute care
- Operating room*
- Patient room*
- Inpatient*

#### SET B (OUTCOMES)
- Cross-infection
- Healthcare-acquired infection
- Healthcare-associated infection
- Hospital-acquired infection
- Hospital-associated infection
- Nosocomial infection
- Colonization
- Contamination
- Decontamination
- Disinfection
- Cost
- Cost-benefit analysis [MeSH]

#### SET B1 (MEDIATOR CONCEPTS)
- Isolation
- Quarantine
- Surveillance
- Cohorting patients
- Infection control [MeSH]
- Hand hygiene*
- Hand sanitizer*
- Hand washing*

#### SET C (FACILITY ELEMENTS, INTERVENTION, OR EXPOSURE)
- Amenities
- Bathroom
- Bed*
- Carpet*
- Chair*
- Countertop
- Curtains
- Décor
- Decor
- Door
- Elevator
- Incubator
- Construction
- Cleaner
- Sterilize*
- Silver
- Medical waste disposal [MeSH]
- Ventilation [MeSH]
- Fabric
- Faucet
- Fixture
- Fitting
- Floor*
- Furnishings
- Interior design
- Layout
- Light Fixture
- Lighting
- Paint
- Wall
- Renovation
- Cleaning
- Disinfect*
- Copper
- Room
- Shower*
- Sink*
- Spigot
- Surfaces
- Table*
- Tile
- Toilet*
- Upholstery
- Water fountain
- Window*
- Workstation
- Ventilation system
- Antimicrobial surfaces
- Cleans*
- Ultraviolet irradiation
- Sanitary engineering [MeSH]
- Human factors engineering [MeSH]
- Air conditioning
- Air handling
- Climate control
- Hot water heater
- HVAC
- Telephone
- Remote control
- Monitors
- Plumbing
- Ventilation duct
- Phone
- Keyboard
- Call button
- Computer
- Elements
- Hydrogen Peroxide

#### NOTES
* Search words that are open to include variants.
MeSH: Search phrases from the controlled vocabulary of the Medical Subject Headings of the U.S. National Library of Medicine.
References

Bartley, J., & Streifel, A. J. (2010). Design of the environment of care for safety of patients and personnel: Does form follow function or vice versa in the intensive care unit? Critical Care Medicine, 38(8), S388–S398. doi:10.1097/CCM.0b013e3181e6d0c1


Expert Opinions on the Role of Facility Design in the Acquisition and Prevention of Healthcare-Associated Infections

Nancy F. Lenfestey, MHA; Megan E. Denham, MAEd; Kendall K. Hall, MD, MS; and Douglas B. Kamerow, MD, MPH

OBJECTIVE: To assess expert knowledge, perceptions, and experience on the role of the built environment in the acquisition and transmission of healthcare-associated infections (HAIs), facility design decision-making considerations, and strategies for intervention through facility design and technologies.

BACKGROUND: Healthcare-associated infections pose a serious and costly threat to public health in the United States. A growing evidence base suggests that the built environment can play a role in interrupting the chain of infection.

METHODS: Semi-structured individual interviews and triads were conducted with 26 experts in hospital administration, architecture, interior design, infection control, and air and water quality. A grounded theory approach was used for interview coding and interpretation.

RESULTS: Participants characterized the shift in thinking about the relationship between the built environment and HAI transmission as a “progression,” as accountability for infection prevention has expanded beyond clinicians. Organizational leaders aim to make informed design decisions, but this can be challenging due to the paucity of efficacy and return on investment data. Emerging interventions include copper impregnated materials, seamless flooring, and chilled beams.

CONCLUSIONS: No single intervention is entirely effective in mitigating HAI risk; multiple interventions are needed. In addition to the built environment, human behavior must be considered, as noncompliance can render even the best designs ineffective. Increased multidisciplinary collaboration is needed to improve the application of evidence and experience in healthcare facility design. In the absence of conclusive evidence regarding interventions aimed at reducing HAI transmission, a combination of research data and practical experience should be used to inform design decisions.

KEYWORDS: Built environment, design process, evidence-based design, healthcare-associated infections, hospital
Healthcare-associated infections (HAIs) are a serious and costly threat to public health in the United States, afflicting an estimated one in twenty hospitalized patients and responsible for $28 to $33 billion in preventable healthcare expenditures annually (U.S. Department of Health & Human Services, 2012). Over the past decade, the importance of these infections as causes of preventable harm has gained increasing attention among both healthcare professionals and other groups, including consumer advocates, insurance providers, and legislators. Stimulated in part by legislative mandates and public reporting of HAI rates, expanded efforts have been made to eliminate preventable HAIs.

While the majority of efforts to date to reduce HAIs have focused on standardizing best practices in healthcare processes, there is growing evidence that the overall building design and its components, referred to as the built environment, can also play a significant role in the transmission of pathogens in healthcare settings. A range of design interventions has been asserted as affecting HAIs, including single-patient rooms, airborne-protective isolation rooms, better sink and toilet room design, antibacterial surfaces, cleanable surfaces, improved location of hand cleaning rubs and sinks, electronic hand hygiene reminder systems, and better air filtering (Bartley & Streifel, 2010; Ulrich et al., 2008).

Although the evidence base linking design to HAI is growing, the field largely remains an idiosyncratic patchwork of best practices and inferential steps from laboratory or epidemiological research. This article is the result of a large multidisciplinary project, examining the role of the environment in the acquisition and prevention of HAIs, which included an extensive literature review used to determine relevant topics for the interview guides. The complete results of the literature review can be found as topical reports available within this special supplement to HERD (Denham et al., 2013; Jacob, Kasali, Steinberg, Zimring, & Denham, 2013; Steinberg, Denham, Zimring, Kasali, Hall, & Jacob, 2013; Zimring, Denham, et al., 2013; Zimring, Jacob, et al., 2013).

We also sought to obtain a better understanding of current practice and potential areas for future research and development in this area through discussions with a multidisciplinary group of experts involved in design decision making in healthcare facilities. We sought their perceptions of the evolution of the role of the built environment in HAI transmission, including its impact on healthcare facility design and the application of evidence-based design. Other topics discussed included factors that may enhance or prohibit the adoption of innovative HAI risk-reduction strategies and the challenges of balancing patient- and family-centered care with HAI risk reduction.

Methods

We conducted in-depth interviews and triads with experts. An in-depth interview is a qualitative research technique that uses open-ended questions to explore an individual’s detailed perspective on various issues and offers a complete picture of opinions and ideas. Triads (interviews with three participants) strike a balance between individual interviews and focus groups, in that they use fewer
participants (3 versus 6–12 participants in focus groups), thereby enabling more in-depth discussion of issues than focus groups.

**Participant Recruitment**

Interview and triad participants were recruited from the project team’s extensive network of professional contacts, comprising a convenience sample. The sample included leading experts in the field of healthcare design and infection control, including presidents, CEOs, and CMOs of top healthcare organizations, and principals of major architectural firms. At the close of each interview and initial triad, participants were asked for recommendations of others who might be able to provide valuable insight as triad participants. This blend of convenience and referral sampling produced a diverse pool of experts across multiple domains. Nine experts were individually interviewed, and 17 experts participated in triad interviews. See Table 1 for the distribution and experience levels of experts across domains. This project was reviewed by the Institutional Review Board and received exempt status as research not involving human research subjects.

**Discussion Guides**

We drafted an initial list of potential interview discussion topics and converted the topics into interview questions. Separate discussion guides were developed for each of the following domains: hospital administration, architecture, interior design, hospital epidemiology and infection control, air quality, and water quality. The interview and triad guides included questions pertaining to perceptions of the role of the built environment in mitigating infection risk in acute care hospital settings; the types of input that healthcare facilities seek from external sources regarding HAI prevention; currently used design strategies; promising strategies for the future; and issues and strategies that are particularly relevant to each respective domain (e.g., the air quality discussion guide included questions regarding high-efficiency particulate air (HEPA) filters, air flow strategies, and the use of ultraviolet germicidal irradiation (UVGI) to prevent spread of airborne infections). For a sample discussion guide, see Appendix A.

<table>
<thead>
<tr>
<th>Table 1. Number of Interview and Triad Participants by Domain.</th>
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<tr>
<td><strong>DOMAIN</strong></td>
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</tr>
<tr>
<td>Hospital administration</td>
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<tr>
<td>Architecture/interior design</td>
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<td>Hospital epidemiology/infection control</td>
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<tr>
<td>Air quality</td>
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<td>Water quality</td>
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<td><strong>TOTAL</strong></td>
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Data Collection and Analysis

Six semi-structured in-depth interviews and seven triads (three mixed triads, including participants from multiple domains, one air quality triad, one water quality triad, and one architecture/interior design triad) were conducted by telephone. See Table 1 for the number of participants broken down by interview type and domain. The interviews lasted approximately 1 hour; the triads lasted 60–75 minutes. All discussions were audio-taped to ensure accuracy of notes. Participants’ responses remained anonymous to project team members not involved in data collection.

Interview and triad notes were transcribed in real time or from an audio recording and then manually coded. Code outputs were reviewed for additional analysis, summary, and interpretation using a grounded theory approach. Developed by Glaser and Strauss, grounded theory is a method for developing themes, based on qualitative data, utilizing a bottom-up perspective (Corbin & Strauss, 2008; Glaser, 1967). In this application, we applied grounded theory methods to develop the set of concepts, categories, and their interrelationships, which are summarized below.

Results

Many themes emerged during the interviews and triads. The experts describe a shift in thinking across domains, with growing recognition that the built environment is an important factor in the transmission of HAIs. This is supported by an increased number of facility design and infection control guidelines. There is little evidence, however, linking design strategies and technologies to a reduction in infection rates, causing the experts to question the accuracy of the term “evidence-based design.” Ultimately, participants rely on a combination of available literature and experience to guide decisions for strategies and technologies to mitigate the risk of infection.

Perceived Role of the Built Environment in the Acquisition and Prevention of HAIs

The participants acknowledged that the built environment plays a role in the transmission and acquisition of HAIs, though the extent of its role remains unclear. Of the three mechanisms for transmission of infection (contact, air, and water), there was consensus among the participants that contact is the primary mode of transmission, estimated to cause 80%–90% of HAIs, followed by air (5%–10%) and water (5%–10%). These estimations are based on the experience of the participants and may not be substantiated by research. The current state of evidence on the transmission of HAIs is reported in subsequent reports available in this special supplement to HERD (Denham et al., 2013; Jacob et al., 2013; Steinberg et al., 2013; Zimring, Jacob, et al., 2013).

Participants characterized the shift in thinking about the relationship between the built environment and transmission of HAIs as a “progression.” Over time, as the discussion of this relationship has expanded and involved broader circles
of professionals—including healthcare administrators and experts in hospital epidemiology and infection control, air quality, water quality, architecture, and interior design—valuable new research, insights, and strategies have emerged. Many participants identified the increasing complexity of patient rooms over time as a catalyst for greater attention to the relationship between HAIs and the built environment. The addition of couches and recliners to accommodate family members, stationary computers, and shelving increases the surface cleaning requirements for room turnover and also provides greater opportunities for contact transmission of HAIs. One participant, an infection preventionist, said, “Thinking back to 1975 when all we had was an overhead table, bedside table, and an IV pole, it was easy to turn over a room. Now, we have a hugely complex environment with frequent patient-to-surface contact—adequate cleaning on a daily basis is becoming insurmountable.”

Other reported contributors to an increased awareness of the role of the built environment in the acquisition and prevention of HAIs include tuberculosis outbreaks, HIV in the late 1980s and, more recently, the Severe Acute Respiratory Syndrome (SARS) epidemic. Research conducted in the late 1980s, examining the impact of construction on indoor air quality, resulted in the development of a list of precautions that should be taken during hospital construction and renovation in order to control exposure to debris. Regulatory agencies, such as the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) and the Centers for Disease Control and Prevention (CDC), established safety and infection control guidelines, which reflected the increased awareness that the environment should be optimized to mitigate infection risk. The experts reported that with this awareness came growing public concern, with increased reports of outbreaks of multidrug-resistant organisms, such as methicillin-resistant \textit{Staphylococcus aureus} (MRSA), in hospitals. Experts noted that research in recent years has also found that organisms such as MRSA, vancomycin-resistant \textit{Enterococcus} (VRE), \textit{Legionella}, \textit{Pseudomonas}, \textit{Acinetobacter}, and norovirus are strongly linked with the environment. See Zimring, Jacob, et al. (2013) for more information on pathogens and their environmental niche.

Guidance for Facility Design
Roughly half the experts indicated that their clients request strategic guidance and data in selecting an approach for HAI prevention. The other half reported having clients who are generally aware of current research findings on HAI prevention and request assistance with fine-tuning their HAI prevention approach, guidance on meeting code requirements, or confirmation that their potential selections are worthwhile investments. Despite the requests for guidance on HAI and design, many experts stated that organizational leaders do not blindly take the advice of the experts and are increasingly requesting data to support expert recommendations, including post-occupancy study data and data demonstrating
a reduction in infection rates. Organizational leaders recognize the importance of design decisions and aim to make informed decisions based on available data.

Participants identified a number of resources that inform their design recommendations, including clinical consulting groups, academic institutions with healthcare design/architecture programs, peer-reviewed journals, and industry standards and guidelines. Standards and guidelines are issued by ASHRAE, Leadership in Energy and Environmental Design (LEED); CDC, National Institutes of Health (NIH), U.S. Environmental Protection Agency (EPA), Facility Guidelines Institute (FGI), Association for Professionals in Infection Control and Epidemiology (APIC), and American Society for Plumbing Engineers (ASPE).

Participants indicated that more data supporting specific interventions’ abilities to reduce infection would be helpful in informing construction decisions. Very little research linking a particular strategy or design to infection outcomes and cost savings currently exists, however. Consequently, decision makers must rely on a combination of experience, evidence, and potential payoffs of a particular technology (e.g., cost savings from delayed replacement of equipment and cleaning agents). In the absence of cost and efficacy data, the design decision-making process still resembles a trial and error process.

Perceived disconnects among the design team, construction team, facilities team, and frontline staff are thought to be part of the reason for this trial and error approach. Interventions may have a higher likelihood of success when there is open dialogue and each party understands the needs and restrictions of multiple stakeholders. Careful analysis from multiple perspectives can avoid costly mistakes from both patient safety and financial standpoints. When assessing new equipment or a decorative feature, part of the analysis should include identification of requirements for proper maintenance (e.g., cleaning regimen, filter replacement) and the persons responsible for maintenance. As an architect who participated said, “There is a massive gap between people responsible for construction and design of healthcare facilities and people who maintain them. The greatest designs can be immediately undone by poor maintenance.”

Evidence-Based Design

The lack of data demonstrating a reduction in infection rates as an outcome for a design strategy prompted a discussion of the definition and parameters of evidence-based design (EBD) among the participants. Evidence-based medicine (EBM) has been defined as “the integration of best research evidence with clinical expertise and patient values” (Sackett, Strauss, Richardson, Rosenberg, & Haynes, 2000). For many, EBD represents a similar high standard. As a result, participants expressed concern that some define and use the term rather loosely, especially in recent years when many viewed EBD as a buzzword in healthcare design. As one administrator participant commented, “If we get hung-up
on the gold standard of research, we do ourselves a disservice. There are people in the field with a lot of experience and history which may not be the gold standard, but it’s pretty good. We need to be open-minded about what we need to do in the interim.”

Given the dearth of rigorous outcome based evidence to support EBD, some prefer the terms “evidence-informed” or “evidence-influenced” design and use the limited evidence that is available to inform decisions in areas that have yet to undergo extensive assessment. In some cases, even if data are not available, many participants find that explaining their rationale in practical terms can be an effective approach to adoption of a proposed intervention. Participants reported commonly applying the precautionary principle to implement interventions that appear to have a promising net benefit, in the absence of data proving that an intervention will cause harm. Some facilities use a phased approach and implement interventions in one area to test them on a limited basis, assessing their experience before proceeding with implementation on a larger scale. One participant who was a mechanical engineer remarked that, “We base all of our design on our experience. We’ve done this 29 times and we know it works and we did it another way and it didn’t work, so evidence is showing us this is the way to do it.”

Despite awareness of EBD, not everyone is a proponent. Opponents noted that in the context of the design decision-making process, hospitals must proceed with their timelines and cannot delay decision making in order to wait for evidence to emerge supporting each decision. Moreover, they noted that there is insufficient funding allocated for this type of research. The arguments against EBD cited most often by participants were the lack of evidence and the diminished value placed on first-hand experience in the assessment of the effectiveness of interventions.

Overall, the participants advocated using a mix of guidelines and peer-reviewed literature to inform design decision making, since both provide useful insights. Although many experts acknowledged the value of the rigor of peer-reviewed literature, they also emphasized the importance of expert judgment and experience when identifying practices and strategies that are deemed effective for HAI prevention.

Strategies with Greatest Impact on Reducing HAI Risk
Contact was cited as the most common mechanism for the transmission of HAIs. The key strategies noted by experts for minimizing the transmission of HAIs through contact included promoting hand hygiene compliance, establishing and monitoring routine cleaning of high-touch surfaces, and improving terminal room cleaning. Increased use of technologies in the patient room, such as touch-screens and stationary computers, create a greater need for determining methods for
routinely disinfecting devices without damaging them. The participants also emphasized the importance of selecting non-porous hard surfaces, which are less likely to promote microbial contamination and are easier to clean, during design or renovation phases, and abandoning the use of pressboard in cabinetry, under-sink storage areas, and plastic laminate around sinks.

Cleaning and disinfecting products are gaining greater attention as hospitals look to consolidate cleaning agents and search for products that can effectively clean and disinfect multiple surfaces. Several experts mentioned a movement towards “green” disinfection products and cited the EPA and LEED as resources for analysis of low-emitting materials and disinfection products. As chemical content analysis research is conducted on various products, experts call for cooperation and partnership among all parties to prioritize an assessment of environmental impact of during the facility design and construction process, as well as during the cleaning process. Manufacturers are urged to become more actively involved in these efforts by sharing data, test results, and descriptions of the chemical content of their products. Such information is needed to identify disinfectants that are effective in reducing HAI risk while also less corrosive and harmful to the environment than some current widely used disinfectants.

Strategies mentioned for mitigating the spread of airborne pathogens included high quality filters, air exchange rates, and room pressurization. Dividing mechanical systems into zones was discussed as a strategy to allow more flexibility for adapting rooms to patients with different levels of illness. It also can reduce the risk of infection by preventing contaminated air from being recirculated into areas with immunocompromised patients. Participants also noted proper filtration and re-circulation as key strategies for ensuring both air and water quality and safety.

More than half of the participants interviewed indicated that single-patient rooms have had the greatest impact on reducing HAI risk in the hospital setting. However, most participants agreed that no single strategy is entirely effective in leading to HAI reduction; instead it has been a combination of strategies that has played a role in reducing HAIs. One participant indicated that raised awareness of HAIs alone has contributed significantly to their reduction, because it has resulted in action at all levels.

Participants agreed that in spite of new technologies and design strategies that may emerge in the future targeting the prevention of HAIs, the most prominent determinants of HAI prevention pertain to human factors and human behavior. They acknowledge that human factors, especially poor hand hygiene compliance, can undermine even the best design.

**Infection Control Technologies**

The three technologies most frequently mentioned for infection prevention include high-efficiency particulate air (HEPA) filters, ultraviolet germicidal irradiation (UVGI), and hydrogen peroxide vapor (HPV). The efficacy of HEPA filters for the reduction of airborne pathogens is strongly supported through
The necessity for their widespread use is still debated, however, because they represent a substantial investment due to increased energy consumption, maintenance costs, and expensive filters that need frequent replacement. The discussion of HEPA filters and their energy consumption is clearly an important consideration for hospital executives designing future facilities. These costs must be weighed against the benefit of the HEPA filtration technology versus other air filtration methods.

Participants noted that UVGI has received increased interest in the peer-reviewed literature, but added that it is not 100% effective against all pathogens (e.g., Clostridium difficile) and requires direct surface exposure in the linear path of UV light for a specified period of time. HPV is also under investigation for its ability as a “touchless” supplemental environmental disinfection strategy (emitted by a sprayer) to disinfect air and surfaces, and it is not limited by line of sight as is UVGI. An advantage of HPV over traditional cleaning strategies is that its only residue is water, which is less toxic and damaging to surfaces than other disinfectants. Both technologies require vacating the room while in use, which increases the length of time needed for room turnover, a characteristic that some experts feel hinders operational efficiency. Participants stated that although UVGI and HPV are effective in killing organisms, operational considerations in terms of requirements for consistent and effective use limit the practicality of these technologies.

The lack of research evidence demonstrating the abilities of HEPA filters, UVGI, and HPV to reduce infection rates contributes to the varying opinions on both technologies, often leaving discussion of cost as the primary determining factor for implementation. For further reading on the current state of evidence on these technologies, see Jacob et al. (2013) and Steinberg et al. (2013).

**Emerging Strategies and Technologies**

Participants mentioned a number of interventions that are currently in limited use that may be promising in the near future. Copper plumbing and copper impregnated materials have been shown to be antimicrobial in comparison to PVC and other materials. Participants noted that copper handrails and door rails were considered by the 2014 Healthcare Guidelines Revisions Committee (the group charged with developing and maintaining the *Guidelines for the Design and Construction of Healthcare Facilities*) as an emerging topic warranting additional assessment. Data exists supporting the antimicrobial properties of copper surfaces, but evidence demonstrating copper’s ability to prevent and reduce infection risks in patients is lacking. For further reading on the applications of copper on surfaces, see Steinberg et al. (2013) and for water decontamination, see Denham et al. (2013) also appearing in this special supplement to *HERD*.

Participants expressed increased interest in flooring materials. Given the 24/7 hospital operating schedule, flooring is a very difficult area in which to maintain cleanliness. For example, the floors of emergency departments are very challenging to keep clean and are areas where infection risk can be quite high given the traffic flow and nature of the patients entering and exiting. This has encouraged
experts to seek out flooring alternatives with lower microbial buildup, such as seamless flooring (i.e., no cracks present at the wall/floor seam).

A greater focus on sustainability issues and reduction of energy use are driving many to look more closely at using alternative air flow strategies such as chilled beams. Chilled beams use chilled water pipes in modular units that are ceiling-mounted and primarily transfer heat through convection rather than radiation (Roth, Dieckmann, Zogg, & Brodrick, 2007). The participants noted greater discussion and debate regarding how to enhance infection reduction while using technologies such as chilled beams to reduce energy consumption, and how such features affect the building codes that are currently in place. ASHRAE Standard 170 currently permits chilled beams, but there is concern about excess condensation and the potential for growth of organisms (i.e., mold) if the systems are not properly maintained.

Resistance to Implementation of Technologies Aimed at Infection Prevention

Healthcare organizations are suffering from decreasing reimbursement rates with increasing operating costs. Changes in reimbursements for preventable events, such as HAIs, have often led decision makers to opt for the safer route, rather than the most innovative; stakeholders are often hesitant to embrace innovative strategies with little evidence demonstrating reductions in HAI rates. Hospital administrators are reported to be gathering more data to make informed decisions in order to promote more judicious use of funds. Participants shared concern from healthcare organizations that often have little cash on hand, making interventions requiring significant up-front investments and ongoing maintenance costs challenging. Many do what is necessary to meet code requirements and guidelines, but they do not go beyond the minimum requirements.

Participants agreed that interventions that have support from the top down, primarily from hospital executives, receive less push-back from clinical and facilities staff and are most easily implemented. On the other hand, high-level executives are also often recognized as deterrents to innovative design approaches. Several experts considered infection control and frontline staff as key proponents of innovative design features with promising potential to reduce HAIs. Participants stated that, given their responsibility for maintaining interventions that may have an impact on HAI prevention, hospital facilities departments largely affect the degree to which interventions are implemented and the likelihood of successful implementation in the long run. Experts agreed that how an intervention is presented and, in particular, the way in which the payback and benefits are described have a lot of influence on staff buy-in of innovative strategies.

Conclusions

As new research emerges over time, more is revealed about the role that the built environment and human factors play in transmitting organisms that result in HAIs. Some participants characterize the prevention of HAI transmission as a
moving target because research is still largely inconclusive on how to effectively manage and prevent transmission of pathogens and aggregations of microorganisms. Optimizing the built environment to minimize the risk of infection can become even more challenging when attempting to build healing environments focused on patient- and family-centered care, which calls for a more aesthetically pleasing, homelike environment. Many experts have found that design considerations are often chosen over infection control, emphasizing the need for continued education for patients and families in addition to healthcare workers.

The multidisciplinary team of experts who participated in these interviews and triads rely on a combination of research and experience. Most are reticent to term this approach “evidence-based” when compared with the level of evidence required in the practice of evidence-based medicine, characterized by randomized control trials, scientific rigor, and peer-reviewed publications. In order to develop a common definition and advance the field of “Evidence-Based Design” for mitigating the risk of HAIs, a methodology for evaluating the quality of evidence still needs to be established. This can only be accomplished with multidisciplinary collaboration involving a broad group of health professionals and design experts in the healthcare facility design planning and decision-making process. Collaboration that is based on a foundation of mutual understanding and open dialogue should lead to improved integration of evidence and experience in efforts to reduce design-related healthcare infections.

Forward-thinking teams are eliminating the previously siloed construction, design, and infection prevention considerations. They are beginning to evolve a more integrated and holistic approach. Healthcare decision makers recognize that until conclusive evidence emerges for interventions aimed at reducing and preventing HAI transmission, they must make best use of the resources available to inform their design decisions—a combination of research data and practical experience.

**Implications for Practice**

- Multiple interventions, including those that focus on the built environment and those that focus on human behavior, are necessary to mitigate healthcare-associated infection risk, as no single intervention is entirely effective.

- Experts suggest that, given the limited availability of data linking design to patient outcomes, decision makers should utilize a combination of guidelines, peer-reviewed literature, expert judgment, and experience to inform design decisions.

- Thorough analysis from multiple perspectives can avoid costly mistakes from both patient safety and financial standpoints. This calls for greater multidisciplinary dialogue and collaboration to improve the application of both evidence and experience in facility design.
The goals of the project are to:

✦ Develop a conceptual framework that describes the relationship between the built environment of healthcare facilities and the acquisition and prevention of HAIs; and

✦ Conduct an environmental scan, which includes a systematic literature review and interviews with experts, to understand the current state of knowledge of HAI prevention through use of the built environment.

For our discussion today, we are interested in discussing designs, strategies and technologies that are proven to reduce transmission of HAIs—and those that are promising, but are not yet substantiated by data. We are also interested in your feedback on potential literature review topics and references, as well as on our draft conceptual framework.

A. ROLE OF THE ENVIRONMENT IN MITIGATING INFECTION RISK

1. What is your sense of the overall importance of the built environment as a risk factor for acquisition of HAIs? When I say “built environment,” I am referring to things like surface material, room design (such as sink and hand sanitizing station placement), air and water purification systems, etc. Would you say that design is very important, somewhat important, or not important in mitigating infection risk? How has your opinion regarding the role of the built environment in HAI prevention changed over time?

B. TYPES OF GUIDANCE AND CONSULTATION SOUGHT

1. What types of guidance and consultation are physicians, other healthcare workers, and hospital/clinic administrators seeking with respect to prevention of HAIs? [PROBE: ventilation systems, carpeting, water features, surface design such as hydrophobic materials, cleaning regimens]

a. Are they seeking your overall general input in terms of strategy? Or are they seeking detailed review of guidelines, current research, and textbooks?

2. What types of resources do you use in your design decision making? Where do you get your information? How often do clients ask you to assess relevant literature before deciding which option to pursue?

C. LITERATURE REVIEW

1. We are conducting a structured literature review of the impact of facility design on HAIs. What, in your view, are the key topics and “must-have” references (research articles or reviews) pertaining to architecture and interior design and HAI prevention that we should include? [PROBE for specific strategies/technologies/design elements]

[If specific references/reports are noted by the respondent, ask if you can follow up with them by email to obtain additional info.]

2. Grey literature—Are there any vendor white papers, company-directed research reports, or other “grey literature” that...
### D. Current Design Elements/Technologies

1. **What do you think are the two or three most important design strategies or features that have the greatest impact on reducing HAI risk? Why did you select these?**

   a. Can you think of any currently used design strategies that should be abandoned? (i.e., that have lack of data to support, have unintended consequences, or are obsolete.)

2. **Same handedness**—Airplane cockpits are largely designed the same way so that a pilot does not encounter problems when trying to navigate a plane during an emergency. In most hospitals, patient rooms are not designed as mirror images; however, some argue that having the same layout in every room can decrease errors since caregivers will know exactly where everything is. This is expensive to do since it requires costlier plumbing and ventilation configurations. **What is the consensus on same-handedness in a hospital environment?**

3. **Water features** have been regarded as effective distractions in hospitals, particularly among the pediatric population. **What is the strength of the evidence that indicates whether fountains and aquariums pose serious HAI transmission risk? Are they safe as long as adequate maintenance is provided? How do you balance/manage the risks that water features may pose?**

   a. Under what conditions/circumstances are water features problematic? Is it more acceptable to have water features in some areas of hospitals than others (e.g., exposure to immunocompromised patients)?

4. **Super-hydrophobic materials** (e.g., lotus leaf materials) do not allow water or bacteria to attach to them and are considered an alternative to anti-microbial surfaces. **How effective are such materials and is there credible evidence to support their effectiveness?**

   How effective are these materials in real hospital applications (under normal cleaning regimes conducted by humans)?

5. **How is optimal placement of sinks determined?** Is there a particular design arrangement (e.g., design of sink, placement of hand hygiene dispensers) that enhances handwashing compliance?

   a. **Guidelines:** Have guidelines determined an optimal sink design to minimize HAIs in healthcare facilities? Is there an optimal water pressure to reduce splash and transmission of HAIs?

6. **There are many interesting public bathroom designs** (e.g., streamlined designs with urinals that have faucets placed directly above; urinals that include a painted fly to improve aim and reduce splash) found in restaurants and other commercial establishments. Are there similar innovative attempts made in healthcare facilities to reduce splash and contamination?

7. **Cleaning regimens:** Various types of new cleaning regimens have been proposed (e.g., moving UV lights into a room that previously housed an infected patient; use of hydrogen peroxide vapor like a bug bomb). How well do normal materials, surfaces, and fabrics hold up under these new cleaning regimens?

   a. Are there guidelines for cleaning? For example, in lab tests do they test to see if cleaning regimens kill bugs, disintegrate fabrics, and/or erode stainless steel? In field tests, are they maintainable, effective?

   b. Does evidence support cleaning versus self-cleaning processes for equipment?

   c. Some people argue that vertically positioned surfaces are cleaned more often than horizontally positioned surfaces, thereby decreasing the likelihood that vertically positioned equipment acts as reservoirs of contamination. **What is the consensus on equipment positioning as a means of decreasing HAIs—is there evidence that surface angle (i.e., vertical vs. horizontal) impacts surface contamination; if so, how might this influence design?**

8. **How do you determine whether it is cost-effective to renovate existing facilities with improved designs versus build a new facility?**

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**APPENDIX: SAMPLE INTERVIEW GUIDE (continued)**

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**ARCHITECTURE AND INTERIOR DESIGN INTERVIEW GUIDE**

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may not be in peer-reviewed journals that may provide insight into future developments.

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OPINIONS ON FACILITY DESIGN AND HAIs RESEARCH
E. PROMISING STRATEGIES, DESIGN ELEMENTS, AND TECHNOLOGIES

1. Looking across new and emerging strategies and technologies to disrupt the transmission of pathogens in the healthcare setting, which are the most promising?
   a. What would you implement now?
      i. Probe for design elements (e.g., decisions about designing/manufacturing the feature—coating of handrail, layout of the room, anterooms, surface materials, curtains, furnishings, amenities such as fountains, shelves, and handrails).

   b. What is promising, but needs more data to facilitate implementation?
      i. What new technologies need more robust data? Probe for technologies and decisions regarding design (e.g., ventilation systems, copper surfaces, hand hygiene sensors, disinfectant strategies, cleaning systems, sensor systems, smart technologies).

   ii. What will it take to get these technologies implemented? (PROBE: More research/research funds, statements from the CDC indicating that these issues/technologies are a priority and have a lot of potential to reduce HAI transmission?)

   iii. Are indirect data sufficient (e.g., UV light reducing environmental contamination) or are outcomes data (prevention of transmission/lower HAI rates) needed before implementation of new technologies? In other words, are hospitals requiring proof that these technologies actually reduce HAIs, or is it sufficient to provide data showing that the technology reduces environmental contamination?

   iv. For low-cost technologies such as impregnated curtains, should the evidence bar be lower, given that studies looking at outcomes such as reducing HAIs are difficult and costly to perform?

2. There has been an increase in antibiotic-resistant pathogens, many of which are untreatable, for which barrier isolation is currently used. There has also been increased emphasis on high-touch patient- and family-centered care. How would you reconcile these two seemingly opposing forces, and design a hospital, in particular, patient rooms, that both protect patients and provide a patient- and family-centered environment? How would you design a smarter environment that mitigates infection risk, while simultaneously optimizing patient- and family-centered care?

F. TRIADS

1. In order to learn more about how facility design impacts the prevention and transmission of HAIs, we plan to conduct triads (small group discussions consisting of three participants) with experts in the following areas: architecture and interior design; hospital epidemiology and infection control; air quality; water quality; and hospital administration. Who would you recommend as potential participants for our small group discussions with experts?

G. CLOSING

1. In closing, is there anything that we haven’t already discussed regarding any other strategies, design elements, or technologies you would recommend? Or is there anything else you’d like to mention about the role that facility design plays in mitigating the transmission of HAIs?

Thank you again for your time!
References

Bartley, J., & Streifel, A. J. (2010). Design of the environment of care for safety of patients and personnel: Does form follow function or vice versa in the intensive care unit? *Critical Care Medicine, 38*(8), S388–S398. doi:10.1097/CCM.0b013e3181e6d0c1


The Role of the Hospital Environment in the Prevention of Healthcare-Associated Infections by Contact Transmission

James P. Steinberg, MD; Megan E. Denham, MAEd; Craig Zimring, PhD; Altug Kasali, MArch, PhD; Kendall K. Hall, MD, MS; and Jesse T. Jacob, MD

OBJECTIVE: This article describes the role of the hospital environment in the spread of pathogens by direct and indirect contact. In addition, the prevention of transmission through interventions involving the built environment is discussed.

BACKGROUND: The hospital environment can become contaminated with pathogenic microorganisms, some of which can persist for long periods of time. Although contamination is common, the contribution of the hospital environment to the development of healthcare-associated infections remains unclear. In part spurred by the development of newer technologies to enhance environmental cleaning or to prevent contamination, research into the role of the environment in causing healthcare-associated infections has accelerated.

TOPICAL HEADINGS: A review of the recent literature finds an increasing body of evidence implicating contaminated surfaces in patient care areas in the transmission of pathogens and the development of infections. Single-patient rooms and optimally placed alcohol hand rub dispensers and other design features can mitigate infection risk. Enhanced environmental cleaning including touchless technologies and self-cleaning surfaces can reduce environmental contamination and may prevent infections.

CONCLUSIONS: The hospital environment contributes to transmission of pathogens in hospitals and to the development of healthcare-associated infections. Newer technologies to prevent environmental contamination or to enhance cleaning are promising although additional studies with the endpoints of reduction of infections are needed before the role of these technologies is known.

KEYWORDS: Built environment, design, hand washing, healthcare-associated infection, hospital, infection control

AUTHOR AFFILIATIONS: James P. Steinberg is a Professor of Medicine in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia. Megan E. Denham is a Research Associate II at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Craig Zimring is a Professor at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Altug Kasali is a Research Assistant at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Kendall K. Hall is a Medical Officer in the Center for Quality Improvement and Patient Safety at the Agency for Healthcare Research and Quality in Rockville, Maryland. Jesse T. Jacob is an Assistant Professor in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia.

CORRESPONDING AUTHOR: James P. Steinberg, MD, Professor of Medicine, Division of Infectious Diseases, Emory University School of Medicine, 550 Peachtree St. NE, Rm. 5-4403, Atlanta, GA 30308; jstei02@emory.edu; (404) 686-8918, (404) 686-4953 (fax).

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Overview
Surfaces in the hospital environment can easily become contaminated with disease-causing, or pathogenic, microorganisms. These microorganisms can come from patients, healthcare workers, visitors, or from external sources. In turn, pathogens that contaminate environmental surfaces can then be spread to patients through direct contact with the surface or indirectly, typically on the hands of healthcare workers, potentially leading to the development of healthcare-associated infections (HAIs).

Background
The ability of organisms to persist on environmental surfaces depends on many factors including the biologic properties of the organism and the presence of organic matter or moisture on surfaces. Many pathogens causing HAIs can survive for weeks to months on dry surfaces (Hota, 2004). Organisms such as Clostridium difficile (C. difficile) can form spores that allow for prolonged survival and are relatively resistant to disinfection. C. difficile causes diarrhea and when patients become incontinent, environmental contamination can become quite high. Common causes of HAIs, notably Staphylococcus aureus (S. aureus), including antibiotic resistant strains such as methicillin-resistant S. aureus (MRSA), and vancomycin-resistant Enterococcus (VRE), also frequently contaminate the environment. The Enterococcus is a normal inhabitant of the human colon and fecal incontinence can promote environmental contamination. Importantly, the environment can become contaminated by persons who are colonized (have the organism on the skin or in the body without causing infection) as well as by those who are infected with organisms that cause HAIs. While bacteria are the most clinically important pathogens that contaminate inanimate surfaces in the hospital, viruses, such as norovirus, can also survive on dry surfaces for 2 weeks or more. For more information on the characteristics of these pathogens, their ecological niche and clinical significance, see Zimring, Jacob, et al. (2013).

The role of contaminated environmental surfaces in causing HAIs is unclear, largely because most HAIs are either caused by endogenous organisms (those that a patient carries on or in their body prior to infection) or transmitted from person to person. Human behavior, such as hand hygiene compliance, can influence whether or not an organism contaminating an environmental surface is transmitted to a patient. The proportion of HAIs attributed to environmental surfaces has been estimated at 20% (Weinstein, 1991), but the actual proportion is unknown and depends on the setting, patient population, pathogen, and type of HAI. At the hospital level, it is important to have a comprehensive infection prevention program that tracks HAIs and major nosocomial pathogens to assess for temporal or geographic patterns that might suggest an environment source of transmission. For example, a clustering of cases of C. difficile diarrhea by hospital ward might lead to enhanced environmental cleaning.
There are several lines of evidence that suggest environmental contamination leads to the development of HAIs, including studies that show increased risk of a patient acquiring the same pathogen as the previous occupant of a room. In a large retrospective cohort study, Huang and colleagues attempted to quantify the risk of acquiring two common nosocomial pathogens, MRSA and VRE, from contaminated rooms (Huang, Datta, & Platt, 2006). Results showed a 40% increased risk of acquiring MRSA and VRE in patients admitted to intensive care rooms when the previous room occupant was known to harbor one of these pathogens. In a retrospective study in an intensive care unit, there was more than a two-fold risk of acquiring C. difficile if the prior room occupant had this infection (Shaughnessy et al., 2011). A similar risk was noted for Acinetobacter spp. and Pseudomonas aeruginosa (P. aeruginosa), but not for other gram-negative bacilli that contaminate environmental surfaces less frequently (Nseir et al., 2011). Studies using molecular typing have found that the same strain of an organism that contaminates the environment can be recovered from patients with HAIs (Huang, Datta, & Platt, 2006; Sexton, Clarke, O’Neil, Dillane, & Humphreys, 2006). Lastly, the importance of environmental contamination is demonstrated by studies showing that enhanced environmental cleaning reduces the risk of acquiring an HAI (see the “Cleaning Strategies and Technologies” section for more information on this topic).

A hierarchy (low to high) for assessing the strength of evidence for evaluating the role of environmental surfaces in the development of HAIs (Rhame, 1998) includes:

1. The ability of an organism to survive on a surface.
2. Culturing a pathogen from an in-use surface.
3. Demonstrating that an organism can grow on a surface.
4. Acquisition of an organism by a patient that cannot be explained by other recognized modes of transmission.
5. Case-control studies show an association between exposure to a contaminated surface and colonization or infection.
6. Prospective studies show that exposure to a surface contaminated with an organism is associated with colonization or infection with the same organism.
7. Prospective studies showing that decontamination of the environment leads to a decrease in the number of infections.

Acquisition of an organism from the environment may lead to colonization but not infection. Alternatively, an infection may develop well after acquisition of the organism so that any linkage to a transmission event becomes obscured. Consequently, studies that use clinical infection as the outcome may not detect transmission of pathogens from the environment to patients even when transmission is occurring. Studies that assess acquisition of organisms by performing surveillance cultures of patients without symptoms of infection are more likely to detect transmission, but these studies are more difficult and costly to conduct. Variables such as healthcare worker hand hygiene compliance and adequacy of
room cleaning can confound efforts to understand the importance of environmental contamination.

The difficulty in assessing the contribution of environmental contamination to the development of HAIs leads to similar challenges in studying the impact of interventions targeting environmental sources. Because clinical outcomes are infrequent, well-conducted intervention studies are hard to conduct and are sparse in the literature. Intermediate endpoints, such as reduction in environmental contamination, are often the measured outcomes, and the resultant reduction of infection risk must be inferred.

**Strategies Involving the Built Environment to Prevent Transmission of Pathogens through Direct or Indirect Contact**

The model presented in Figure 1 depicts opportunities to prevent transmission of pathogens by direct and indirect contact using interventions involving the built environment. This model and the discussion that follows also include interventions that use the built environment to influence human behavior such as by promotion of hand hygiene compliance. The design and major findings or relevant clinical studies are summarized in the accompanying Appendix.

**Cleaning Strategies and Technologies**

Common hospital-acquired pathogens often can be recovered from hospital room surfaces after conventional room cleaning with standard disinfectants. Ineffective cleaning practices appear to be the reason for this residual contamination. After researchers carefully performed a thorough terminal cleaning using conventional methods and standard cleaning products, environmental cultures did not detect VRE and rarely detected *C. difficile*; in contrast, these pathogens could be recovered from 10% to 30% of high-touch surfaces following terminal cleaning by environmental services personnel (Eckstein et al., 2007). This study demonstrates that the failure of routine cleaning to remove pathogens from the environment is not due to ineffective disinfectants, but rather to the lack of strict adherence to cleaning protocols by environmental services personnel, who often have relatively low wages, high turn-over rates, and are under significant time pressure to clean rooms quickly. Monitoring effectiveness of room cleaning by various methods including the measurement of adenosine triphosphate (ATP) bioluminescence and feeding back results to environmental service workers has been studied to a strategy to improve the quality of room cleaning. Measurement of ATP bioluminescence has been used in other industries including the food and beverage industries for years. ATP is present in all organic material including microorganisms, food, and human secretions and its measurement before and after cleaning is a general indicator of cleanliness. While some studies show promising results using ATP bioluminescence, further study is needed before conclusions can be made about the efficacy of this strategy (Boyce et al., 2009).

The increased risk of transmission of pathogens to patients in rooms previously occupied by colonized or infected patients can be reduced by improved termi-
**Figure 1.** Contact chain of transmission interventions model.

**Reservoir:** Place (human or environmental) where organisms reside and multiply.

**Source:** Place from which an organism is transmitted to the host. Source may be the same as the reservoir or become contaminated from the reservoir (e.g., a surface or instrument).
nal cleaning (cleaning when the patient is transferred out of the room (Carling & Bartley, 2010). Enhanced room cleaning has been shown to decrease the risk of MRSA and VRE acquisition for patients placed in rooms where the previous patient had these pathogens (Datta, Platt, Yokoe, & Huang, 2011; Hayden et al., 2006). *C. difficile* incidence was reduced when room cleaning was changed to bleach, which can better kill spores produced by this organism (Orenstein, Aronhalt, McManus, & Fedraw, 2011).

Novel materials and cleaning technologies have been developed to overcome the difficulties in successfully implementing effective cleaning protocols. These technologies do not replace the need for manual cleaning because it is necessary to remove organic material and debris from surfaces for these technologies to work optimally (Rutala & Weber, 2008). The most developed technologies to date include antimicrobial surfaces such as copper, ultraviolet light, and hydrogen peroxide systems. Antimicrobial surfaces have the significant advantage of providing continuous antimicrobial activity. Given that contamination of high-touch surfaces can occur frequently as part of daily patient care, surfaces that have continuous, effective, intrinsic antimicrobial activity would be advantageous, even when routine daily cleaning is optimized.

**Ultraviolet Germicidal Irradiation**

Ultraviolet germicidal irradiation (UVGI) that can kill most pathogens including *C. difficile* spores and, when in line of sight, can reduce surface contamination by several logs (Karpanen et al., 2012; Rutala, Gergen, & Weber, 2010). Several systems have been developed for delivering UVGI in patient rooms, all of which require patients and staff to vacate the room while UVGI is in use. Nonetheless, UVGI offers advantages over other innovative cleaning technologies such as hydrogen peroxide in that there are no hazardous vapors produced or harmful residues left behind. Decontamination using UVGI can take up to 1 hour to kill the spores of *C. difficile*, although bacteria and viruses are killed more quickly. Consequently, UVGI has been used for terminal disinfection and not daily cleaning. A disadvantage of UVGI is its decreased efficacy on surfaces not directly exposed to the UV light. Technologies and strategies to increase the efficacy of UVGI and decrease the exposure time necessary to decontaminate surfaces are beginning to emerge in the literature. A nanostructured UV-reflective wall coating has been shown in experimental settings to enhance killing of bacteria indirectly exposed to UVGI and can reduce the time needed to effectively treat a room with UVGI from 43 minutes to 10 minutes to kill *C. difficile* and from 25 minutes to 5 minutes for MRSA (Rutala, Gergen, Tande, & Weber, 2013).

While UVGI is a promising technology, additional research is needed to demonstrate the efficacy of UVGI in preventing transmission of pathogens in hospitals and in reducing infections. Better strategies to maximize the ability of UVGI to decontaminated surfaces not exposed to direct light are also needed.
Hydrogen Peroxide

Hydrogen peroxide (HP) has also been used for terminal cleaning and can be delivered as a vapor (HPV) or mist. The vapor system creates HP in gaseous form, while the mist system creates an aerosol with HP droplets of 8μ–10μ. In head to head laboratory testing, HPV was more effective than mist in killing bacterial spores (Holmdahl, Lanbeck, Wullt, & Walder, 2011). The reduction of surface pathogens is greater with HP compared to UVGI, and HP has the additional advantage of permeating the entire room, with no line of sight limitations to achieve full efficacy (Boyce, Havill, & Moore, 2011). Decontamination with HP as reported in the literature typically requires 3–5 hours, although new HP systems are currently marketed as needing shorter exposure times. HP is more difficult to deliver than UVGI; the room, including HVAC ducts, must be sealed. Nonetheless, this technology has been used for routine hospital cleaning, although the impact of hospital-wide use on infection rates was not reported (Otter et al., 2009).

Most published studies evaluating HP, both vapor and mist, use the end point of reduction or elimination of environmental contamination and HP consistently shows marked reduction or elimination of surface contamination after application (Falagas et al., 2011). HPV in conjunction with other infection control measures has been used to interrupt an outbreak of *Acinetobacter* infections in ICUs but given the multiple interventions involved, the impact of HPV is unclear (Chmielarczyk et al., 2012). HP has been shown to decrease the incidence of *C. difficile* infection in high incidence wards (Boyce et al., 2008). In a prospective cohort study involving six high-risk units, HPV decontamination of rooms where the departing occupant was known to harbor a multidrug-resistant organism (MDRO) was implemented in three units. Patients admitted to decontaminated rooms were overall significantly less likely to acquire any MDRO compared to patients in the control units. VRE acquisition was significantly reduced; there was non-statistically significant reduction of other organisms such as MRSA and *C. difficile* (Passaretti et al., 2013).

Similar to UVGI, more research with the endpoint of reduction of infections is needed to establish the role of HP as an adjunct to physical cleaning. The effect of repeated exposures of HP to surface materials and equipment also needs additional study.

Surfaces

Contaminated surfaces can serve as sources for transmission of HAI. Strategies to interrupt the chain of infection include selecting surfaces that resist contamination and are easily cleaned. Novel materials that have antimicrobial properties, particularly those containing copper, are being investigated for their ability to decrease surface contamination and prevent the spread of pathogens.
Copper

Copper ions are lethal to a wide variety of pathogens and can be incorporated into surface materials (Grass, Rensing, & Solioz, 2011; Huang, Shen, Chiou, Huang, & Hsu, 2009). Copper antimicrobial surfaces have been shown to reduce surface pathogens in both laboratory and clinical settings. Microbial killing on copper surfaces typically occurs within hours, but the killing rate depends on many factors, including the copper content (more rapid killing with higher copper content), environmental conditions such as temperature and moisture, as well as the pathogen (Grass et al., 2011). Resistance genes have been identified in bacteria including *P. aeruginosa* that affect survival on copper, which suggests that bacteria could develop some degree of resistance to copper (Elguindi, Wagner, & Rensing, 2009).

Copper alloys have been developed for high-touch surfaces such as door handles, bed rails, toilet seats, and plumbing fixtures. In clinical settings, these copper surfaces significantly reduce contamination with common pathogens, including MRSA and VRE, when compared to standard surfaces (Casey et al., 2010; Karpanen et al., 2012). One randomized controlled trial found a reduction in HAIs and MRSA or VRE colonization in patients assigned to intensive care unit rooms fitted with copper surfaces on high-touch items (Salgado et al., 2013). This study also found less environmental contamination in rooms fitted with copper surfaces and a significant association between microbial burden in the rooms and HAI risk. However, copper surfaces may be more reactive and prone to a build-up of debris following repeated cleaning compared to stainless steel surfaces, which might impact antimicrobial effectiveness over time (Airey & Verran, 2007). Treating copper surfaces with coating agents to prevent corrosion would interfere with contact killing by copper ions.

Floor Coverings

Carpets offer many potential benefits in hospitals and may be appropriate in select areas of the facility. They add aesthetic value, reduce noise, offer skid resistance, and add protection from falls. Carpets can also reduce fatigue for healthcare workers required to stand or walk. However, carpets have been found to support higher colony counts of pathogenic bacteria than hard floor coverings, can easily become contaminated, are more difficult to clean, and take time to dry when wet. Carpeted rooms are also more likely to become contaminated with *C. difficile* (Skoutelis, Westenfelder, Beckerdite, & Phair, 1994). In addition, pediatric patients hospitalized in carpeted rooms have been shown to become colonized with bacteria previously isolated from wool carpets in the patient room (Anderson, Mackel, Stoler, & Mallison, 1982). However, this study and other studies in non-outbreak settings did not find an association between carpeted patient rooms and an increased risk of the development of HAIs. The small size of these studies with few infections as outcomes may have contributed to these negative findings. There is one report of an outbreak of aspergillosis in immunocompromized patients in which carpet contamination was with fungal spores was noted (Stanton, Parker, Jacobs, Creger, & Lazarus, 1994). The outbreak subsided after the carpets were cleaned and the authors suggest that the fungal
transmission was due to the carpet contamination. However, other factors contributed to the outbreak including extensive construction at the medical center and a fire with subsequent demolition of an adjacent building prior to onset of the outbreak. Based on these data, the Healthcare Infection Control Practices Advisory Committee (HICPAC) does not recommend carpeting in protective isolation rooms (Siegel, Rhinehart, Jackson, & Chiarello, 2007).

Due to practical considerations regarding cleaning, as well as their potential to harbor pathogens, carpets should be avoided in patient care areas that are likely to be exposed to fluids, such as operating rooms or intensive care unit rooms. However, they have benefits in other areas, including hallways and waiting rooms, and data on infection risk in these areas are lacking.

Physical Barriers

Physical barriers, such as single-patient rooms, can potentially decrease transmission of pathogens by providing spatial separation. Other barriers, such as curtains, are touched frequently and easily become contaminated with bacteria. The role these partitions play in the acquisition and prevention of healthcare-associated infections is uncertain.

Single-patient Rooms

Single-patient rooms, compared to semi-private or open ward design, have been associated with decreased healthcare-associated infection rates and decreased acquisition of major hospital-acquired pathogens including *Staphylococcus aureus*, *Pseudomonas*, and *Acinetobacter*. Studies investigating private rooms are often quasi-experimental, before and after in design, or are retrospective and have confounders such as variable hand hygiene compliance that make interpretation difficult. However, many studies have shown a benefit of single-patient rooms. Most of the studies showing benefit of single-patient rooms in reducing HAIs have been conducted in adult intensive care units (Bloemendaal et al., 2009; Bracco, Dubois, Bouali, & Eggimann, 2007; Mulin et al., 1997). Single-patient rooms have also been associated with decreased infection rates in burn units and in pediatric intensive care units (Ben-Abraham et al., 2002; McManus, Mason, McManus, & Pruitt 1994).

Physical separation of patients in private rooms may reduce opportunities for direct contact with contaminated surfaces and can potentially prevent indirect contact by limiting healthcare workers from moving from patient to patient without performing hand hygiene. The decrease in infections seen with single-bed rooms may be in part related to other changes to the physical environment associated with private rooms including improved sink to bed ratios, elimination of privacy curtains, private toilets, and more frequent room cleaning, particularly terminal room cleaning that is done when the room is vacated after patient discharge (Ulrich et al., 2008).
Single-patient rooms also have logistical advantages, in that they can obviate the need to transfer patients for contact isolation and can improve patient flow. Single-patient rooms enhance privacy that can facilitate exchange of sensitive information, allow for more family presence, reduce noise, and may have other patient safety benefits. The Facility Guidelines Institute began to require single-patient rooms for new construction starting with the 2010 Edition. Along with the movement towards patient- and family-centered care, critical care societies have endorsed the inclusion of dedicated spaces for family members and encouraging family presence in critical care units (Davidson et al., 2007). To date, there are no studies that have investigated the impact of increased family presence on room contamination and on infection risk to patients.

**Curtains**

Curtains are used in hospitals to provide privacy and to function as movable partitions in many multi-bed spaces, such as perioperative units, emergency departments, semi-private rooms, and open wards. Curtains are sometimes used in single occupancy rooms including intensive care unit rooms. Of note, none of the studies comparing infection rates in single-patient rooms to semi-private rooms or open units address contaminated privacy curtains as a potential confounder. Contamination of curtains is common with a variety of pathogens, including MRSA, VRE, and *C. difficile* (Trillis III, Eckstein, Budavich, Pultz, & Donskey, 2008). Contaminated curtains have been linked to an outbreak of multidrug-resistant *Acinetobacter* spp. The outbreak was terminated with a set of interventions, including enhanced environmental cleaning, attention to hand hygiene, antibiotic restriction, and frequent replacement of the curtains (Das et al., 2002). Curtains are considered “high-touch” surfaces by the CDC in the *Guidelines for Environmental Infection Control in Health-Care Facilities* (Sehulster & Chinn, 2003). These guidelines recommend more frequent cleaning of curtains than with low-touch surfaces, but they do not specify a cleaning frequency or method.

While curtain contamination is common and plausibly linked to transmission in an outbreak setting, the role of curtains in transmission of pathogens in non-outbreak settings is unknown. Handprint cultures after touching contaminated curtains show that pathogens such as MRSA can be transferred to hands, but that only a few organisms are transmitted in these exchanges (Trillis III et al., 2008). The ability of these few organisms to then be transferred to patients by touch leading to patient colonization and infection is not known.

Although there is uncertainty in the role of curtains in transmission of pathogens, low-cost steps to minimize or eliminate contact with privacy curtains are reasonable. Curtains in private rooms should be assessed to determine their value and removed if not needed. Window treatments may be able to replace curtains in some settings. Switchable privacy glass and film, or windows with built-in blinds may reduce or eliminate the contamination risks. When there are no design alternatives to curtains, such as those found in semi-private rooms or wards, curtain cleaning frequency and efficacy should be reviewed. Curtains made with antimicrobial materials or coatings are available in the market. One study found
that antimicrobial curtains did not prevent contamination with pathogens, but delayed contamination for 2 weeks (Schweizer et al., 2012). In sum, the ability of these curtains to reduce transmission of pathogens is unknown and merits further study. Emphasizing hand hygiene after touching curtains is prudent.

Hand Hygiene Infrastructure

Hand hygiene is generally accepted as the most important infection prevention measure to reduce transmission of pathogens in hospitals, yet achieving high compliance with hand hygiene has been elusive (Boyce & Pittet, 2002; Pittet & Allegranzi, 2006). Poor design of healthcare facilities has been cited as a contributor to low hand hygiene compliance rates. In response, a human factors engineering approach has been proposed to improve compliance. This approach includes having abundant sinks and alcohol hand rub dispensers placed in clearly visible, convenient, and standard locations at comfortable heights (Suresh & Cahill, 2007).

Prior to the widespread adoption of alcohol-based hand rubs, sink-to-bed ratios and sink locations were studied to assess the impact of sink number and placement on hand hygiene compliance. Hand hygiene compliance was significantly higher in an ICU with a 1:1 sink to bed ratio compared to a 1:4 ratio (Kaplan & McGuckin, 1986). However, in other studies, hand hygiene compliance remained poor when additional sinks were placed in open wards and when sinks dedicated to healthcare worker use were placed in private rooms (Lankford et al., 2003; Whitby & McLaws, 2004). Current guidelines recommend that in most situations alcohol-based hand rubs should be the primary method of hand hygiene, in part due to their ease of use and the ability to install dispensers at optimal locations in rooms independent of plumbing fixtures. Use of alcohol-based hand rubs has been associated with an improved rate of hand hygiene compliance compared to soap and water (Rupp et al., 2008).

Strategic placement of hand rub dispensers has been shown to improve hand hygiene compliance rates. In simulation-based testing, placing hand rub dispensers in clear view of physicians as they observed patients significantly improved hand hygiene compliance (Birnbach et al., 2010). In one ICU setting, dispensers in conspicuous locations in immediate proximity to patients also improved hand hygiene compliance (Thomas, Berg-Copas, Vasquez, Jackson, & Wetta-Hall, 2009).

Direct observation and immediate feedback have been shown to further improve hand hygiene compliance. In a study of video surveillance with direct feedback, hand hygiene rates were less than 10% during a 16-week pre-feedback period, and in the 16-week post-feedback period it was 81.6%. This increase was maintained through 75 weeks at 87.9% (Armellino et al., 2012). Radio-frequency identification (RFID) and other electrical sensors have been developed to assist with monitoring hand hygiene compliance (Polgreen, Hlady, Severson, Segre, & Herman, 2010; Sahud et al., 2010). Some monitoring systems affix the sensors to healthcare worker identification badges and monitor use of alcohol hand rub dispensers. Other systems provide reminders to healthcare workers on room entry.
(Venkatesh et al., 2008). Widespread implementation of these systems has been limited by installation and monitoring costs. It is likely that as these technologies improve and costs decrease, they will replace human observers as the primary strategy to promote and monitor hand hygiene compliance.

Conclusions
Pathogens contaminating environmental surfaces can spread to patients by direct contact with the surface or indirectly, typically on the hands of healthcare workers. Multiple strategies can help mitigate this risk of direct or indirect contact by decreasing surface contamination and improving cleaning of contaminated surfaces. Cleaning of surfaces, as routinely performed in most hospitals, does not entirely eliminate environmental contamination. While measurement of cleaning efficacy with feedback of results may improve quality of cleaning, novel strategies including surfaces that resist contamination and touchless cleaning systems have been developed to augment manual room cleaning. These novel strategies do not replace routine cleaning as it is still necessary to remove organic material and other debris, the presence of which diminishes efficacy of any cleaning system. The need to consider enhanced strategies to clean the environment depends to some degree on the burden of HAIs following implementation of other infection prevention measures.

UVGI and HP are emerging technologies that are effective against a wide variety of pathogens; however it is necessary for all personnel and patient to vacate the room while the technologies are in use, making them practical only for terminal cleaning. Compared to UVGI, HP has greater efficacy in terms of exponential killing of pathogens and is not limited by direct line-of-sight. However, HP is more cumbersome to use and takes longer to decontaminate a room. UVGI may ultimately prove to be more practical as an adjunct for routine terminal cleaning in high-risk areas, while HP may be more effective in the setting of an outbreak of a pathogen linked to environmental contamination. Neither of these strategies will prevent environmental contamination that occurs during routine daily care. Additional research demonstrating a reduction of HAIs, and determining the impact of repeated exposure on surfaces and equipment are needed before these systems become standard practice. Innovations are needed that improve the effectiveness of these technologies, reduce the exposure time needed for room cleaning, and lower cleaning costs.

Use of antimicrobial surfaces is an alternative strategy that can potentially resist ongoing surface contamination. Copper has been acknowledged by the EPA for its ability to kill microorganism and can be embedded in high-touch surface materials. Copper surfaces resist contamination, but additional research is needed to determine long-term performance in hospital settings, including additional outcome studies measuring HAI rates.

The built environment can alter behavior and improve hand hygiene compliance through conveniently and strategically placed sinks and alcohol rubs. Spatial
separation is an additional strategy to limit direct or indirect contact. Single-patient rooms are now required for new construction and reduce the need for privacy curtains, which frequently become contaminated. The role of curtains in contributing to HAIs and optimal strategies to clean or eliminate the need of curtains require further study.

Future strategies may also involve redesign of patient care areas to minimize opportunities for healthcare workers to come in contact with pathogens, thus limiting healthcare worker role in perpetuation the chain of transmission. An unexplored area that requires further research is the impact of increased family presence in patient rooms on transmission of pathogens and how the built environment can mitigate this potential risk.

Much of the research using novel strategies to reduce environmental contamination such as with antimicrobial surfaces and using new cleaning technologies has been conducted in the past 5 years. These technologies are still evolving and additional studies to assess their ability to reduce HAIs are underway. Results of these studies will not only clarify the roles of these technologies, but will also help answer questions about the role of the environment in the development of HAIs though contact transmission.

**Implications for Practice**

- The hospital environment readily becomes contaminated with pathogens capable of causing healthcare-associated infections. These organisms can persist on surfaces for prolonged periods of time and can be transmitted to susceptible patients.

- Routine room cleaning as practiced in most hospitals is often suboptimal and does not completely eliminate the risk of acquisition of pathogens from the environment. The need for enhanced cleaning strategies depends on the burden of infections that appear to be related to transmission from the environment.

- Antimicrobial surfaces and touchless cleaning strategies such as ultraviolet germicidal irradiation and hydrogen peroxide vapor or mist can decrease environmental contamination but, presently, the role of these technologies in hospitals is not clear.

- Design of the patient care area including visible placement of hand hygiene dispensers can influence behavior and decrease transmission of pathogens by contact.
## APPENDIX: CONTACT EVIDENCE TABLE

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>STUDY TYPE</th>
<th>SETTING</th>
<th>PATHOGEN(S)</th>
<th>RISK FACTOR/INTERVENTION</th>
<th>COMPARISON</th>
<th>ENDPOINT</th>
<th>RESULTS</th>
<th>COMMENTS</th>
<th>FOCUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airey, P., &amp; Verran, J. (2007).</td>
<td>Other</td>
<td>Laboratory</td>
<td><em>Staphylococcus aureus</em></td>
<td>Repeatedly cleaned copper and stainless steel surfaces with 2 cleaning agents</td>
<td>Stainless steel</td>
<td>Bacterial load and residual mass on surfaces.</td>
<td>Copper observed to be reacting with the cleaning agents which led to accumulation of residual cells and soil. Stainless steel remained more cleanable.</td>
<td>The study emphasized various properties of cleaning agents and surfaces. The study may impact use of copper.</td>
<td>Copper</td>
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<tr>
<td>Anderson, R. L., Mackel, D. C., Stoler, B. S., &amp; Mallison, G. F. (1982).</td>
<td>Case-control</td>
<td>Patient rooms in a pediatric hospital</td>
<td>Multiple</td>
<td>Carpets and associated cleaning protocols</td>
<td>Carpeted vs. non-carpeted rooms</td>
<td>Environmental contamination (bacterial load on floors); infection (<em>C. difficile</em>)</td>
<td>Higher microbial counts detected on carpets. However, the study reported no statistically significant differences in <em>C. difficile</em> in patients in the carpeted and non-carpeted rooms.</td>
<td>The study not powered to find infection as outcomes. Authors also emphasized air above carpeting containing more consistent concentrations of organisms.</td>
<td>Carpets</td>
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<tr>
<td>Ben-Abraham, R., Keller, N., Saxid, O., Vardi, A., Weinberg, M., Barzilay, Z., &amp; Paret, G. (2002).</td>
<td>Pre-post intervention</td>
<td>Pediatric ICU</td>
<td><em>Nosocomial infections</em></td>
<td>Single patient rooms</td>
<td>Open ward</td>
<td>Infection</td>
<td>After conversion of ICU to single-bed rooms, there was a significant reduction of nosocomial infections primarily ventilator associated pneumonias. CLABSIs and UTIs.</td>
<td>This was a relatively small study. Pre-intervention data was collected 3 years prior to post intervention increasing likelihood of confounders.</td>
<td>Single-patient rooms</td>
</tr>
<tr>
<td>Birnbach, D. J., Nevo, I., Scheiman, S. R., Fitzpatrick, M., Shekhter, I., &amp; Lombard, J. L. (2010).</td>
<td>Randomized control trial</td>
<td>Patient room mock-up</td>
<td>—</td>
<td>Placement of alcohol-based hand-rub dispenser in clear view of physicians</td>
<td>Room with dispensers not in field of view</td>
<td>Hand hygiene compliance</td>
<td>Hand hygiene compliance in rooms with dispensers in clear view was 53.8% compared to 11.5% in room with dispensers not in field of view (p = 0.001).</td>
<td>The study was conducted with 52 physicians who volunteered to examine a standardized patient in 2 simulation rooms.</td>
<td>Hand hygiene</td>
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<td>SOURCE</td>
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<td>5</td>
<td>Cohort</td>
<td>6 ICUs in 6 European countries</td>
<td><em>Staphylococcus aureus</em></td>
<td>Twice weekly surveillance cultures (nasal and perineal swabs)</td>
<td>—</td>
<td>S. aureus acquisition</td>
<td>ICU with open floor plan was a risk factor for <em>S. aureus</em> acquisition (<em>p</em> = 0.05 for all <em>S. aureus</em>; <em>p</em> = 0.03 for MRSA).</td>
<td>Relatively small study with short observation period of 3 months.</td>
<td>Multiple including single patient rooms</td>
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<tr>
<td>6</td>
<td>Other</td>
<td>Patient rooms</td>
<td><em>Clostridium difficile</em></td>
<td>UVGI</td>
<td>—</td>
<td>Environmental contamination</td>
<td>UVGI significantly reduced colony counts and <em>Clostridium difficile</em> spores on contaminated surfaces. The unit was significantly better in reducing contamination on surfaces in direct line of sight.</td>
<td>Conflict of interest was reported.</td>
<td>UVGI</td>
</tr>
<tr>
<td>7</td>
<td>Pre-post intervention</td>
<td>5 wards in a 500-bed university hospital</td>
<td><em>Clostridium difficile</em></td>
<td>Hydrogen peroxide vapor (HPV)</td>
<td>Baseline period</td>
<td>Environmental contamination and infection</td>
<td>Hydrogen peroxide vapor decontamination was reported to be effective in eradicating <em>C. difficile</em> from contaminated surfaces in studied wards.</td>
<td>HPV was presented as an option to eradicate <em>C. difficile</em> in hospital settings. Conflict of interest was reported.</td>
<td>Hydrogen peroxide</td>
</tr>
<tr>
<td>8</td>
<td>Observational</td>
<td>14-bed medico-surgical ICU</td>
<td>MRSA, Pseudomonas spp.</td>
<td>Single patient rooms</td>
<td>Bay rooms with 2–3 beds per room</td>
<td>Infection</td>
<td>Lower infection rates observed in single patient rooms.</td>
<td>Allocation of patients not randomized. Handy hygiene compliance not monitored.</td>
<td>Single-patient rooms</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td><strong>9</strong></td>
<td>Review</td>
<td>Healthcare environments</td>
<td>—</td>
<td>Cleaning</td>
<td>—</td>
<td>Environmental contamination and patient infection</td>
<td>Thoroughness of environmental hygiene can be improved through structured interventions and improved cleaning of high-risk surfaces both decreases environmental contamination and patient acquisition of infections.</td>
<td>A good review integrating a discussion with regards to guidelines and standards.</td>
<td>Room cleaning</td>
</tr>
<tr>
<td><strong>10</strong></td>
<td>Case-control</td>
<td>Acute medical ward</td>
<td>Staphylococcus aureus (MRSA, MSSA), VRE, C. difficile, and coliform bacteria</td>
<td>Toilet seat, tap handles, door push plate containing copper</td>
<td>Conventional materials</td>
<td>Environmental contamination; bacterial load on surfaces</td>
<td>Copper-containing materials reduced microbial bioburden of surfaces by 90%–100%</td>
<td>The authors recommended a mixed practice combining the use of copper surfaces and appropriate cleaning protocols.</td>
<td>Copper</td>
</tr>
<tr>
<td><strong>11</strong></td>
<td>Other</td>
<td>ICU with outbreak</td>
<td>Acinetobacter</td>
<td>HPV; enhanced infection control measures</td>
<td>—</td>
<td>Environmental contamination; infection</td>
<td>Outbreak interrupted after instituting multiple measures including HPV.</td>
<td>Role of HPV in ending outbreak unclear.</td>
<td>Hydrogen peroxide</td>
</tr>
<tr>
<td><strong>12</strong></td>
<td>Cohort</td>
<td>ICU rooms in a 750-bed hospital (medical, cardiac, burn/trauma, surgical)</td>
<td>MRSA, VRE</td>
<td>A set of interventions including targeted feedback, cleaning clothes saturated with disinfectant, and increased education</td>
<td>Pre- and post-intervention comparison</td>
<td>Infection</td>
<td>Acquisition of MRSA and VRE was significantly reduced. The study introduced a cleaning intervention bundle to reduce MRSA and VRE transmission.</td>
<td>With regards to acquisition risk from prior occupants, the cleaning intervention had differential effect for MRSA and VRE. The intervention did not erase the increased acquisition risk associated with VRE-positive patients previously occupying the ICU rooms.</td>
<td>Room cleaning</td>
</tr>
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<td>SOURCE</td>
<td>STUDY TYPE</td>
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<tr>
<td>13</td>
<td>Pre-post intervention</td>
<td>Neonatal intensive care unit (NICU)</td>
<td>Nosocomial sepsis and non-infectious outcomes</td>
<td>Single-family rooms</td>
<td>Open bays</td>
<td>Neonatal sepsis</td>
<td>Sepsis incidence 6% in single family room and 11% in open bay; no statistics applied.</td>
<td>Infection was a secondary focus in this paper. Historical unit had open bays. Infectious and non-infectious outcomes measured after move to new unit with single-family rooms</td>
<td>Single-patient rooms</td>
</tr>
<tr>
<td>14</td>
<td>Pre-post intervention</td>
<td>Patient rooms</td>
<td><em>Clostridium difficile</em>, <em>VRE</em></td>
<td>Enhanced education and training of housekeeping staff; disinfection with 10% bleach; cleaning by research team member</td>
<td>Baseline room cleaning by housekeeping</td>
<td>Environmental contamination</td>
<td>Rooms of patients with <em>VRE</em> and <em>C. difficile</em> heavily contaminated before room cleaning. Contamination of many surfaces persisted after routine cleaning by housekeeping. Cleaning by research personnel using 10% bleach eliminated targeted pathogens from surfaces demonstrating that cleaning, if properly done, could be effective. After educational intervention and with use of 10% bleach, cleaning by housekeeping personnel removed <em>VRE</em> and <em>C. difficile</em> from most environmental surfaces.</td>
<td>Routine room cleaning inadequate. Process improvement interventions involving front line housekeeping staff demonstrated that room cleaning, if properly done, can successfully remove pathogens from surfaces.</td>
<td>Room cleaning</td>
</tr>
<tr>
<td>15</td>
<td>Other</td>
<td>Laboratory</td>
<td><em>Pseudomonas aeruginosa</em></td>
<td>Copper</td>
<td>—</td>
<td>Contamination</td>
<td>The study demonstrated that <em>P. aeruginosa</em> was rapidly killed on different copper cast alloys. The study also found that genes involved in conferring copper resistance in copper-containing medium also influenced the length of survival time.</td>
<td>The authors stated that the temperature was a factor influencing the rate of killing on copper cast alloys.</td>
<td>Contact</td>
</tr>
<tr>
<td>SOURCE</td>
<td>STUDY TYPE</td>
<td>SETTING</td>
<td>PATHOGEN(S)</td>
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<tr>
<td>16</td>
<td>Review</td>
<td>Clinical settings</td>
<td>MRSA, Clostridium difficile, and other bacteria</td>
<td>Hydrogen peroxide vapor (HPV) and hydrogen peroxide mist</td>
<td>—</td>
<td>Environmental contamination</td>
<td>Systematic review of 10 studies assessing ability of hydrogen peroxide (vapor or mist) to decontaminate surfaces in patient rooms. All studies showed decreased environmental contamination by pathogenic bacteria including C. difficile spores in 3 studies. Percent of environment cultures with bacterial growth ranged from 8–62% pre- to 0–4% post-decontamination</td>
<td>While decrease in environmental contamination was impressive in all studies, none assessed clinical infections as endpoint</td>
<td>Hydrogen peroxide</td>
</tr>
<tr>
<td>17</td>
<td>Outbreak investigation</td>
<td>Bone marrow transplant/ leukemia service</td>
<td>Aspergillus</td>
<td>Enhanced carpet cleaning</td>
<td>—</td>
<td>Bacterial load on carpets and infection</td>
<td>Outbreak of invasive aspergillosis related to nearby construction and open window. Carpet contamination documented. Outbreak waned when carpets cleaned.</td>
<td>Letter to the editor implicating carpet in sustaining Aspergillus outbreak in a transplant/ leukemia ward</td>
<td>Carpets</td>
</tr>
<tr>
<td>18</td>
<td>Other</td>
<td>Laboratory</td>
<td>Staphylococcus aureus (MRSA, MSSA), PSA, E. coli, VRE</td>
<td>Copper surfaces</td>
<td>Stainless steel</td>
<td>Environmental contamination; bacterial load on surfaces</td>
<td>Most pathogens not detectable after 40–60 minutes on copper surfaces. Stainless steel had no impact on survival.</td>
<td>The study focused on the use of pure copper, and demonstrated its effectiveness in decreasing bacterial load.</td>
<td>Copper</td>
</tr>
<tr>
<td>SOURCE</td>
<td>STUDY TYPE</td>
<td>SETTING</td>
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<td>RISK FACTOR/INTERVENTION</td>
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<tr>
<td>19</td>
<td>Pre-post intervention</td>
<td>ICU</td>
<td>Vancomycin-resistant Enterococci (VRE)</td>
<td>Cleaning education, multi-modal hygiene intervention</td>
<td>Baseline measurement period vs. post-intervention periods</td>
<td>Environmental contamination and patient infection</td>
<td>VRE acquisition rates decreased significantly after the baseline period and then remained stable following interventions. The study associated reduced VRE contamination on surfaces, cleaner healthcare worker hands, and reduced cross-contamination with enforcing routine cleaning measures.</td>
<td>Cleaning was done with a mop soaked in the standard hospital quaternary ammonium detergent disinfectant (Virex; SC Johnson). Study was funded by CDC.</td>
<td>Room cleaning</td>
</tr>
<tr>
<td>20</td>
<td>Other</td>
<td>Laboratory</td>
<td>G. stearothermophilus</td>
<td>Hydrogen peroxide vapor (HPV)</td>
<td>Aqueous hydrogen peroxide mist</td>
<td>Killing of bacterial spores</td>
<td>HPV was more effective than aqueous HP mist</td>
<td>Only study comparing HPV to mist</td>
<td>Hydrogen peroxide</td>
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<tr>
<td>21</td>
<td>Cohort</td>
<td>8–10-bed intensive care units at a tertiary care hospital</td>
<td>Methicillin-resistant Staphylococcus aureus (MRSA), vancomycin-resistant Enterococci (VRE)</td>
<td>Rooms occupied by infected patients</td>
<td>Rooms previously occupied by non-infected patients</td>
<td>Infection (MRSA, VRE)</td>
<td>Odds ratios for MRSA or VRE infection in patients admitted to room where previous occupant had the organism were both 1.4 (p &lt;0.05)</td>
<td>The reported risk was accounted for less than 10% of all cases of ICU acquisition. It was regarded as a small fraction of the total cases of acquired in ICUs studied.</td>
<td>Room contamination</td>
</tr>
<tr>
<td>22</td>
<td>Observational</td>
<td>2 ICUs with open floor plan</td>
<td>—</td>
<td>1:1 bed to sink ratio</td>
<td>4:1 bed to sink ratio</td>
<td>Hand hygiene compliance after patient contact</td>
<td>Hand hygiene compliance was significantly higher in the 1:1 ratio ICU compared to the 4:1 ratio ICU (p &lt;0.05).</td>
<td>This was a small study. The unit with 1:1 ratio was a medical ICU; unit with 4:1 ratio was a surgical ICU so this was not an equal comparison</td>
<td>Hand hygiene</td>
</tr>
<tr>
<td>SOURCE</td>
<td>STUDY TYPE</td>
<td>SETTING</td>
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<tr>
<td>23</td>
<td>Crossover</td>
<td>19 bed acute-care medical ward</td>
<td>MRSA, MSSA, VRE, C. difficile, and coliforms</td>
<td>Copper-alloy furnishes</td>
<td>Conventional materials</td>
<td>Environmental contamination; bacterial load on surfaces</td>
<td>Hand hygiene compliance</td>
<td>Hand hygiene compliance was 53% at old hospital and 23% at new hospital with additional sinks. Hand hygiene performance much less likely if higher ranking person in room did not clean hands.</td>
<td>Factors other than sink location were more important drivers of hand hygiene compliance. There were other difference between pre and post interventions might have confounded results (personnel change, different soap product, removal of hall sinks, increased patient days).</td>
</tr>
<tr>
<td>24</td>
<td>Pre-post intervention</td>
<td>Medical and surgical intensive-care, hematology/oncology, and solid organ transplant units</td>
<td>—</td>
<td>New hospital rooms with sink dedicated for healthcare workers inside every patient room</td>
<td>Old hospital with fewer sinks and mixed room designs</td>
<td>Hand hygiene compliance</td>
<td>Hand hygiene compliance was 53% at old hospital and 23% at new hospital with additional sinks. Hand hygiene performance much less likely if higher ranking person in room did not clean hands.</td>
<td>24 week sampling, crossover at 12 weeks.</td>
<td>Hand hygiene</td>
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<tr>
<td>25</td>
<td>Pre-post intervention</td>
<td>Burn unit</td>
<td>Gram-negative, gram-positive pathogens and yeast</td>
<td>Single-patient rooms</td>
<td>Open ward</td>
<td>Bloodstream infections and mortality</td>
<td>Significant decrease gram negative bloodstream infections and mortality due to gram negative infections after move to single patient rooms. There was a less dramatic but significant reduction in gram positive infections but not in fungemia.</td>
<td>Data were collected 10 years before and 10 years after move to a single bed unit. so sample size was large but long data collection period increased likelihood of confounders</td>
<td>Single-patient rooms</td>
</tr>
<tr>
<td>26</td>
<td>Pre-post intervention</td>
<td>A surgical intensive-care unit (SICU) in a French hospital</td>
<td>Acinetobacter baumanii</td>
<td>Remodeling of ICU into all private rooms with sinks</td>
<td>Old floor plan with 7 private rooms and two 4-bed open rooms</td>
<td>Acquisition of Acinetobacter</td>
<td>Respiratory tract colonization with Acinetobacter occurred in 21.5% of patients in the pre-renovation period compared to 1.1% in the post-renovation period. 87% of colonized patients acquired an epidemic strain.</td>
<td>Other factors may have contributed to decrease in colonization. The ICU was not used for 4 months during the renovations. No environmental cultures were performed and hand hygiene compliance was not measured. Use of curtains in the ICU not described.</td>
<td>Single-patient rooms</td>
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<td><strong>APPENDIX: CONTACT EVIDENCE TABLE</strong> (continued)</td>
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<td>28</td>
<td>Orenstein, R., Aronhalt, K., McManus, J. E., Jr., &amp; Fedraw, L. (2011). A targeted strategy to wipe out <em>Clostridium difficile</em>. Infection Control and Hospital Epidemiology, 32(11), 1137–1139.</td>
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<tr>
<th><strong>STUDY TYPE</strong></th>
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<tbody>
<tr>
<td>Cohort</td>
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<tr>
<td>Pre-post intervention</td>
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<tr>
<td>Observational</td>
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<tr>
<td>Other</td>
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<table>
<thead>
<tr>
<th><strong>SETTING</strong></th>
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<tbody>
<tr>
<td>30-bed ICU</td>
</tr>
<tr>
<td>2 medical units in a 1,249-bed hospital</td>
</tr>
<tr>
<td>Patient rooms</td>
</tr>
<tr>
<td>Patient room</td>
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<table>
<thead>
<tr>
<th><strong>PATHOGEN(S)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Multidrug-resistant (MDR) Gram-negative bacilli</em></td>
</tr>
<tr>
<td><em>Clostridium difficile</em></td>
</tr>
<tr>
<td>Automated system to monitor hand hygiene compliance</td>
</tr>
<tr>
<td>MRSA, <em>C. difficile</em></td>
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<table>
<thead>
<tr>
<th><strong>RISK FACTOR/INTERVENTION</strong></th>
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<tbody>
<tr>
<td>Room assignment</td>
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<tr>
<td>Bleach-based wipes</td>
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<table>
<thead>
<tr>
<th><strong>COMPARISON</strong></th>
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<tbody>
<tr>
<td>Patients who developed infection vs. patients who did not</td>
</tr>
<tr>
<td>Before-after comparison</td>
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<tr>
<th><strong>ENDPOINT</strong></th>
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<tbody>
<tr>
<td>Infection</td>
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<tr>
<td>The intervention reduced hospital-acquired <em>Clostridium difficile</em> infection.</td>
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<tr>
<th><strong>RESULTS</strong></th>
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<tbody>
<tr>
<td>It was reported that admission to an ICU room previously occupied by a patient with MDR <em>P. aeruginosa</em> or <em>A. baumannii</em> is an independent risk factor for acquisition of these bacteria by subsequent room occupants.</td>
</tr>
<tr>
<td>The study reported that daily room cleaning with 0.55% germicidal bleach wipes led to a sustained reduction in <em>Clostridium difficile</em> infection.</td>
</tr>
<tr>
<td>Feasibility study using new technology to capture hand hygiene observations on room entry and room exit.</td>
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<tr>
<td>Log kill of target organisms after exposure to UVGI</td>
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<tr>
<th><strong>COMMENTS</strong></th>
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<tbody>
<tr>
<td>Infection control policy included cleaning of ICU rooms at patient discharge using quaternary ammonium disinfectant.</td>
</tr>
<tr>
<td>The study provided an estimate cost for hospital acquired <em>Clostridium difficile</em> infection ($5,000 to $8,000 per infection)</td>
</tr>
<tr>
<td>Authors introduced a novel low-cost method for monitoring hand hygiene compliance.</td>
</tr>
<tr>
<td>Excellent log kill of MRSA and <em>C. difficile</em> exposed to direct and indirect light with short exposure times (5 minutes for MRSA and &lt;10 minutes for <em>C. difficile</em></td>
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<tr>
<th><strong>FOCUS</strong></th>
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<tbody>
<tr>
<td>Room colonization</td>
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<tr>
<td>Hand hygiene</td>
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<tr>
<td>UVGI</td>
</tr>
<tr>
<td>SOURCE</td>
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<tr>
<td>-----------------------------------------------------------------------</td>
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<tr>
<td>Rahal, A. G., Bhanot, N., Bajwa, R., Manyam, H., &amp; Post, J. C. (2010).</td>
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<tr>
<td>A pilot study exploring surrogate markers for hand hygiene compliance.</td>
</tr>
<tr>
<td>Infection Control and Hospital Epidemiology, 31(6), 634–639.</td>
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<td>dispensing units</td>
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<tr>
<td>Salgado, C., Sepkowitz, K. A., John, J., Cantey, J., Attaway H.,</td>
</tr>
<tr>
<td>surfaces reduce the rate of hospital-acquired infections in the intensive care unit.</td>
</tr>
<tr>
<td>Infection Control and Hospital Epidemiology, 34(5), 479–486.</td>
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<td>Schweizer, M., Graham, M., Olt, M., Heilman, K., Boyken, L., &amp;</td>
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<tr>
<td>Diekema, D. (2012). Novel hospital curtains with antimicrobial</td>
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<td>properties: A randomized, controlled trial. Infection Control and</td>
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<td>Hospital Epidemiology, 33(11), 1081–1085.</td>
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<tr>
<td>Rutala, W. A., Gergen, M. F., &amp; Weber, D. J. (2010). Room</td>
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<td>decontamination with UV radiation. Infection Control and Hospital</td>
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<td>Epidemiology, 31(10), 1025–1029.</td>
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### APPENDIX: CONTACT EVIDENCE TABLE (continued)

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>STUDY TYPE</th>
<th>SETTING</th>
<th>PATHOGEN(S)</th>
<th>RISK FACTOR/INTERVENTION</th>
<th>COMPARISON</th>
<th>ENDPOINT</th>
<th>RESULTS</th>
<th>COMMENTS</th>
<th>FOCUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>Cohort</td>
<td>ICU at a tertiary care hospital</td>
<td>Clostridium difficile</td>
<td>Prior patient in room had <em>C. difficile</em></td>
<td>Prior occupant without <em>C. difficile</em></td>
<td>Infection (<em>C. difficile</em>)</td>
<td>11% and 4.6% of patients developed <em>C. difficile</em> if prior occupant did or did not have <em>C. difficile</em>, respectively (<em>p</em> = 0.01)</td>
<td>Study supports the importance of room contamination in development of <em>C. difficile</em>. The antibiotic exposure before hospitalization was not evaluated.</td>
<td>Rooms colonization</td>
</tr>
<tr>
<td>36</td>
<td>Other</td>
<td>Patient rooms in a community-teaching hospital</td>
<td>Clostridium difficile</td>
<td>Private, carpeted patient rooms</td>
<td>Non-carpeted rooms</td>
<td>Environmental contamination - bacterial load on floors; infections (<em>C. difficile</em>)</td>
<td>Carpeted floors more likely to be contaminated with same strain of <em>C. difficile</em> as occupant. Only one case of <em>C. difficile</em> developed in rooms known to be contaminated.</td>
<td>Small study in a non-epidemic setting with few infections as endpoint. Hard to make conclusion about contribution of carpets to risk of <em>C. difficile</em></td>
<td>Carpets</td>
</tr>
<tr>
<td>37</td>
<td>Other</td>
<td>General ward, PICU, NICU in a children’s hospital</td>
<td>—</td>
<td>Novel evaluation tool for hand hygiene resources in the hospital environment</td>
<td>—</td>
<td>Hand hygiene resources</td>
<td>Deficiencies in visibility, accessibility, redundancy of hand hygiene resources were identified that hinder hand hygiene compliance.</td>
<td>Implementation of ergonomic principles were suggested as a means to achieve better hand hygiene compliance.</td>
<td>Hand hygiene</td>
</tr>
<tr>
<td>38</td>
<td>Observational</td>
<td>ICU rooms</td>
<td>—</td>
<td>Alcohol hand-rub dispenser placement and number</td>
<td>(1) Dispensers at standard locations; (2) standard locations with increased number of dispensers; and (3) dispensers at conspicuous and immediate proximity to patient</td>
<td>Hand hygiene compliance measured by product use</td>
<td>Conspicuous placement of dispensers increased daily product use but use of multiple dispensers had minimal impact compared to control.</td>
<td>The authors acknowledged a possible confounding factor presented by the move to a new ICU facility during the study.</td>
<td>Hand hygiene</td>
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### APPENDIX: CONTACT EVIDENCE TABLE (continued)

<table>
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<tr>
<th>SOURCE</th>
<th>STUDY TYPE</th>
<th>SETTING</th>
<th>PATHOGEN(S)</th>
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<th>ENDPOINT</th>
<th>RESULTS</th>
<th>COMMENTS</th>
<th>FOCUS</th>
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<tbody>
<tr>
<td>Trillis III, F., Eckstein, E. C., Budavich, R., Pultz, M. J., &amp; Doneskey, C. J. (2008). Contamination of hospital curtains with healthcare-associated pathogens. <em>Infection Control and Hospital Epidemiology, 29</em>(11), 1074–1076.</td>
<td>Microbiologic survey</td>
<td>7 wards in a 202-bed acute-care hospital</td>
<td><em>Clostridium difficile</em>, MRSA, VRE</td>
<td>Privacy curtains</td>
<td>—</td>
<td>Environmental contamination (curtains); hand imprint cultures</td>
<td>The curtains were contaminated with MRSA (42%), VRE (22%), and C. difficile (4%). The study reported a trend toward a higher rate of detection of pathogens on curtains in isolation rooms. MRSA and VRE transferred to hands after curtain contact but colony count was low.</td>
<td>A small study with only 50 curtains cultured. Nonetheless, curtain contamination was common and pathogens were transferred from curtains to hands. Under if quantities of organisms transferred to hands is sufficient to lead to transmission to patients</td>
<td>Curtains</td>
</tr>
<tr>
<td>Venkatesh, A. K., Lankford, M. G., Rooney, D. M., Blachford, T., Watts, C. M., &amp; Noskin, G. A. (2008). Use of electronic alerts to enhance hand hygiene compliance and decrease transmission of vancomycin-resistant <em>Enterococcus</em> in a hematology unit. <em>American Journal of Infection Control, 36</em>(3), 199–205.</td>
<td>Pre-post intervention</td>
<td>A 30-bed hematology unit</td>
<td>Vancomycin-resistant <em>Enterococcus</em> (VRE)</td>
<td>Alcohol hand rub dispenser provided audible and visual reminders (beeps and flashing lights) to perform hand hygiene</td>
<td>No alerts</td>
<td>Hand hygiene compliance; infection (VRE rate on unit)</td>
<td>Hand hygiene compliance improved from 36.3% to 70.1% in the post-intervention period. There were 1.0 VRE infections/month in intervention period compared to 3.6 infections per month in previous 12 months (<em>p</em> = 0.058)</td>
<td>Alerts improved hand hygiene compliance. There was a trend towards reduced VRE infections</td>
<td>Hand hygiene</td>
</tr>
<tr>
<td>Weaver, L., Michels, H. T., &amp; Keevil, C. W. (2008). Survival of <em>Clostridium difficile</em> on copper and steel: Futuristic options for hospital hygiene. <em>Journal of Hospital Infection, 68</em>(2), 145–151.</td>
<td>Other</td>
<td>Laboratory</td>
<td><em>Clostridium difficile</em></td>
<td>5 copper alloys</td>
<td>Stainless steel</td>
<td>Culture and viability dye assays to measure C. difficile on surfaces</td>
<td>Copper alloys with a copper content &gt;70% provided a significant reduction in survival of <em>C. difficile</em>. Pure copper produced more rapid killing. Survival prolonged on stainless steel surfaces (&gt;72 hours)</td>
<td>There was decrease <em>C. difficile</em> viability on all surfaces within several hours, attributed to exposure to aerobic environment. The use of copper alloys was suggested to reduce <em>C. difficile</em>.</td>
<td>Copper</td>
</tr>
<tr>
<td>Whitby, M., &amp; McLaws, M. L. (2004). Handwashing in healthcare workers: Accessibility of sink location does not improve compliance. <em>Journal of Hospital Infection, 58</em>(4), 247–253.</td>
<td>Pre-post intervention</td>
<td>ICU, infectious diseases, internal medicine, and urology wards in a 800-bed hospital</td>
<td>—</td>
<td>Move to new hospital with more sinks</td>
<td>Old hospital with large wards with 1 sink</td>
<td>Hand hygiene compliance</td>
<td>No significant change in hand hygiene compliance after moving from hospital with large open wards with 1 sink to a new hospital with mostly 4 bed wards with one sink.</td>
<td>Compliance rates went up in 3 of 4 units shortly after the move but were not sustained. An MRSA outbreak confounded the study in 1 unit.</td>
<td>Hand hygiene</td>
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References


The Role of the Hospital Environment in Preventing Healthcare-Associated Infections Caused by Pathogens Transmitted through the Air

Jesse T. Jacob, MD; Altug Kasali, MArch, PhD; James P. Steinberg, MD; Craig Zimring, PhD; and Megan E. Denham, MAEd

OBJECTIVE: To assess and synthesize available evidence in the infection control and healthcare design literature on strategies using the built environment to reduce the transmission of pathogens in the air that cause healthcare-associated infections (HAIs).

BACKGROUND: Air can serve as a route for transmission of important HAI pathogens, including Mycobacterium tuberculosis and influenza, and may play a role for others typically transmitted by contact, including Staphylococcus aureus and Clostridium difficile.

TOPICAL HEADINGS: Four primary interventions can be used interrupt the transmission of pathogens in air: ventilation, filtration, decontamination, and isolation. Many studies demonstrate that unidirectional airflows, when combined with very clean air and frequent air changes, reduce bacterial counts in the air, though mostly focused on the operating room. A high-efficiency particulate air filter removes almost all particles from the air and is used in protective environments such as the operating room, but little evidence supports its broader application. Ultraviolet germicidal radiation can augment the performance of heating, ventilation, and air conditioning systems. Isolation with negative pressure ventilation prevents spread of airborne pathogens such as tuberculosis.

CONCLUSIONS: Current evidence is limited by the complexity of the interactions between pathogens and potential hosts, and in the methods used to assess impact of these strategies. Because the factors that affect transmission of the pathogens are complex and transcend disciplines, a collaborative approach among the key stakeholders in healthcare facility design should be actively pursued from planning to completion of construction and in rigorous research to best determine how design can reduce HAIs.

KEYWORDS: Built environment, evidence-based design, infection control, healthcare-association infection, hospital

AUTHOR AFFILIATIONS: Jesse T. Jacob is an Assistant Professor in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia. Altug Kasali is a Research Assistant at SimTigate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. James P. Steinberg is a Professor of Medicine in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia. Craig Zimring is a Professor at SimTigate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Megan E. Denham is a Research Associate II at SimTigate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia.

CORRESPONDING AUTHOR: Jesse T. Jacob, MD, Orr Building, 550 Peachtree St. NE, Ste. 1020, Atlanta, GA 30308; jtjacob@emory.edu; (404) 686-1564, (404) 686-5770 (fax).

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Pathogens transmitted through air causing healthcare-associated infections (HAIs) include the influenza virus, the bacterium *Mycobacterium tuberculosis*, and the soil mold *Aspergillus*, the etiologic agents of influenza, tuberculosis, and aspergillosis, respectively. Characteristics of these pathogens are described elsewhere (Zimring, Jacob, et al., 2013). Because these pathogens enter the body via the respiratory tract, disease often manifests there first, but dissemination can result in a range of diseases from a relatively mild acute viral syndrome or potentially fatal pneumonia with influenza, to a chronic pneumonia or a life-threatening acute illness with invasive aspergillosis, to a chronic severe pulmonary or extrapulmonary disease with tuberculosis. These HAIs can affect both patients and healthcare providers and can increase patient length of stay, mortality and costs but may be mitigated through interventions, including those directed toward the environment.

Infection from organisms transmitted via air is a result of a complex interaction of the pathogen, the individual, and the inanimate environment. Some pathogens such as *Mycobacterium tuberculosis*, require only a few organisms to cause disease, and others, such as *Aspergillus* spp., can produce hardy spores that are resistant to drying out (desiccation). Host factors predispose certain individuals to particular infections. For instance, some pathogens such as *Aspergillus* spp. rarely cause invasive disease in healthy individuals, but pose a substantially higher risk for transplant recipients. Environmental factors such as airflow patterns and humidity can affect the distribution of the pathogen in a given area. The relative contribution of each of these interactions between pathogen, individual and environment has proven difficult to quantify. Studies that measure particle dynamics or air sampling methods may not accurately predict how transmission occurs in biologic systems. For pathogens that can opportunistically be airborne but whose main route of transmission is by contact or droplet spread (influenza, *Staphylococcus aureus*), the relative contribution of airborne dissemination is difficult to measure.

Airborne transmission of respiratory pathogens, such as *Mycobacterium tuberculosis*, occurs when smaller particles (≤5μm) containing organisms are generated by coughing or sneezing, remain suspended in the air and are inhaled by a susceptible host. Other pathogens such as *Aspergillus* spp. can become airborne following disruption of the local environment, such as during construction projects. These airborne organisms can spread widely by air currents leading to the importance of ventilation systems in prevention of transmission. Airflow, which determines the magnitude and direction of distribution, can be modified by several factors, including ventilation, filtration, temperature gradients, room configuration and the movement of equipment or people. Environmental conditions, such as humidity, can affect droplet size and the survival of various microbes (Memarzadeh, 2012). Pathogens typically spread by direct contact that may have an airborne component, such as *Staphylococcus aureus*, or may contaminate surfaces, including open surgical wounds in the operating room (OR), after being suspended in the air.

There is a distinction between small particle airborne transmission and large droplet transmission (>5μm), which can be considered a form of contact trans-
mission. These large droplets are expelled by coughing or sneezing by persons with respiratory tract infections such as influenza, and can travel ballistically up to 6 feet and cause infection after being directly deposited on mucous membranes, or through indirect contact after being deposited on environmental surfaces. Droplets can also be generated from water sources such as sinks, showers, or humidifiers (Denham, Kasali, Steinberg, Cowan, Zimring, & Jacob, 2013). Transmission of these larger droplets can be reduced through humidity control in the ventilation systems discussed in this chapter and can be mitigated by spatial separation. Movement of large droplet nuclei is not influenced by ventilation systems in most settings.

The available infection control, healthcare epidemiology, and healthcare design literature was reviewed to determine how transmission of pathogens through air can be mitigated (Zimring, Denham, et al., 2013). Based on this review and a conceptual framework (Figure 1), four primary interventions can be used to interrupt the airborne transmission of pathogens:

1. Ventilation systems (controlling the flow and quality of air to minimize exposure to airborne pathogens);
2. Filtration (using filters to trap particles, including pathogens, and remove them from circulation);
3. Decontamination (eliminating/reducing pathogens from the air); and
4. Airborne isolation (reducing the risk of cross-contamination through isolation).

**Ventilation Systems**

Heating, ventilation, and air conditioning (HVAC) systems are the primary mechanism for controlling air in the hospital environment. The goals of ventilation systems are to replace potentially contaminated air with clean air, to minimize the mixing of dirty and clean air, and to regulate ambient temperature and humidity. There is little consensus on which HVAC system minimizes the risk of airborne spread of infectious agents. Although minimum standards for the amount of outside air are specified (American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 2012), some facilities chose to supply outside air well above these minimum standards. Terms such as mechanical, natural and hybrid ventilation are common, although not well or consistently defined (Berrouk, Lai, Cheung, & Wong, 2010; Memarzadeh, 2011; Nielsen, 2009).

Multiple technologies are currently available to control the direction of airflow inside the hospital, although no consensus exists whether turbulent, displacement, or unidirectional airflow is most effective. Recent approaches to reducing surgical site infections have included specific attention to technologies for the OR that provide very clean air and airflows that discourage any pathogens shed by healthcare workers from landing in the surgical site. These pathogens can reside on “squames,” which are cells shed from exposed skin of personnel in the OR. Such approaches augment other interventions, such as pre-operative antibiotic prophylaxis, appropriate surgical attire and surgical site preparation to
INTERRUPTING THE TRANSMISSION OF PATHOGENS IN AIR RESEARCH

Figure 1. Air chain of transmission interventions model.

Human Reservoirs

Environmental sources and reservoirs of pathogens

Transmission Event
- direct or indirect contact including transient carriage (e.g., hands of healthcare workers)
- airborne/droplet

Opportunities for interventions through the built environment

Ventilation
Filtration
Decontamination
Isolation

RESERVOIR OR SOURCE IN THE HOSPITAL

EXTTERNAL SOURCE

COLONIZED OR INFECTED HOST

Patients
HCWs
Visitors

HAI

Transmission event

Reservoir: Place (human or environmental) where organisms reside and multiply.

Source: Place from which an organism is transmitted to the host. Source may be the same as the reservoir or become contaminated from the reservoir (e.g., a surface or instrument).
Recent approaches to reducing surgical site infections have included specific attention to technologies for the OR that provide very clean air and airflows that discourage any pathogens shed by healthcare workers from landing in the surgical site.

reduce infection. The built environment can influence traffic patterns of providers and healthcare workers, which can affect the amount of pathogens in the air. No clear link has been established between traffic in the OR even using the surrogate marker of number of people for the duration of surgery, though minimizing traffic appears to be good practice (Pryor & Messmer, 1998).

Most traditional ventilation systems in patient care areas utilize turbulent air to direct airflow rapidly away from patients. With turbulent airflow systems, intake ducts are placed close to the floor and between patients in multi-bed wards to extract air efficiently. An alternative to turbulent airflow is upward displacement, in which air is supplied through multiple diffusers distributed over the floor, and removed through intake ducts placed on the ceilings. Both ventilation systems have strengths and weaknesses. Simulated surgical procedures have demonstrated that a turbulent ventilation system in operating rooms achieving 16 air changes per hour (ACH) was most effective at removing larger particles (>10μm) from the air, while an upward displacement system achieved 17 ACH, and was more effective at removing smaller particles (<10μm) from the air (Friberg, Friberg, Burman, Lundholm, & Ostensson, 1996). One reported disadvantage of displacement systems is the need for a high ventilation index, with the ventilation system completing rapid cycles of introducing clean air and removing existing, potentially contaminated air. This can also make maintaining comfortable room temperature difficult (Nielsen, 2009).

Laminar airflow (LAF, also called unidirectional airflow), used most commonly in the OR, is a method of air ventilation in which ultra-clean air that has passed through a high-efficiency particulate air (HEPA) filter is distributed either vertically or horizontally in a smooth stream directed over the patient. The layers of ultra-clean air prevent mixing with particles, which could ultimately contaminate the surgical site. The airflow is then directed away from the surgical site and into the intake ducts. An alternative to vertical air distribution systems, or downflow, is a horizontal distribution system, also known as cross-flow. In this scenario, air entering from one wall is directed across the patient bed and removed by an intake duct on the opposite wall. In one study, air samples taken near the surgical site during 36 orthopedic operations showed both down-flow and cross-flow reduced bacteria and particle count (Whyte, Shaw, & Barnes, 1973). Cross-flow offers some advantages: it is less expensive to install; does not require modification of existing lighting systems; and is less obtrusive for surgeons who do not need to lean into the down-flow of clean air to optimize visualization of the surgical field (Van Der Waaij, Heidt, & Hendriks, 1974).

Many studies, both in the laboratory and in clinical settings, demonstrate that LAF, when combined with very clean air and frequent air changes, reduces the bacterial burden measured from direct air sampling or by indirect sampling using strategically placed open culture plates. However, its impact on infection rates remains unresolved (Ahl, Dalen, Jorbeck, & Hoborn, 1995; Cornet et al., 1999; Evans, 2011; Friberg & Friberg, 2005; Howorth, 1986; Nolard, 1994;
INTERRUPTING THE TRANSMISSION OF PATHOGENS IN AIR RESEARCH

Petrova, Klyasova, & Funygina, 2003; Ritter, Eitzen, French, & Hart, 1976; Ritter, French, & Hart, 1973; Sherertz et al., 1987; Whyte, Shaw, & Freeman, 1974). In 2008, 55 hospitals participating in the German nosocomial infection surveillance system (KISS) responded to surveys regarding the types of ventilation systems currently utilized in the ORs. The surgical site infection rate in the KISS hospitals using LAF with HEPA were compared to the infection rate in hospitals using turbulent air systems (Brandt et al., 2008). Overall in this study that included nearly 100,000 operations, the infection rate was not lower in the hospitals using LAF. Moreover, in one of the six procedures assessed, there was a statistically significant higher infection rate in the LAF group. This study was criticized for not considering factors such as surgical technique, LAF system position, size, or ceiling height, and because the ventilation system type was self-reported (Assadian et al., 2009), although in a subsequent KISS hospital survey, LAF efficacy was not impacted by ceiling size (Breier, Brandt, Sohr, Geffers, & Gastmeier, 2011). In another study of 80 orthopedic surgical procedures comparing no LAF, small LAF (380 cm × 120cm), and large LAF (518 cm × 383 cm), results showed that the large LAF unit was associated with significantly lower bacterial colony counts in a dose-dependent fashion compared to small LAF or no LAF (Diab-Elschahawi et al., 2011). Larger LAFs may provide superior ventilation, but it remains unclear if this benefit exceeds its increased costs and inconveniences.

Studies using computational fluid dynamics models have helped inform the guidelines of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Facility Guidelines Institute (FGI). Modeling and experimental studies have explored the impact of air changes, air speed, location of supplies and louvers, and ceiling height on the clearance of particles from the room and whether particles would be likely to land on a wound. These studies found that the location of air supplies and return, air speed, and ceiling heights all affected the exhaust and landing of particles (Balocco, 2011; Beggs, Kerr, Noakes, Hathway, & Sleigh, 2008; Van Der Waaij et al., 1974). Both wall-mounted and ceiling-mounted returns and ceiling heights up to 12 feet all provided adequate performance at the recommended air changes of 20–25 ACH. The drawbacks of LAF include installation and operating costs, discomfort to patients or staff, and noise, although the noise levels have decreased with improvements in technology.

Activities in patient rooms (e.g., bed-making) and movement of healthcare providers and visitors can also significantly impact the quantities of pathogens in the air. An aerobiological survey demonstrated a correlation between airborne particle counts and ward activity (Roberts et al., 2006). The results showed airborne methicillin-resistant Staphylococcus aureus (MRSA) levels were significantly higher 15 minutes after bed-making than during the resting period (Shiomori et al., 2002). Controlling airflow in areas outside of the OR may therefore be an important area to explore further.

Despite several studies assessing the effect of different ventilation systems or activities on particle or pathogen density, there is a paucity of clinical outcomes data. The 2003 Centers for Disease Control and Prevention (CDC) environ-
mental cleaning guidelines, for example, recognize the substantial investment required for installation and maintenance of such systems, and conclude that the direct evidence linking unidirectional airflow to a reduction in infections is insufficient to make a recommendation (Sehulster & Chinn, 2003). Even with this lack of endorsement, many ventilation strategies, such as unidirectional airflow that moves air smoothly from a source to an exhaust, combined with high numbers of ACHs (typically 20–25), have become standard in many hospital ORs (Miner, Losina, Katz, Fossel, & Platt, 2005). Many of these strategies have subsequently been adopted by guidelines, including those issued by FGI in 2010.

Although there is limited evidence directly linking ventilation strategies such as unidirectional airflow to a reduction in the incidence of infection, LAF has consistently been shown to reduce the number of pathogens in the air. The absence of a clear relationship between LAF and reduction in infection rates may be due in part to other determinants of surgical site infection risk. In addition, surgical site infection rates for procedures for which LAF is used, such as joint replacement surgery, are low, requiring large, resource-intensive studies to demonstrate a significant potential difference in these rates. The literature provides a range of methods for measurement of particle counts, and the relevance of particle counts to the actual bacterial burden is unclear (Scaltriti et al., 2007). Meanwhile, large studies, such as those from KISS, have been unable to measure important confounding variables, such as surgical technique, position of air intakes and outlets, and the size and efficiency of the LAF system in place. More research into the appropriate metrics of success is needed to determine the effectiveness of different ventilation strategies both within and outside the OR.

**Filtration**

Filtration of ventilated air can reduce the number of airborne pathogens. Few hospitals utilize 100% fresh outside air due to high cost and energy requirements to maintain a desirable temperature indoors. Hospitals located in urban areas must also consider the quality of outside air due to environmental pollutants. The alternative to 100% outside air is a combination of outside and recirculated air. Before the air can be reintroduced to the hospital environment, it must be filtered. Air filters are rated based on the size of particles they are able to remove, and HEPA filters are mostly widely used in healthcare settings. The U.S. Department of Energy defines a HEPA filter as having a minimum efficiency of 99.97% at a test aerosol diameter of 0.3μm (U.S. Department of Energy, 2005). HEPA filters remove airborne pathogens in critical areas such as ORs, transplant wards, isolation rooms, and intensive care units. Although the use of HEPA is not mandatory, guidelines published by the CDC (Sehulster & Chinn, 2003), ASHRAE (2008), and the Joint Commission recommend its application to prevent the spread of airborne pathogens in these critical areas.

HEPA filtration alone may be insufficient, particularly during construction when *Aspergillus* spp. poses an increased risk of infection (Sherertz et al., 1987).
Interrupting the Transmission of Pathogens in Air

During construction projects, hospitals frequently employ multiple interventions to limit airborne spread of pathogens including the use of portable HEPA filters. Isolating the impact of individual interventions has proved to be difficult (Berthelot et al., 2006). One hospital in Paris evaluated the effectiveness of several air ventilation and filtration technologies in their hematology wards over a 2-year period of renovations. Multiple units were sampled before, during, and after renovations with a variety of ventilation systems, including HEPA, HEPA combined with LAF, and wards with no protective measures. The wards with no protective measures experienced a significant increase in invasive pulmonary aspergillosis after renovations, as did the wards with HEPA filtration alone. In contrast, the ward with HEPA filtration and LAF yielded no positive samples for Aspergillus spp. at any point before, during, or after renovations (Cornet et al., 1999). This suggests that the combination of LAF and HEPA is more effective than HEPA alone for high-risk populations.

There are a number of additional strategies used to augment the efficacy of HEPA filters and increase the efficiency of the HVAC system. Filters can be treated with antimicrobial agents, which have been shown to significantly reduce bacterial and fungal growth (Verdenelli, Cecchini, Orpianesi, Dadea, & Cresci, 2003). As is the case with many of the other studies covered in this report, a direct link between the intervention and actual infection rates or cases could not be established. Ultraviolet germicidal irradiation (UVGI) has also been shown to improve HEPA performance as discussed below in the section on decontamination.

Filtration is a strategy that utilizes several levels of filters, the highest of which traps 99.97% of particles in the air, limiting airborne transmission. The use of HEPA filters is widespread in hospitals, especially in areas that house immunocompromised patients. The ongoing research on HEPA filters is looking to increase the efficiency and efficacy, as HEPA alone may be suboptimal in preventing infections in high-risk populations.

**Decontamination**

A variety of decontamination strategies are utilized in the hospital environment, many of which have multiple applications. For the purpose of this review, the technologies are discussed within the context of their intended application, as it applies to the built environment.

UVGI damages DNA and is lethal to most airborne pathogens. UVGI has been recognized for its ability to control tuberculosis since 1957 (Riley, Wells, Mills, Nyka, & McLean, 1957). Innovations in standard measures such as administrative controls, use of negative pressure isolation and personal protective measures such as N-95 respirators have led to the effective prevention of tuberculosis in hospitals. Almost all transmission occurs with unrecognized cases when standard controls are not in use. Because prevention efforts are effective without UVGI, the National Institute for Occupational Safety and Health’s 2009 guidelines for preventing the transmission of tuberculosis in healthcare settings lists UVGI as an optional environmental control measure (National Institute for Occupational Safety and Health, 2009).
UVGI can be used in a central HVAC system to augment, but not replace HEPA filtration according to the 2003 CDC guidelines (Sehulster & Chinn, 2003). UVGI can be used in this setting if risk assessment indicates that supplemental engineering controls are needed. In one quasi-experimental study, a neonatal intensive care unit with a high ventilator-associated pneumonia (VAP) rate demonstrated a reduction in VAP and a reduction in tracheal colonization by common pathogens after installation of UVGI in the HVAC systems equipped with 95% filters (Ryan et al., 2011). This study has several limitations, including a baseline pneumonia rate much higher than most contemporary facilities, possible confounding by an increase in earlier extubation in the post-intervention period and a declared conflict of interest, but these findings merit confirmation in a larger trial. Modeling studies suggest that UVGI alone may not be sufficient to provide adequate decontamination in central HVAC systems due to multiple variables, such as airflow, temperature and humidity, which can impact its efficacy (Wang, Mortazavi, & Haghighat, 2009).

UVGI can also be installed near ceilings to irradiate upper room air in ORs; this method can also be an effective strategy to augment the performance of HVAC systems by increasing filter efficacy and efficiency through controlling the growth of biofilm on filters (Chuaybamroong et al., 2010; Memarzadeh, 2010). Some evidence supports upper-room UVGI as an effective means for deactivating bacteria (Miller & Macher, 2000).

UVGI has been used historically for the control of tuberculosis, but guidelines now relegate its role to a supplemental measure since standard controls are effective. For pathogens such as Aspergillus spp. and Staphylococci, UVGI can be effective in reducing airborne pathogens when combined with filtration, but there are limited data showing efficacy in reducing infection risk both in central HVAC systems and in the OR. Additional outcome research demonstrating a reduction in infection is needed.

**Airborne Isolation**

Isolating a patient in a room with controlled airflow is another strategy to prevent airborne spread of infection. The 2003 CDC guidelines address controlling airflow from unclean to clean through the use of pressurization and anterooms. Positive pressure rooms prevent outside air from getting into the room and are useful for keeping potentially contaminated air away from immunocompromised patients, including those with neutropenia following chemotherapy.

Patients with highly transmittable airborne pathogens should be placed in a negative pressure isolation room, which can prevent transmission of pathogens such as *Mycobacterium tuberculosis*, varicella (chickenpox), and rubeola (measles) (Sehulster & Chinn, 2003; Lim, Cho, & Kim, 2010; Montecalvo et al., 1999; Ostrowsky et al., 2001; Stelfox, Bates, & Redelmeier, 2003; World Health Organization, 1999). These negative pressure isolation rooms are typically single-patient rooms. Successfully interrupting transmission requires optimal performance of air-
borne infection isolation (AII) rooms, and the maintenance of negative pressure requires vigilance. In one study of 672 airborne isolation rooms, only 32% met standards of sufficient negative pressure (–2.5 Pa) when tested with tracer gas, with air not sufficiently drawn into the rooms (Saravia, Raynor, & Streifel, 2007). Rooms with solid ceilings had much higher overall pressures (–4.4 Pa) than those with dropped ceilings (–2.0 Pa). The CDC’s 2003 environmental guidelines specify requirements for AII rooms (6 ACH for existing facilities and 12 ACH for new construction or renovation), with air either exhausted to the outside or HEPA filtration if re-circulated.

While special ventilation systems are not needed to prevent transmission of respiratory pathogens such as influenza, which are transmitted by large droplets, spatial isolation in private rooms is recommended. These large droplets do not remain infectious in the air over distances more than 6 feet but can be transmitted over short distances. Humidity and temperature can increase influenza transmission in animal models, with optimal conditions for transmission occurring at the driest (20%–35%) and coldest (20°C) conditions (Lowen, Mubareka, Steel, & Palese, 2007), consistent with the increased incidence of influenza in the winter. In a modeled residential setting the predicted concentration of infectious droplets in air was 2.4 times higher at 10% relative than at 90% relative humidity (Yang & Marr, 2011), suggesting that hospitals should consider using the higher-end of the FGI recommended range of humidity (20%–60%) for most hospital areas, not just in inpatient rooms as is recommended, during times with influenza activity above endemic thresholds. This decision needs to account for individual comfort at different levels of humidity and to control static discharge as well as the potential costs of energy and maintaining humidifiers.

Isolation with negative pressure ventilation is an important strategy to prevent airborne spread of disease from patients known to have or be at high risk of having infections spread by the respiratory route. Positive pressure ventilation is used to protect vulnerable patients. While the needed number of rooms with special ventilation depends to some degree on the patient population served by the hospital, single patient rooms with negative pressure ventilation should be included in all existing and new construction.

**Conclusions**

Ventilation systems and other interventions to prevent airborne transmission of pathogens are important in several distinct settings. They are important in protecting vulnerable patients such as those undergoing a surgical procedure where organisms suspended in the air could land in the operative field, and they are important in protecting immunosuppressed patients from inhaling environmental organisms. Ventilation systems are also important in protecting healthcare workers as well as patients and visitors from being exposed to patients with infectious diseases that are transmitted through the airborne route; some evidence suggests that facilities may not be fully meeting the current FGI recommenda-
tions for negative pressure in AII rooms. While some common pathogens are usually transmitted through contact, and others such as *Staphylococcus aureus* and *Clostridium difficile* can become airborne and contaminate surfaces, it is unclear if interventions involving ventilation systems can decrease transmission of these pathogens. Environmental cleaning of contaminated surfaces and hand hygiene may be the most important strategies to prevent transmission of these pathogens. While controlled air movement in ORs is critical in minimizing contamination of the operative field, the optimal ventilation system for the surgical suite is not yet known.

HEPA filtration is commonly employed, especially with immunocompromised patients, but appears to be insufficient when used alone. Disinfection methods such as UVGI in rooms or in the ventilation system hold promise but are not recommended for routine use at this time because of lack of evidence that these systems reduce infections enough to justify the expense of installation and maintenance. Humidity control can impact survival of large droplets that travel ballistically.

Additional research, though difficult to conduct, is needed to assess the impact of airflow on infection rates and to evaluate the impact of HEPA filtration on patients and staff outside protected environments. Innovations that lower the cost of technologies such as HEPA filtration, in-duct UVGI, or laminar flow could lead to more widespread use of these technologies, but additional studies establishing their efficacy are needed as well. Preventing the transmission through the air of pathogens HAIs can be accomplished by following current evidence-based or best practice design guidelines, though there are clear knowledge gaps that need to be filled.

**Implications for Practice**

- Designers should engage key stakeholders, including hospital epidemiologists and infection preventionists, early in the design process to determine the optimal ventilation and filtration systems for a given facility using good practices and adhering to existing guidelines.
- Expanded use of ultraviolet germicidal irradiation to decontaminate heating, ventilation, and air conditioning systems may reduce pathogen burden, but their role in reducing healthcare-associated infections remains unclear. Therefore their individualized decisions should weigh both the potential benefits against increased energy and maintenance costs.
- Given increased awareness of an increase in potentially serious pathogens transmitted through air during construction, appropriate ventilation and filtration should be considered not only for its eventual use but during building, demolition, and renovations.
- The current paradigm for airborne isolation using negative pressure with or without an anteroom should be implemented in appropriate settings but strategies such as natural ventilation deserve further study.
Despite the broad adoption of ventilation and filtration systems, the optimal use to prevent healthcare-associated infections caused by pathogens transmitted through the air remains unclear, and may differ depending on hospital area (operating room vs. general ward). These knowledge gaps should ideally be addressed by researchers from the design, hospital epidemiology and infection prevention communities working in collaboration using rigorous methods and when possible, clinically relevant endpoints.
<table>
<thead>
<tr>
<th>NO.</th>
<th>SOURCE</th>
<th>STUDY TYPE</th>
<th>SETTING</th>
<th>PATHOGEN(S)</th>
<th>INTERVENTION</th>
<th>COMPARISON</th>
<th>ENDPOINT</th>
<th>RESULTS</th>
<th>COMMENTS</th>
<th>FOCUS</th>
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<tbody>
<tr>
<td>1</td>
<td>Ahl, T., Dalen, N., Jorbeck, H., &amp; Hoborn, J. (1995). Air contamination during hip and knee arthroplasties. Horizontal laminar flow randomized vs. conventional ventilation. Acta Orthopaedica Scandinav,ia, 66(1), 17–20.</td>
<td>Randomized control trial</td>
<td>90 patients undergoing total hip or knee arthroplasty in 2 adjacent ORs</td>
<td>Unspecific pathogens</td>
<td>Horizontal LAF or horizontal LAF plus occlusive clothing</td>
<td>Conventional ventilation with occlusive clothing</td>
<td>Environmental contamination (air)</td>
<td>In hip and knee surgeries, the 2 LAF arms were superior to the conventional ventilation arm. For knee surgeries, LAF + occlusive clothing had lower contamination (1 CFU/m$^3$) compared to LAF alone (2.9 CFU/m$^3$). All 3 groups had ultraclean air.</td>
<td>In room with conventional system, the air passed through a prefilter and a microfilter, whereas for the room with horizontal LAF, HEPA filter was utilized. Study did not adjust for confounders, though those measured appeared balanced.</td>
<td>Ventilation</td>
</tr>
<tr>
<td>2</td>
<td>Airey, P. J., Beggs, C. B., Kerr, K. G., &amp; Snelling, A. M. (2010). Effect of relative humidity on the survival of airborne opportunistic Gram-negative pathogens. Clinical Microbiology and Infection, 16(s2), S442.</td>
<td>Observational</td>
<td>Hospital ward room (not occupied)</td>
<td>Acinetobacter baumannii, Stenotrophomonas maltophilia, Burkholderia cepacia, and Pseudomonas aeruginosa</td>
<td>Relative humidity at 70% (high) and 30% (low)</td>
<td>Environmental contamination (air)</td>
<td>Low counts, but viable bacteria at 90 min. Recovery increased 1–2 logs at higher humidity compared to ambient. Few or no bacteria at low humidity (except B. cepacia).</td>
<td>Small study done in an unoccupied hospital room suggests more bacterial can survive in the environment with increasing relative humidity.</td>
<td>Humidity</td>
<td></td>
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<td>4</td>
<td>Araujo, R., Cabral, J. P., &amp; Rodrigues, A. G. (2008). Air filtration systems and restrictive access conditions improve indoor air quality in clinical units: Penicillium as a general indicator of hospital indoor fungal levels. American Journal of Infection Control, 36(2), 129–134.</td>
<td>Observational</td>
<td>18 rooms / wards, both patient and non-patient</td>
<td>Aspergillus spp., Penicillium, and other fungi</td>
<td>Positive air flow, multiple filter types (pre-filter G4, fine filter F8, H13 HEPA filters, synthetic bay filters F7-F9)</td>
<td>Environmental contamination (air and tap water)</td>
<td>Mean concentration for all fungi was ~100 CFU/m$^3$. HEPA and F9 filtered rooms had lowest measured and modeled contamination using cluster and principal component analyses. Lower contamination in wards with HEPA filters. Addition of anterooms and positive airflow were additive. Fungal strains rarely recovered from tap water.</td>
<td>Use of multiple room types with different configurations makes clear assessment of one design feature challenging.</td>
<td>Ventilation</td>
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<td>SOURCE</td>
<td>STUDY TYPE</td>
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<td>Balocco, C. (2011). Hospital ventilation simulation for the study of potential exposure to contaminants. Building Simulation, 4(1), 5–20.</td>
<td>Case-control</td>
<td>Immuno-suppressed patients in isolation rooms</td>
<td>Unspecific pathogens</td>
<td>A room equipped with an HVAC, with variable air volume primary air system, combined with a ceiling radiant panel, with door closed</td>
<td>Same room with door open</td>
<td>—</td>
<td>Based on computational models, the best position for the room studied, of the extract air diffuser that should be at low levels (close to the floor and between and behind the head of 2 patients).</td>
<td>—</td>
<td>HEPA and LAF</td>
<td></td>
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<tr>
<td>Beggs, C. B., Kerr, K. G., Noakes, C. J., Hathway, E. A., &amp; Sleigh, P. A. (2008). The ventilation of multiple-bed hospital wards: Review and analysis. American Journal of Infection Control, 36(4), 250–259.</td>
<td>Observational</td>
<td>Computational fluid dynamics model</td>
<td>Unspecific pathogens</td>
<td>Low-high, high-low, ceiling ventilation regimens on bioaerosol</td>
<td>—</td>
<td>Environmental contamination (air)</td>
<td>Bioaerosol concentration in the study room to be substantially lower (2467 CFU/m$^3$) when air was supplied and extracted through the ceiling compared to other regimens (&gt;10,000 CFU/m$^3$).</td>
<td>Purely computational study suggestive of improved air cleaning with ceiling ventilation. Contour plots show that bioaerosol is removed before mixing with ambient air.</td>
<td>—</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Benet, T., Nicolle, M. C., Thiebaut, A., Piens, M. A., Nicolini, F. E., Thomas, X., ..., Vanhems, P. (2007). Reduction of invasive aspergillosis incidence among immunocompromised patients after control of environmental exposure. Clinical Infectious Diseases, 45(6):682–686.</td>
<td>Observational</td>
<td>3 hematology units with 14 single rooms each</td>
<td>Aspergillus spp.</td>
<td>Relocation with all rooms using positive pressure and HEPA filters</td>
<td>2 units with a mix of conventional and HEPA filters with LAF</td>
<td>Infection (invasive nosocomial aspergillosis)</td>
<td>Rate of invasive aspergillosis dropped from 13.2% to 1.6% in intervention unit.</td>
<td>Quasi-experimental design did not adjust for confounders; total of 21 cases over 1-year study period</td>
<td>—</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Berg, M., Bergman, B. R., &amp; Hoborn, J. (1991). Ultraviolet radiation compared to an ultra-clean air enclosure: Comparison of air bacteria counts in operating rooms. Journal of Bone and Joint Surgery-British Volume, 73(5), 811–815.</td>
<td>Case-control</td>
<td>113 total hip arthroplasties in 2 ORs</td>
<td>Unspecific pathogens</td>
<td>UVGI, occlusive clothing or both</td>
<td>Charnley-Howorth enclosure</td>
<td>Environmental contamination (air)</td>
<td>Mean bacterial burden (in CFU/m$^3$) of air sampled next to wound dropped from control group (2.96) with use of UVC (0.47).</td>
<td>Comparison group impractical (requires wearing a cumbersome helmet), but shows potential impact of UVC. Did not adjust for confounders.</td>
<td>—</td>
<td>Ventilation</td>
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<tr>
<td>Source</td>
<td>Study Type</td>
<td>Setting</td>
<td>Pathogen(s)</td>
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<td>9</td>
<td>Observational</td>
<td>2 hematology wards (one 4-bed unit with positive pressure and HEPA filters in each room, and one 19-bed unit over 6 years)</td>
<td>Aspergillus spp.</td>
<td>Multiple infection control-related measures during construction projects</td>
<td>—</td>
<td>Environmental contamination (surface); infection (invasive aspergillosis)</td>
<td>While hospital construction projects increased, rates of invasive pulmonary aspergillosis/1000 patients decreased from 1.19 to 0.21. Most environmental samples were surface (&gt;90%) and the percent positive for Aspergillus fumigatus did not appear to change over time (range: 3.7–15.2).</td>
<td>No comment on other interventions during this time, including potential increased use of antifungal prophylaxis.</td>
<td>UV</td>
<td></td>
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<tr>
<td>10</td>
<td>Cohort</td>
<td>99,230 abdominal and orthopedic surgeries in 55 hospitals</td>
<td>Unspecific pathogens</td>
<td>ORs with vertical LAF or turbulent ventilation both with HEPA filters</td>
<td>Naturally ventilated ORs</td>
<td>Infection (surgical site infection)</td>
<td>In multivariate analysis, compared to conventional ventilation, LAF associated with increased odds of surgical site infection in 5 of the 6 procedures studies, although only statistically significant in one.</td>
<td>Unexpected finding (lack of benefit of LAF) inconsistent with much of literature. Accounted for many patient and hospital-level confounders. Large study using national German surveillance system but several factors not captured (smoking, use of cautery).</td>
<td>UV</td>
<td></td>
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<tr>
<td>11</td>
<td>Cohort</td>
<td>61,766 patients undergoing elective or urgent hip or knee replacement</td>
<td>Unspecific pathogens</td>
<td>LAF in OR, and LAF size (&lt;3.2 m x 3.2 m vs. &gt;3.2 m x 3.2 m)</td>
<td>No LAF in OR</td>
<td>Infection (surgical site infection)</td>
<td>There was no association between presence or size of LAF and infection.</td>
<td>Large study of severe SSI using national German surveillance system was consistent with prior registry studies.</td>
<td>Ventilation</td>
<td></td>
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<tr>
<td>12</td>
<td>Observational</td>
<td>3 different hospital wards with similar air conditioning (2 adult hematology wards and an infectious disease ward)</td>
<td>Nosocomial invasive filamentous fungi infections</td>
<td>Ward with preventive measures including HEPA filtration for filamentous fungi</td>
<td>Ward with conventional measures of filamentous fungi</td>
<td>Environmental contamination</td>
<td>The hematology wards with filamentous fungi preventive measures were significantly less contaminated compared conventional wards.</td>
<td>Outdoor factors (mean outdoor temperature, wind speed, rainfall, outdoor airborne spores) associated with increased burden of filamentous fungi.</td>
<td>Ventilation</td>
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### APPENDIX: AIR EVIDENCE TABLE (continued)

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>STUDY TYPE</th>
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<tbody>
<tr>
<td>Brown, I. W., Moor, G. F., Hummell, B. W., Marshall, W. G., &amp; Collins, J. P. (1996). Toward further reducing wound infections in cardiac operations. <em>Annals of Thoracic Surgery, 62</em>(6), 1783–1789.</td>
<td>Observational</td>
<td>1,717 cardiac surgery patients over 4.5 years in one 900-bed community hospital</td>
<td>Unspecific pathogens</td>
<td>Ceiling-mounted UVGI in OR</td>
<td>Historical data from other published studies</td>
<td>Infection (mediastinitis)</td>
<td>Low rate (0.23%) of mediastinitis.</td>
<td>No direct comparison group makes it difficult to discern the impact of UV compared to other preventative measures on infection rate.</td>
<td>UV</td>
</tr>
<tr>
<td>Carlsson, A. S., Nilsson, B., Walder, M. H., &amp; Osterberg, K. (1986). Ultraviolet radiation and air contamination during total hip replacement. <em>The Journal of Hospital Infection, 7</em>(2), 176–184.</td>
<td>Randomized control trial</td>
<td>30 patients undergoing total hip replacement</td>
<td>Unspecific pathogens</td>
<td>UVGI in OR using zonal ventilation</td>
<td>No UVGI in OR using zonal ventilation</td>
<td>Environmental contamination (air)</td>
<td>8 of 15 patients had ultraclean air (&lt;10 CFU/m³) near wound in UV arm, with none in the standard arm; 14 of 15 in UV arm had ultra-clean air outside zonal ventilation.</td>
<td>Non-blinded study with small numbers in zonally ventilated ORs. In conventionally ventilated ORs, UV is unlikely to be sufficient in achieving ultra-clean air.</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Chuaybamroong, P., Chotigawin, R., Supothina, S., Sribenjalux, P., Larpkiattaworn, S., &amp; Wu, C. Y. (2010). Efficacy of photocatalytic HEPA filter on microorganism removal. <em>Indoor Air, 20</em>(3), 246–254.</td>
<td>Observational</td>
<td>Laboratory</td>
<td>Aspergillus niger, Penicillium obtusum, Staphylococcus epidermidis, Bacillus subtilis</td>
<td>Photocatalytic oxidation on HEPA filters</td>
<td>Standard HEPA filters</td>
<td>Environmental contamination (air)</td>
<td>50% disinfection with ~3 h of irradiation, with up to 77% reduction for Aspergillus, but effect decreased by half with increase in humidity</td>
<td>Minimal drop in pressure for HVAC, but cost and installation may outweigh benefits based on this preliminary study.</td>
<td>Other</td>
</tr>
<tr>
<td>Cornet, M., Levy, V., Fleury, L., Lortholary, J., Barquinet, S., Courroux, M. H., …, Bouvet, A. (1999). Efficacy of prevention by high-efficiency particulate air filtration or laminar air flow against Aspergillus airborne contamination during hospital renovation. <em>Infection Control and Hospital Epidemiology, 20</em>(7), 508–513.</td>
<td>Observational</td>
<td>Air and surface sampling in 4 wards with different ventilation systems every 2 weeks for 2 years during hospital renovation</td>
<td>Aspergillus spp.</td>
<td>LAF plus HEPA filters</td>
<td>HEPA filters</td>
<td>Environmental contamination (air and surface)</td>
<td>More air samples were positive before and after (51.5%), compared to during (31.7%), renovation in a unit without a protected air supply. HEPA filtration resulted in an increase in samples positive Aspergillus in an adjacent unit during renovation. No Aspergillus was found in the unit with LAF plus HEPA filtration.</td>
<td>HEPA alone may be effective in normal conditions, but not with construction in this study. The LAF plus HEPA unit had the fewest samples per period (28–60).</td>
<td>Ventilation</td>
</tr>
</tbody>
</table>
### APPENDIX: AIR EVIDENCE TABLE (continued)

<table>
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<tr>
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<th>Comments</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Dansby, W., Purdue, G., Hunt, J., Arnoldo, B., Phillips, D., Moody, ...</td>
<td>Case-control</td>
<td>2 control rooms and 2 study rooms in a burn unit with active surveillance for MRSA</td>
<td>MRSA</td>
<td>Dressing changes (typically 30–60 min) in MRSA positive patient rooms</td>
<td>Dressing changes in non-MRSA positive patients</td>
<td>Environmental contamination (air)</td>
<td>No MRSA detected in control rooms, but positive in 11 of 35 samples in rooms of patients with MRSA. These findings contributed to renovation of unit with improved air exchanges, and increased size allowing door to be closed during dressing, with nearly 10-fold less MRSA on surveillance after renovation.</td>
<td>Ventilation</td>
<td></td>
</tr>
<tr>
<td>Diab-Elschahawi, M., Berger, J., Blacky, A., Kimberger, O., Oguz, R., Kuelpmann, R., ... Assadian, O. (2011). Impact of different-sized laminar air flow versus no laminar air flow on bacterial counts in the operating room during orthopedic surgery. American Journal of Infection Control, 39(7), e25–29.</td>
<td>Case-control</td>
<td>80 orthopedic surgeries</td>
<td>Unspecific pathogens</td>
<td>OR with LAF with either small (3.8 m x 1.2 m) or large (5.2 m x 3.8 m) ceilings</td>
<td>OR without LAF</td>
<td>Environmental contamination (air)</td>
<td>Mean CFU/m³ at site closest to patient decreased from 1,982 (no LAF) to 1,373 (small LAF) to 880 (large LAF). No surgical site infections noted during study.</td>
<td>High bacterial burden even with large LAF indicates that this feature is insufficient by itself.</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Eames, I., Shoaib, D., Kietzner, C. A., &amp; Taban, V. (2009). Movement of airborne contaminants in a hospital isolation room. Journal of the Royal Society Interface, 6, S757–66.</td>
<td>Observational</td>
<td>Scaled model of isolation room using food dye as marker in laboratory</td>
<td>Unspecific pathogens</td>
<td>Turbulence caused by movement and door opening/closing</td>
<td>—</td>
<td>Environmental contamination (air)</td>
<td>Turbulence significantly enhances horizontal and vertical dispersion.</td>
<td>Turbulence can dilute and spread airborne contaminants, and is an important consideration in design, including occupancy and use of doors.</td>
<td>Other</td>
</tr>
<tr>
<td>Friberg, B., &amp; Friberg, S. (2005). Aerobiology in the operating room and its implications for working standards. Proceedings of the Institution of Mechanical Engineers Part H. Journal of Engineering in Medicine, 219(2), 153–160.</td>
<td>Observational</td>
<td>—</td>
<td>Unspecific pathogens</td>
<td>Exponential LAF</td>
<td>Vertical ultra-clean LAF and the horizontal ultra-clean LAF, both with extra walls</td>
<td>Environmental contamination (surface)</td>
<td>The bacteriological efficiency of the exponential LAF was equal to the horizontal and vertical LAF units with extra walls. The three systems studied easily fulfilled the criteria for ultra-clean air.</td>
<td>Standardized simulated operations (except for the horizontal LAF) were used to provide a comparison across cases.</td>
<td>Other</td>
</tr>
<tr>
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<tr>
<td>Lee, L. D., Berkheiser, M., Jiang, Y., Hackett, B., Hachem, R. Y., Chemaly, F., &amp; Raad, I. I. (2007). Risk of bioaerosol contamination with Aspergillus species before and after cleaning in rooms filtered with high-efficiency particulate air filters that house patients with hematologic malignancy. <em>Infection Control and Hospital Epidemiology</em>, 28(9), 1066–1070.</td>
<td>Observational</td>
<td>OR</td>
<td>Aspergillus spp.</td>
<td>Cleaning in HEPA room</td>
<td>—</td>
<td>Environmental contamination (air and surfaces)</td>
<td>Cleaned rooms were positive for Aspergillus in air more frequently than before cleaning on multivariate analysis. There was no difference in the density of Aspergillus between rooms with negative and positive airflow.</td>
<td>Cleaning may disturb spores that have settled on surfaces and result in increased air density for up to 1 hour.</td>
<td>Airborne</td>
</tr>
<tr>
<td>Lim, T., Cho, J., &amp; Kim, B. S. (2010). The influence of ward ventilation on hospital cross infection by varying the location of supply and exhaust air diffuser using CFD. <em>Journal of Asian Architecture and Building Engineering</em>, 9(1), 259–266.</td>
<td>Observational</td>
<td>OR</td>
<td>SARS</td>
<td>Ventilation diffuser location, and air supply and exhaust volumes</td>
<td>—</td>
<td>Environmental contamination (air)</td>
<td>Suggests causal link following an imbalance between the air supply and the exhaust which can cause a static pressure within a room. This can cause interior air to be transmitted to other spaces, which can cause virus particles spread from an infected person’s exhaled breath.</td>
<td>30 patients infected with SARS</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Memarzadeh, F. (2010). Health and safety risk assessment methodology to calculate reverse airflow tolerance in a biosafety level 3 (BSL-3) or airborne infection isolation room (AII) environment. <em>International Journal of Risk Assessment and Management</em>, 14(1-2), 157–175.</td>
<td>Observational</td>
<td>—</td>
<td>Unspecific pathogens</td>
<td>Model of positive pressure reversal in a biosafety Level 3 facility</td>
<td>—</td>
<td>—</td>
<td>Proposed model maybe employed to perform a health and safety risk assessment to determine the reverse airflow tolerance.</td>
<td>This lab simulation may be utilized for other spaces such as airborne infection isolation rooms.</td>
<td>—</td>
</tr>
<tr>
<td>SOURCE</td>
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<tr>
<td>Miller, S. L., &amp; Macher, J. M. (2000).</td>
<td>Other</td>
<td>—</td>
<td>B. subtilis, M. luteus, E. coli HB101</td>
<td>15-watt UVGI lamps</td>
<td>UVI lamps with and without louvers</td>
<td>Environmental contamination (air)</td>
<td>UVGI lamps demonstrated reductions in B. subtilis (50%), M. luteus (50%), and E. coli HB101 (100%).</td>
<td>The experiment was conducted in a 36m² test room with one window, two doors, a linoleum floor, and walls and ceiling of painted sheet rock or plywood.</td>
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<tr>
<td>Miner, A. L., Losina, E., Katz, J. N., Fossel, A. H., &amp; Platt, R. (2005).</td>
<td>Other</td>
<td>—</td>
<td>Unspecific pathogens</td>
<td>LAF, body exhaust, and UVGI</td>
<td>Use of LAF, body exhaust, and UVGI across surveyed hospitals</td>
<td>—</td>
<td>Although these clean air practices are not recommended by any U.S. governmental or professional organization, they are used in nearly 2/3 of total knee replacement procedures. The survey respondents were RNs.</td>
<td>Ventilation</td>
<td></td>
</tr>
<tr>
<td>Perdelli, F., Cristina, M. L., Santini, M., Spagnolo, A. M., Dallera, M., Ottria, G., …, Orlando, P. (2006).</td>
<td>Observational</td>
<td>10 hospitals in patient rooms and non-patient rooms</td>
<td>Airborne fungi</td>
<td>Sampling air in various environments</td>
<td>—</td>
<td>Environmental contamination (air)</td>
<td>Mean fungal concentration (in CFU/m³) was lowest in the OR and wards compared to kitchens and outside. Aspergillus concentration was &lt; 2 in ORs and wards. Although concentrations were low, 7% of ORs and 45% of wards were contaminated. Appropriate use of air handling systems appears to be effective in reducing contamination with airborne fungi.</td>
<td>Other</td>
<td></td>
</tr>
<tr>
<td>Ritter, M. A., Eitzen, H. E., French, M. L., &amp; Hart, J. B. (1976).</td>
<td>Observational</td>
<td>ORs (heart surgeries and 20 total hip arthroplasties)</td>
<td>Skin flora, including Staphylococcus epidermidis</td>
<td>ORs with LAF</td>
<td>ORs without LAF</td>
<td>Environmental contamination (surface)</td>
<td>When scrub nurses picked up hemostats, nearly 50% were contaminated in conventional group compared to &lt;10% in LAF group. Frequency of contamination increased with time.</td>
<td>—</td>
<td>LAF</td>
</tr>
</tbody>
</table>
### APPENDIX: AIR EVIDENCE TABLE (continued)

<table>
<thead>
<tr>
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<th>RESULTS</th>
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<th>FOCUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ritter, M. A., French, M. L. Y., &amp; Hart, J. B. (1973). Microbiological studies in a horizontal wall less laminar air flow operating room during actual surgery. <em>Clinical Orthopaedics and Related Research, 97</em>, 16–18.</td>
<td>Observational</td>
<td>320 orthopedic surgery patients</td>
<td>Unspecific pathogens</td>
<td>OR with horizontal wall less LAF</td>
<td>Conventional ventilation</td>
<td>Environmental contamination (air)</td>
<td>At wound, lower rate of bacterial contamination (CFU/ft²/h) comparing LAF (23) to conventional ventilation (288).</td>
<td>Suggest that the movement of people and bed making is more likely to be associated with the production of &gt;3 m particles.</td>
<td>LAF</td>
</tr>
<tr>
<td>Roberts, K., Hathway, A., Fletcher, L. A., Beggs, C. B., Elliott, M. W., &amp; Sleigh, P. A. (2006). Bioaerosol production on a respiratory ward. <em>Indoor and Built Environment, 15</em>(1), 35–40.</td>
<td>Observational</td>
<td>2 identical 4-bed bays on a respiratory ward, one with patients on non-invasive ventilators</td>
<td>Gram-negative bacteria</td>
<td>Activity of people</td>
<td>Ward with high-dependency patients versus ward with non-high-dependency patients</td>
<td>Environmental contamination (air)</td>
<td>Aerobiological survey that correlated with ward activity during working hours. Able to correlate magnitude of certain size particles with specified activities, suggesting that activities generating one size particle may not cause an increase in all particle sizes.</td>
<td>Most measurements were correlation with dust particles, and not directly related to bacterial contamination.</td>
<td>Ventilation</td>
</tr>
<tr>
<td>Ryan, R. M., Wilding, G. E., Wynn, R. J., Welliver, R. C., Holm, B. A., &amp; Leach, C. L. (2011). Effect of enhanced ultraviolet germicidal irradiation in the heating ventilation and air conditioning system on ventilator-associated pneumonia in a neonatal intensive care unit. <em>Journal of Perinatology, 31</em>(9), 607–614.</td>
<td>Observational</td>
<td>Neonatal ICU with routine environmental (including HVAC) and tracheal cultures</td>
<td>Ventilator-associated pneumonia; various bacteria and fungi</td>
<td>Enhanced UVGI in HVAC system</td>
<td>HVAC system prior to enhanced UVGI</td>
<td>Infection (ventilator-associated pneumonia); environmental contamination (air and surface)</td>
<td>UV caused a 3 log drop in HVAC cultures in 3 days, which turned negative by 5 months. Surface cultures and tracheal cultures also markedly reduced. VAP decreased from 74% to 55% at 6 months, although ventilator days also decreased.</td>
<td>Marked reduction in both environmental and clinical cultures. Most other practices were maintained the same in this quasi-experimental study. Costs and maintenance not discussed.</td>
<td>UV</td>
</tr>
<tr>
<td>Scaltriti, S., Cencetti, S., Rovesti, I., Marchesi, I., Bargellini, A., &amp; Borella, P. (2007). Risk factors for particulate and microbial contamination of air in operating theatres. <em>Journal of Hospital Infection, 66</em>(4), 320–326.</td>
<td>Observational</td>
<td>23 surgeries in 3 conventionally ventilated ORs</td>
<td>Unspecific pathogens</td>
<td>Room activity</td>
<td>—</td>
<td>Environmental contamination (air)</td>
<td>Number of individuals in room did not affect number of dust particles, but was inversely correlated with the number of door openings (mean 0.9 opening/min). Mean of 5.5 CFU/dm²/h in surgeon area. In multivariate analysis, only surgical technique (conventional vs. endoscopic) was correlated with presence of particles ≥5μm.</td>
<td>Most measurements were correlation with dust particles, and not directly related to bacterial contamination of OR.</td>
<td>Ventilation</td>
</tr>
</tbody>
</table>
### APPENDIX: AIR EVIDENCE TABLE (continued)

<table>
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<tr>
<th>Source</th>
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<th>Results</th>
<th>Comments</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Sherertz, R. J., Belani, A., Kramer, B. S., Ellenboin, G. J., Weiner, R. S., Sullivan, M. L., ... Samsa, G. P. (1987). Impact of air filtration on nosocomial Aspergillus infections. Unique risk of bone marrow transplant recipients. <em>The American Journal of Medicine, 83</em>(4), 709–718.</td>
<td>Observational</td>
<td>Bone marrow transplant patients in setting of outbreak</td>
<td>Aspergillus</td>
<td>HEPA filters</td>
<td>Standard filtration methods</td>
<td>Environmental contamination (air)</td>
<td>Prior to HEPA filtration, bone marrow transplant patients were exposed to 0.16–0.4 CFU/m$^3$ of Aspergillus compared to 0.009. Multivariate model in this group found that 7.6 infections were expected, while none were observed in the HEPA group, suggesting that this was the most important intervention.</td>
<td>Difficult to isolate effect of HEPA filtration given outbreak over 4 years, construction of new hospital and multiple interventions in this quasi-experimental study.</td>
<td>HEPA</td>
</tr>
<tr>
<td>Shiomori, T., Miyamoto, H., Makishima, K., Yoshida, M., Fujiyoshi, T., Udaka, T., ... Hiraki, T. (2002). Evaluation of bedmaking-related airborne and surface methicillin-resistant Staphylococcus aureus contamination. <em>Journal of Hospital Infection, 50</em>(1), 30–35.</td>
<td>Observational</td>
<td>13 hospital rooms occupied by patients infected or colonized with MRSA (8 with MRSA pneumonia)</td>
<td>MRSA</td>
<td>Bed-making</td>
<td>Airborne MRSA before, during, and after bed-making</td>
<td>Environmental contamination (air)</td>
<td>The MRSA containing particles was significantly higher 15 min. after bed-making than during the resting period, or at 30 or 50 min. MRSA was detected on multiple surfaces beyond the bed, all suggesting that MRSA was recirculated in the air, especially after movement.</td>
<td>Effect likely depends on relative burden and clinical site of MRSA, as well as composition of sheets. Relative importance unclear, compared to contact, considered the major way MRSA is transmitted.</td>
<td>Other</td>
</tr>
<tr>
<td>Van der Waaij, D., Heidt, P. J., &amp; Hendriks, W. D. H. (1974). Bacteriological evaluation of a laminar cross flow tunnel for surgery under operational conditions. <em>Journal of Hygiene, 72</em>(2), 145–153.</td>
<td>Observational</td>
<td>Laboratory mockup of OR using dummy surgical teams</td>
<td>Aerosolized <em>E. coli</em></td>
<td>Horizontal LAF tunnel at different velocities</td>
<td>—</td>
<td>Environmental contamination (air)</td>
<td>Velocity of 0.45 m/s provided maximum reduction. Cross-flow ventilation in surgical rooms was recommended by this laboratory mock-up, but needs further study.</td>
<td>Ventilation</td>
<td></td>
</tr>
<tr>
<td>Verdenelli, M. C., Cecchini, C., Orplanesi, C., Dadea, G. M., &amp; Cresci, A. (2003). Efficacy of antimicrobial filter treatments on microbial colonization of air panel filters. <em>Journal of Applied Microbiology, 94</em>(1), 9–15.</td>
<td>Observational</td>
<td>Laboratory</td>
<td>Specific bacteria and fungi</td>
<td>Antimicrobial treatments on HEPA filters</td>
<td>—</td>
<td>Environmental contamination (surface)</td>
<td>Used filters were generally more amenable to colonization compared to unused filters. Uncoated filters had a higher burden of bacteria and yeast. Coating decreased filtration efficacy.</td>
<td>Standard clinical strains of common pathogens including MRSA and Pseudomonas used. Effectiveness of coating lasted up to 180 days.</td>
<td>Ventilation</td>
</tr>
</tbody>
</table>
### APPENDIX: AIR EVIDENCE TABLE (continued)

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<tr>
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<tbody>
<tr>
<td>37</td>
<td>Case-control</td>
<td>46 orthopedic surgeries in 2 identical ORs</td>
<td>Unspecific pathogens</td>
<td>Horizontal vs. vertical LAF at differing velocities</td>
<td>Conventional ventilation</td>
<td>Environmental contamination (air)</td>
<td>Mean CFU/m³ in conventional ventilated OR was 350. At all velocities, down-flow ventilation gives a lower average concentration of bacteria than cross-flow. Suggests that velocity of 0.3 m/s for optimal efficiency.</td>
<td>Cross-flow is easier to build and install while down-flow may impede accessibility.</td>
<td>Ventilation</td>
</tr>
<tr>
<td>38</td>
<td>Observational</td>
<td>5 hip replacement surgeries</td>
<td>Airborne bacteria</td>
<td>Vertical LAF with partial walls in OR</td>
<td>Conventional ventilation</td>
<td>Environmental contamination (air)</td>
<td>Mean bacteria count of 10.8/m³ during surgeries was about 30 times cleaner than comparison.</td>
<td>This is one of the early studies providing intermediate endpoint for LAF.</td>
<td>Ventilation</td>
</tr>
</tbody>
</table>

**NOTES:**
- CFU: colony forming units, a measure of microbiologic burden
- HEPA: high-efficiency particulate air
- HVAC: heating, ventilation, and air conditioning
- ICU: intensive care unit
- LAF: laminar air flow
- MRSA: methicillin-resistant Staphylococcus aureus
- OR: operating room
- UV: ultraviolet, usually in reference to subtype C (UVC)
- UVGI: ultraviolet germicidal irradiation
References


Breier, A. C., Brandt, C., Sohr, D., Geffers, C., & Gastmeier, P. (2011). Laminar airflow ceiling size: No impact on infection rates following hip and knee prosthesis. *Infection Control and Hospital Epidemiology*, 32(11), 1097–1102. doi:10.1086/662182


Lim, T., Cho, J., & Kim, B. S. (2010). The influence of ward ventilation on hospital cross infection by varying the location of supply and exhaust air diffuser using CFD. *Journal of Asian Architecture and Building Engineering, 9*(1), 259–266.


The Role of Water in the Transmission of Healthcare-Associated Infections: Opportunities for Intervention through the Environment

Megan E. Denham, MAEd; Altug Kasali, MArch, PhD; James P. Steinberg, MD; David Z. Cowan, MS; Craig Zimring, PhD; and Jesse T. Jacob, MD

OBJECTIVE: To assess and synthesize available evidence in the infection control and healthcare design literature on strategies using the built environment to reduce the transmission of pathogens in water that cause healthcare-associated infections (HAIs).

BACKGROUND: Water can serve as a reservoir or source for pathogens, which can lead to the transmission of healthcare-associated infections (HAIs). Water systems harboring pathogens, such as Legionella and Pseudomonas spp., can also foster the growth of persistent biofilms, presenting a great health risk.

TOPICAL HEADINGS: Strategies for interrupting the chain of transmission through the built environment can be proactive or reactive, and include three primary approaches: safe plumbing practices (maintaining optimal water temperature and pressure; eliminating dead ends), decontamination of water sources (inactivating or killing pathogens to prevent contamination), and selecting appropriate design elements (fixtures and materials that minimize the potential for contamination).

CONCLUSIONS: Current evidence clearly identifying the environment’s role in the chain of infection is limited by the variance in surveillance strategies and in the methods used to assess impact of these strategies. In order to optimize the built environment to serve as a tool for mitigating infection risk from waterborne pathogens—from selecting appropriate water features to maintaining the water system—multidisciplinary collaboration and planning is essential.

KEYWORDS: Built environment, healthcare-associated infection, hospital, infection transmission

AUTHOR AFFILIATIONS: Megan E. Denham is a Research Associate II at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Altug Kasali is a Research Assistant at SimTigate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. James P. Steinberg is a Professor of Medicine in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia. David Z. Cowan is a Senior Research Scientist for the Health Systems Institute at Georgia Institute of Technology in Atlanta, Georgia. Craig Zimring is a Professor at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Jesse T. Jacob is an Assistant Professor in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia.

CORRESPONDING AUTHOR: Megan E. Denham, SimTigrate Design Lab, College of Architecture, Georgia Institute of Technology, 828 West Peachtree St. NW, Suite 334, Atlanta, GA 30332-0477; megan.denham@coa.gatech.edu; (404) 385-3274.

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Several pathogens causing healthcare-associated infections (HAIs) can be transmitted through a waterborne route. *Legionella*, a bacterium that thrives in warm water and can become aerosolized through evaporation of contaminated water and then inhaled, is probably the most recognized. In hospitalized patients who usually have a concurrent illness, legionellosis can range from a mild pneumonia to a life threatening disseminated disease. Some pathogens that survive in water systems are opportunistic; they are part of the human microbiome (organisms that normally live harmlessly in or on humans) and cause infection only under certain conditions. For example, *Pseudomonas aeruginosa*, a bacteria that can harmlessly live in the human intestinal tract, can cause a wide range of serious diseases including wound infection, pneumonia, and bloodstream infection when it contaminates water used in patient care. Additional bacteria include *Acinetobacter* spp., which, although a low virulence organism, frequently causes pneumonia or bloodstream infections in patients residing in the intensive care unit, in part because of its ability to persist in the environment. As a whole, pathogens from water sources, described in further detail elsewhere (Zimring, Jacob, et al., 2013) account for only a small fraction of HAIs. Isolated cases with one of the above mentioned common pathogens could actually be related to an unrecognized water source or other environmental source. Thus, the burden of HAIs from water sources may be underestimated. The occurrence of a single case of infection caused by organisms for which water is the exclusive source, such as *Legionella* spp., should prompt investigation of waterborne transmission and interventions to eradicate the contaminated water source.

The incidence of legionellosis appears to be increasing in the United States, with more than 3,000 cases reported in 2009 to the Centers for Disease Control and Infection (CDC) (Hicks, Garrison, Nelson, & Hampton, 2011). These data likely underestimate the true burden, as *Legionella*-specific diagnostic tests are often not routinely performed. The proportion of hospital-associated cases is not clear but may be rising (Lin, Stout, & Yu, 2011) and is concerning since legionellosis carries a significant attributable mortality rate (Jespersen, Søgaard, Schønheyder, Fine, & Østergaard, 2010). Prior to 2003, the CDC did not recommend preventative measures or disinfection for hospital water systems unless a *Legionella* infection was identified. With the updated 2003 guidelines however, the CDC adopted a more proactive approach that more closely aligns with Environmental Protection Agency (EPA) and Occupational Safety and Health Administration (OSHA) standards (Sehulster & Chinn, 2003). These recommendations include testing in healthcare facilities with high-risk patients (e.g., transplant patients) and implementing additional infection control measures, even in the absence of *Legionella* infections, with the goal of no detectable *Legionella* in water. Routine surveillance cultures used to detect contaminated water sources are recommended only in special circumstances, such as in dialysis water systems (Bartley & Streifel, 2010; Morin, 2000; Rutala & Weber, 1997).

When a water source supports the active replication of organisms over a period of time, it is referred to as a reservoir and can act as an ongoing source of transmission. Water can also support the growth of biofilms, which are communities of bacteria that adhere to surfaces and are encased in a polysaccharide matrix that protects the organisms from external forces, including decontamination and
sterilization efforts (Donlan & Costerton, 2002). Water reservoirs can be located in community water systems (Martinelli, Caruso, Moschini, Turano, Scarcella, & Speciani, 2000), hospital plumbing systems (Colville, Crowley, Dearden, Slack, & Lee, 1993), cooling towers (Vincent-Houdek, Muytjens, Bongaerts, & van Ketel, 1993), fixtures such as sinks (Hota et al., 2009; La Forgia et al., 2010), bathtubs (Snyder et al., 1990) and shower heads (Oliveira et al., 2007; Salvatorelli, Medici, Finzi, De Lorenzi, & Quarti, 2005), medical equipment, and decorative water fixtures (Haupt et al., 2012; Palmore et al., 2009). Acquisition of a pathogen by consumption of contaminated water is less frequently reported in the hospital setting (Borau, Czap, Strellrecht, & Venezia, 2000; Hosein et al., 2005; Sniadack et al., 1993; States et al., 1985). The presence of plumbing in all areas of a facility means that waterborne pathogens can potentially be found throughout hospitals (Anaissie et al., 2003; Keane, 2004; La Forgia et al., 2010; Miuetzner et al., 1997; Rohr, Senger, Selenka, Turley, & Wilhelm, 1999; States et al., 1985). Use of molecular typing to look for a common strain from clinical cases and the hospital environment can be helpful in determining if the infection is nosocomial and to locate the reservoir or source.

Environmental conditions, such as temperature, impact the survival of pathogens in water and can be managed to make hospital water supplies less hospitable to microbial growth. For example, water temperatures between 35°C and 46°C are ideal for growth of *Legionella*; however, the organism does not multiply well above 51°C (Best et al., 1983; Sniadack et al., 1993). Standing or stagnant water in plumbing systems may increase the formation of difficult to eradicate biofilms by organisms such as *Pseudomonas* spp. or *Legionella* spp. (Declerck, 2010).

Pathogens, in addition to *Pseudomonas* spp. and *Legionella* spp., have been associated with waterborne transmission in hospitals. *Acinetobacter* spp. can replicate on medical equipment and environmental surfaces that collect moisture. Non-tuberculous mycobacteria including *Mycobacterium fortuitum* can colonize in hydrotherapy pools or can be transmitted as aerosol from showerheads (Squier, Yu, & Stout, 2000). Molds such as *Fusarium* are less common causes of infection arising from water sources (Anaissie et al., 2001).

**Environmental Strategies to Reduce HAIs from Water Sources**

Transmission of pathogens from water sources occurs through contact with contaminated water or through aerosolization of contaminated water. Patients can also aspirate contaminated water while showering or drinking. The intervention strategies for interrupting the chain of transmission through the built environment are aimed at eliminating or reducing pathogens from a water reservoir or source or preventing contact with potentially contaminated water. Figure 1 illustrates this chain of transmission and opportunities for intervention through the built environment.

Proactive and reactive approaches can be used to target water sources of microbial growth. A proactive approach includes the maintenance and treatment of water systems to prevent any or high levels of bacterial growth using strategies such as temperature control, the use of chemicals (e.g., chlorination) or technolo-
**Reservoir**: Place (human or environmental) where organisms reside and multiply.

**Source**: Place from which an organism is transmitted to the host. Source may be the same as the reservoir or become contaminated from the reservoir (e.g., a surface or instrument).
gies such as copper-silver ionization. A reactive approach to water decontamination typically is implemented after an outbreak has occurred (or sometimes after a single infection in the case of nosocomial legionellosis). These proactive and reactive approaches can be divided into three strategies:

1. Safe plumbing practices (maintaining optimal water temperature and pressure; eliminating dead ends);
2. Decontamination of water sources (inactivating or killing pathogens to prevent contamination); and
3. Design elements (selecting fixtures and materials that minimize the potential for contamination).

**Safe Plumbing Practices**

The community water system in the United States is consistently treated and tested, and while it may contain pathogens, the concentrations are generally low. Although inconsequential to the general population, even these low concentrations of pathogens can be dangerous for immunocompromised patients. This creates a need for additional strategies to protect the water storage, distribution and disposal system within the hospital environment, referred to as “premise” plumbing. Premise plumbing can serve as reservoirs for pathogens, leading to dissemination of pathogens throughout the hospital plumbing system and to susceptible hosts. Occasionally, *Pseudomonas* spp. are found in tap water, likely related to contamination of plumbing (Bert, Maubec, Bruneau, Berry, & Lambert-Zechovsky, 1998). Proper design and maintenance of the hospital plumbing system can effectively reduce this risk of transmission (Anaissie et al., 2003).

There is limited research on premise plumbing, in part due to the challenges and expense required, but also due to the lack of robust data linking water sources to endemic hospital-associated infections (those occurring outside of a recognized outbreak). Most recommendations are based on *in vitro* simulations and outbreak investigations, rather than prospective field-based studies. These data support proactive strategies to minimize creating environments that promote the growth of pathogens. The primary method to inhibit the growth of *Legionella* spp. uses an optimal temperature range (below 35°C and above 51°C) (Best et al., 1983; Ezzeddine, Vanossel, Delmee, & Wauters, 1989; Leoni et al., 2005). It is also important to maintain optimal temperatures in water holding tanks, especially in warmer climates (Hanrahan, Morse, & Scharf, 1987).

As hospital facilities are renovated after decades of use, pipes are frequently rerouted. If not properly closed off, “dead ends” can create opportunities for biofilm growth and lead to ongoing *Legionella* contamination and infections, despite eradication efforts (Chen et al., 2008; Chen et al., 2005). Because water flow minimizes microbial growth, it is important to eliminate stagnant and low flow areas of the plumbing throughout the plumbing system (Leoni et al., 2005).

Although there is a paucity of rigorous data for premise plumbing, current knowledge and prior experience suggest that attention to appropriate maintenance and
design during both new construction and renovation of existing facilities is an essential part of preventing HAIs through design. Simple, low-cost steps such as appropriate temperature regulation and minimizing dead ends in pipes can minimize the potential growth of pathogens.

Decontamination

Decontamination of water supplies can be accomplished with multiple methods, using either proactive or reactive approaches. Often, multiple strategies are necessary in cases of persistent outbreaks (Franzin, Cabodi, & Fantino, 2002). Many factors, including risk and cost assessments, should be considered when deciding which approach is most appropriate for a facility.

Chlorination

Chlorination is the most common proactive approach to the decontamination of water. Community water is typically treated with 0.5 parts per million (ppm) of free chlorine which limits growth of most pathogens (Rutala & Weber, 1997). While inexpensive, chlorine may result in corrosion of metal plumbing, and in higher concentrations, can cause skin irritation. Maintaining appropriate chlorine levels by proper monitoring can be challenging since the farthest outlet from the treatment point must have adequate concentrations, while the closest outlet must not exceed the allowed maximum concentration.

Hyperchlorination

Hyperchlorination is a reactive approach that involves flushing the system with water containing 2–6 parts per million (ppm) of free chlorine (bleach) or chlorine gas. When used repeatedly for decontamination, this method may be effective against *Legionella* spp. but is potentially corrosive to plumbing (Helms et al., 1988). Other reports using long-term (17 years) environmental surveillance noted persistence of one serotype of chlorine-sensitive *Legionella* despite periodic hyperchlorination (García et al., 2008). Chlorine dioxide may be less effective than free chlorine for hyperchlorination in hospital water systems. One study found chlorine dioxide to be ineffective (Hosein et al., 2005), while a second study demonstrated a limited, but long-term effect (Casini et al., 2008).

Superheat-and-Flush

Superheat-and-flush is a reactive strategy for rapid disinfection of water systems when environmental surveillance cultures reveal multiple positive samples, or in response to outbreaks. In this process, superheated water is run simultaneously through all outlets inside the facility to kill and flush out any pathogens. Superheat-and-flush and hyperchlorination are the two strategies recommended in the CDC 2003 guidelines as the appropriate initial response to one or two cases of *Legionella* infections in facilities with high-risk patients (such as transplant recipients).
When utilizing superheat-and-flush, the water supply temperature should be increased to between 60°C and 80°C (Allegra et al., 2011; Best et al., 1983; Emmerson, 2001; Perola et al., 2005). One study suggested maintaining the high temperatures in the water system for 72 hours prior to flushing (Best et al., 1983), although doing so temporarily increases the risk of scalding patients, visitors, and healthcare workers. More recently, an in vitro study suggests that **Legionella** can become heat resistant with long-term heat exposure (Allegra et al., 2011), although the relevance of this remains unclear.

Once the water becomes superheated, all outlets in the entire facility must be turned on simultaneously to flush out the system. While the CDC 2003 guidelines recommend 5 minutes for duration of flushing, some studies assert that five minutes is insufficient to eradicate persistent contamination and recommend a 30-minute flush (Best et al., 1983; Perola et al., 2005; Snyder et al., 1990; Stout & Yu, 2003b). However, a 30-minute flush in large facilities is labor intensive and hospital hot water reserves may be insufficient to provide superheated water to all outlets for that length of time.

**Copper-silver Ionization**

In cases of persistent contamination, alternative strategies such as copper-silver ionization can be used to augment water decontamination (Stout & Yu, 2003a). Copper-silver ionization uses positively charge copper and silver ions, which bond to the negatively charged bacterial cell walls causing cell death (Liu et al., 1994).

Many hospitals report installing copper-silver ionization systems after repeated trials of superheat-and-flush and hyperchlorination failed (Biurrun, Caballero, Pelaz, Leon, & Gago, 1999; Liu et al., 1994; Miuetzner et al., 1997; Rohr et al., 1999; Stout, Lin, Goetz, & Muder, 1998; Stout & Yu, 2003a). Unlike superheat-and-flush and hyperchlorination, which demonstrate rapid but short-term reduction in **Legionella** spp., copper-silver ionization is reported to be efficacious at reducing or eliminating **Legionella** spp. over the long-term, with a residual effect even when the system is turned off (Liu et al., 1994; Miuetzner et al., 1997; Stout et al., 1998; Stout & Yu, 2003a).

Copper-silver ionization for water treatment has a strong evidence base from the early 1990s. Multiple studies have demonstrated that copper-silver ionization decreases the quantitative burden of **Legionella** spp. in water systems and outlet points, and can reduce the incidence of nosocomial **Legionella pneumophila** infection (Miuetzner et al., 1997; Stout et al., 1998; Stout & Yu, 2003a). However, it is essential to monitor water quality, as high pH levels can decrease the efficacy of copper. In a multi-hospital system with copper-silver ionization technology, **Legionella** spp. was successfully controlled in all hospitals except one (Lin, Vidic, Stout, & Yu, 2002), where unusually high water pH levels (8.5 to 8.9) were detected. The authors postulated that high pH prevented the copper from adhering to the cell walls. There also appeared to be an inverse correlation between the solubility of copper and pH level.
Additional considerations for copper-silver ionization systems include the volume of water flowing through the system. Infrequently used outlets, such as showers and faucets, may not receive effective concentrations of copper and silver. Flushing outlets with warm running water for 5 minutes twice a week has been used to ensure effective ion concentrations (Kusnetsov, Iivanainen, Elomaa, Zacheus, & Martikainen, 2001). Low-volume systems can also experience excessive build-up of copper and silver in the water holding tanks. The levels of copper and silver at the outlets must therefore be monitored to ensure they do not exceed allowed levels (Miettinen et al., 1997).

These observational data suggest that copper-silver ionization is an effective strategy for long-term control of *Legionella* spp., and can be used for systems with refractory problems. This promising technology has advantages over hyperchlorination (which is corrosive to plumbing) and over superheat-and-flush (which is labor intensive). However, it has not been broadly adopted as a routine strategy in hospitals without identified presence of *Legionella*, mostly due to cost and maintenance requirements.

**Ultraviolet Germicidal Irradiation**

Ultraviolet germicidal irradiation (UVGI) is another proactive strategy with the potential for controlling *Legionella* in hospital water supplies. This method uses short wavelength light that disrupts nucleic acids, leading to bacterial death. The 2003 CDC guidelines concluded that there was insufficient evidence to recommend UVGI for water treatment. Currently there is still a paucity of rigorous data on the application of UVGI in hospital water systems. While studies have reported promising findings, they have evaluated UVGI in conjunction with other interventions, making it challenging to determine UVGI's singular efficacy (Franzin et al., 2002; Matulonis, Rosenfeld, & Shadduck, 1993).

In an *in vitro* comparison of several decontamination strategies, including UVGI, chlorine, heat, and ozone, UVGI demonstrated a significantly faster kill rate for *L. pneumophila*; all other methods took 3 hours to reach the log reduction that UVGI accomplished in 20 minutes (Muraca, Stout, & Yu, 1987). A longitudinal study published in 2003 reported that a newly constructed oncology facility with a UVGI system in the water supply remained *Legionella*-free for the entire 13-year follow-up period, while an adjacent hospital without UVGI continued to experience *Legionella* contamination. When a pipe leak occurred in the new facility causing water to bypass the UV lamps, water samples showed *Legionella* growth (Hall, Giannetta, Getchell-White, Durbin, & Farr, 2003). While UVGI may be effective in controlling *Legionella*, it does not have a residual effect on the water systems. Additional research is needed to determine if UVGI water decontamination acts on other organisms in addition to preventing *Legionella* infection.

Several different proactive and reactive strategies are available for the control of pathogens, especially *Legionella*, in water sources. Chlorination carries low costs and should be the first-line approach for prevention. Other strategies, such as hyperchlorination or superheat-and-flush should be employed if *Legionella* is
found in the water supply, as recommended in the CDC environmental guidelines. Superheat-and-flush can be implemented quickly and without the need to install costly equipment, making it a good strategy to employ in outbreak situations. However, this method is labor intensive, involves high energy consumption, and may not provide long term benefit. Copper-silver ionization is a promising emerging strategy for long-term control of *Legionella* and should be used for systems with refractory problems with *Legionella*. UVGI may offer similar long-term control of *Legionella*, although it does not have a residual effect on the water systems.

Further research is needed to determine the most effective strategy in different circumstances (e.g., contamination of water system without documented infection, outbreaks of infection, new construction). This is especially true for technologies such as UVGI, where the evidence is primarily based on laboratory studies. Additionally, the roles of UVGI and the use of copper-silver ionization should be explored for pathogens other than *Legionella*.

**Design Elements**

Patients may become colonized with *Pseudomonas aeruginosa* after coming in contact with contaminated tap water sources. In addition, tap water sources may become contaminated from human contact (Rogues et al., 2007). This multidirectional mechanism for transmitting waterborne pathogens creates a greater need to focus on strategies that interrupt this chain of transmission, including selecting fixtures and materials that minimize the potential for contamination.

**Faucets, Sinks, and Aerators**

Patients may become colonized with *Pseudomonas aeruginosa* after coming in contact with contaminated tap water sources. In addition, tap water sources may become contaminated from human contact (Rogues et al., 2007). Design of faucets and sinks should take into consideration the potential for splashing and flow of water. Sinks should be designed so that the water flow never directly hits the drain, in order to avoid splashing the water from the drain or trap. In one study, an outbreak of multidrug-resistant *Pseudomonas aeruginosa* in a transplant facility resulted in 36 infected or colonized transplant recipients, with 17 deaths. The outbreak was traced to shallow drains with biofilm growth, which splashed within the range of the patients’ beds. Attempts to decontaminate failed twice; the outbreak stopped when the sinks were replaced by a new design (Hota et al., 2009). Another report found that while sinks and sink traps were a reservoir for *Pseudomonas*, this source could not be linked to infections, though the findings are limited by the short (7 weeks) follow-up period (Levin, Olson, Nathan, Kabins, & Weinstein, 1984).

Faucets and aerators are known sources for pathogens, especially *P. aeruginosa*, *Acinetobacter* spp. and other gram-negative bacteria (Kappstein, Grundmann, Hauer, & Niemeyer, 2000; Wang, Chen, Lin, Chang, & Chen, 2009). Attempts to fully understand the direction of transmission of water between faucets and human carriers are challenging. These water outlets can be contaminated by
patients and healthcare workers while performing hand hygiene, although usually the source of contamination is unknown. Using alcohol hand rubs as the primary method of hand hygiene, and potentially the use of sterile water for patient care (such as for tube feeding), can minimize risk of transmission of pathogens from water sources in high risk patient areas (Reuter, Sigge, Wiedeck, & Trautmann, 2002).

The design, material choice, and frequency of maintenance of aerators influence the risk of contamination. For example, aerators made of wire mesh, can create a hospitable environment for bacterial contamination (Kappstein et al., 2000). Outbreaks of infections have been traced to contaminated aerators and consideration should be given to removal of aerators if they are implicated in transmission (Wang et al., 2009; Weber, Rutala, Blanchet, Jordan, & Gergen, 1999).

Point-of-use Filters

Point-of-use filters are a strategy for eliminating refractory pathogens that thrive in water such as *Legionella*, *P. aeruginosa*, and *Acinetobacter* spp. (Holmes, Cervia, Ortolano, & Canonica, 2010; Marchesi et al., 2011; Trautmann, Halder, Hoegel, Royer, & Haller, 2008; Trautmann, Lepper, & Haller, 2005; Vonberg, Eckmanns, Bruderek, Ruden, & Gastmeier, 2005; Vonberg, Rotermund-Rauchenberger, & Gastmeier, 2005). Point-of-use filters have the advantage of quick installation, with immediate results on faucets where contaminated water could be especially dangerous, such as in the ICU. In one study, mounting disposable 0.2 mcg sterile water filters reduced the rate of *Pseudomonas* infections among 1,234 patients in a surgical ICU from 11.7 to 5.0% over 2 years (Trautmann et al., 2008). A pediatric oncology ward experienced similar success in the elimination of *Legionella* and *Pseudomonas aeruginosa* from all water samples with both reusable and disposable point-of-use filters (Vonberg, Rotermund-Rauchenberger, et al., 2005).

Multiple factors should be considered before implementing point-of-use filters, as they can require a substantial financial investment and ongoing maintenance commitment (Marchesi et al., 2011). Most disposable filters must be replaced after 7 days, which can result in a significant amount of waste. While reusable filters produce less waste, they require frequent cleaning and staff education, as improper handling can contaminate the filter. A small quasi-experimental study showed a favorable cost benefit with the cost of HAIs prevented exceeding cost of filters (Holmes et al., 2010).

Electronic Faucets

Electronic faucets are intended to reduce transmission of HAIs by eliminating the need to touch, and potentially contaminate or become contaminated from the faucet handles. In theory, these devices minimize cross-contamination, reduce water usage and decrease splashing. However, unintended consequences of these design features have been reported. Low flow with these devices may predispose to contamination by *Legionella* or *Pseudomonas* (Chaberny & Gastmeier, 2004). There is also potential for retrograde contamination when users
become impatient waiting for the water to start and touch the faucet. Luke-warm temperatures (from mixing of hot and cold water) and bacterial colonization of the magnetic valves have been mentioned as contributors to increasing risk of water contamination with use of these devices, including contamination with *Pseudomonas* spp. (Chaberny & Gastmeier, 2004; Halabi, Wiesholzer-Pittl, Schöberl, & Mittermayer, 2001; Hargreaves et al., 2001; Leprat, Denizot, Bertr, & Talon, 2003; Merrer et al., 2005; Yapicioglu et al., 2011). Some brands of electronic faucets are more prone to contamination than others, suggesting that design is important (Hargreaves et al., 2001).

One academic medical center removed all of the electronic faucets after finding a higher incidence of *Legionella* within electronic faucets compared to conventional faucets (95% vs. 45%) and the water from the faucets (50% vs. 15%), despite use of chlorine dioxide for decontamination (Sydnor et al., 2012). There is one report implicating electronic faucets as the source of an outbreak in an acute care setting. Three cases of *Pseudomonas aeruginosa* bacteremia occurred in a neonatal ICU and *Pseudomonas* with the same molecular type was isolated from electronic faucets and from liquid hand soap. All eight electronic faucets were replaced in the NICU, but an additional four cases occurred, suggesting that the electronic faucets were not the only source. These data suggest that electronic faucets can be predisposed to microbial contamination, and potentially lead to HAIs, when vulnerable patient populations are exposed to contaminated water. The propensity for contamination may vary depending on the design and materials used, although innovative designs may be able to overcome the apparent risks seen with these devices. Based on these limited data, the risks and benefits of electronic faucets should be carefully considered before extensive implementation in the hospital. Foot- or elbow-operated faucets may provide a viable, minimal touch alternative to electronic faucets until more data are available.

**Decorative Fountains**

Indoor decorative water features are aesthetic design elements that can serve as a potential reservoir for pathogens. Fountains offer many functions from the design perspective, such as providing a visually appealing distraction and noise reduction. However, reports of two small, but significant, outbreaks suggest that improperly designed or maintained water features represent an infection risk (Haupt et al., 2012; Palmore et al., 2009). In one hospital, the fountain was initially treated with chlorine, but, due to the offensive odor, an ozone filter was installed instead. The fountain was turned off for 4 months during construction, at which time a pipe containing stagnant water likely facilitated biofilm growth. This pipe fed water from a lower pool, which was routinely topped off with unfiltered municipal tap water and back to the top water cascade. An outbreak of *Legionella* occurred shortly after the fountain was turned back on. The fountain was drained, and no additional cases of legionellosis were reported. Maintenance was otherwise reported to be routine and appropriate.

The second report linked a *Legionella* outbreak to a decorative fountain in a hospital lobby. Eight previously healthy people were diagnosed with legionellosis, none of whom were inpatients at the hospital; all eight were hospitalized, and
three required admission to the ICU and mechanical ventilation. Similar to the first outbreak, the fountain harboring the *Legionella* had fundamental design and user flaws. A porous, foam-like material was placed under the decorative rocks at the base of the wall of the fountain in an attempt to reduce splashing. This foam-like material was found to be heavily contaminated with *Legionella*. The water frequently pooled under the rocks, and the fountain was switched off from 9 p.m. to 6 a.m. Lights shining on the fountain were suspected to have heated the stagnant water to a temperature that promoted bacterial growth. An electric fireplace was located in close proximity to the fountain, which also likely contributed to increased water temperature. Temperature was not monitored as part of routine maintenance (Haupt et al., 2012).

Fountains should be designed in a way that ensures all water is treated sufficiently (through filters, chlorination, ozone, or ionization). Porous materials, such as foam, that are conducive to microbial growth, should be avoided. If installed, proper ongoing maintenance is required, and designs should provide free flowing water outside of the temperature range that promotes pathogen growth; these plans should be established collaboratively during the design phase. Further research is needed to assess if properly designed and maintained fountains pose an infection risk.

Decorative fountains have aesthetic advantages and can serve as positive distraction for patients, family, and staff. Ideally, experts in design, environmental services (involved in ongoing maintenance), and infection control should carefully discuss the risks and benefits of decorative fountains based on available evidence and potential area of placement. The CDC’s Hospital Infection Control Practices Advisory Committee (HICPAC) recommends avoiding fountains in or near high-risk patient care areas because of the increased risk for severe legionellosis (Sehulster & Chinn, 2003).

Design elements are frequently based on form and function, but the decision process should also include an assessment of infection risk. The design of features, such as sinks and type of faucet, may influence the environmental burden of pathogens. Use of decorative fountains requires careful evaluation during the design process. The decision to include water features should include stakeholders such as infection preventionists, designers, and environmental services, to ensure consensus that the design is safe, effective, and has an optimal, long-term maintenance plan. Design innovation should focus on creating water features that offer the benefits but minimize or eliminate infection risk, for example by allowing for easy error-free maintenance.

**Conclusions**

Reports of HAIs due to pathogens from a water source are generally infrequent, but these may be under-recognized and underreported. This risk can be minimized, however, by following safe plumbing practices, including ensuring that dead-ends are closed off, maintaining optimal water temperature and chlorine levels throughout the system and regular utilization of all outlets to discourage biofilm growth.
The 2003 CDC guidelines recommend hyperchlorination or superheat-and-flush when one or more nosocomial cases of legionellosis are identified. While these strategies are fast-acting and do not require costly equipment, hyperchlorination is corrosive to plumbing, superheat-and-flush is labor intensive to perform, and neither offer long-term protection against reoccurrence. Technologies such as copper-silver ionization and UVGI offer promising long-term control of refractory pathogens, although there is little data available to perform a cost-benefit analysis for the installation and ongoing maintenance costs. Point-of-use filters are highly effective and immediately reduce contamination. The drawbacks include frequent filter changes or cleaning, as well as the need for education regarding proper handling to avoid contamination during cleaning.

The design of sinks, faucets and aerators also play an important role in reducing risks for transmitting waterborne pathogens. Sinks should be designed so that the faucet is not directly above the drain as this design can cause splashing and aerosolization of any contaminated water. Electronic faucets have faced scrutiny for presenting an increased risk for contamination; additional research is needed to verify this concern. Faucet aerators may reduce splashing, but poor design and lack of maintenance can foster biofilm growth. If present, aerators should be cleaned regularly.

Decorative water features can provide a positive distraction, but proper precautions are necessary to minimize or eliminate the infection risk that has been associated with these features. If used, they should follow the general rules for water safety, including regular maintenance and monitoring, temperature control, and decontamination strategies. Placement near high risk patients should be avoided.

Proper attention to the built environment can decrease risk of water contamination and interrupt the chain of transmission of pathogens that cause HAIs. This requires a multidisciplinary approach to assess risk factors, establish clear maintenance procedures and educate all healthcare workers on the potential dangers associated with inadequate care.

**Implications for Practice**

- Healthcare organizations should develop comprehensive and accessible guides for maintaining safe plumbing practices. The guides should include maintenance schedules and designated individuals responsible for monitoring water systems.
- Healthcare workers, including environmental services, facilities and engineers, should receive training on safe plumbing practices and the risks waterborne pathogens can pose to patients.
- During renovations of existing facilities, architects and engineers should ensure that plumbing components no longer in use are properly sealed off, to avoid creating “dead ends,” which can harbor dangerous pathogens.
- When determining the most appropriate reactive strategy, such as hyperchlorination, superheat-and-flush, copper-silver ionization, UVGI, and
point-of-use filters, decision makers should consider multiple factors, such as patient population and persistence of pathogens, in addition to cost.

- Decorative water features, such as fountains, remain a contentious topic across disciplines. Architects and designers should consider the risk of infection, proximity to immunocompromised patients, in addition to aesthetic and noise benefits, when installing a water feature. Design flaws and improper maintenance are the primary causes of outbreaks. Health-care organizations should develop care guides, such as those described above for safe plumbing practice, including maintenance schedules and designated individuals responsible for monitoring the decorative water features.
### APPENDIX: WATER EVIDENCE TABLE

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>STUDY TYPE</th>
<th>SETTING</th>
<th>PATHOGEN(S)</th>
<th>INTERVENTION</th>
<th>COMPARISON</th>
<th>ENDPOINT</th>
<th>RESULTS</th>
<th>COMMENTS</th>
<th>FOCUS</th>
<th>SUB-FOCUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Observational</td>
<td>A French university hospital</td>
<td><em>Legionella</em></td>
<td>In vitro heat shock treatments</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>After an in vitro treatment of 30 min. at 70°C, the mean percentage of viable cells and viable but not culturable cells varied from 4.6% to 71.7%. Legionella in one circuit could not be controlled easily with increasing water temperature, and a sufficient temperature could not be achieved in another circuit.</td>
<td>Flow cytometric assay may be useful to quickly evaluate the heat susceptibility of <em>Legionella</em> strains. Methods other than superheating maybe needed.</td>
<td>Water</td>
<td>Heating</td>
</tr>
<tr>
<td>2</td>
<td>Observational</td>
<td>A 250-bed hospital with a single case of nosocomial pneumonia</td>
<td><em>Legionella pneumophila</em></td>
<td>Cu-Ag ionization system and a continuous chlorination system</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>5 months after installation of the Cu-Ag ionization system in both hot and cold water systems the number of colonized sites reduced from 58% to 17% and no new clinical cases noted.</td>
<td>Measures taken after shock hyperchlorination failed. Effectiveness difficult to determine since only one case prompted the interventions.</td>
<td>Water</td>
<td>Cu-Ag</td>
</tr>
<tr>
<td>3</td>
<td>Observational</td>
<td>5 ICUs in a 870-bed hospital supplied by 2 different water systems over 1 year</td>
<td><em>Pseudomonas aeruginosa</em></td>
<td>—</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>There were 132 clinical cultured identified, among which 42% were isolates identical to those found in the faucets. One of the 9 genotypes accounted for 30 clinical isolates</td>
<td>Provides circumstantial evidence that water serves as a reservoir, though exact mode of transmission could not be clearly established.</td>
<td>Water</td>
<td>Faucets</td>
</tr>
<tr>
<td>4</td>
<td>Observational</td>
<td>ICUs after 2 cases of nosocomial <em>Legionella</em></td>
<td><em>Legionella</em></td>
<td>Superheating on a periodic basis</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Legionella remained below detectable levels in the potable hot water and no further cases of nosocomial legionellosis for 6 years after implementation of superheating.</td>
<td>Suspected cause was using potable water for feeding solutions which were then aspirated; a change in nursing practice could have avoided this. Small sample size, without clear evidence of cause and effect.</td>
<td>Water</td>
<td>—</td>
</tr>
<tr>
<td>SOURCE</td>
<td>STUDY TYPE</td>
<td>SETTING</td>
<td>PATHOGEN(S)</td>
<td>INTERVENTION</td>
<td>COMPARISON</td>
<td>ENDPOINT</td>
<td>RESULTS</td>
<td>COMMENTS</td>
<td>FOCS</td>
<td>SUB-FOCUS</td>
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<tr>
<td>5</td>
<td>Casini, B., Valentini, P., Baggiani, A., Torracca, F., Frateschi, S., Nelli, L. C., &amp; Privitera, G. (2008). Molecular epidemiology of <em>Legionella pneumophila</em> serogroup 1 isolates following long-term chlorine dioxide treatment in a university hospital water system. <em>Journal of Hospital Infection</em>, 69(2), 141–147.</td>
<td>Observational</td>
<td>5 year monitoring program in an Italian university hospital</td>
<td><em>Legionella</em></td>
<td>Chlorine dioxide, as part of multipronged safety plan</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Decrease from 67% positive cultures pre-intervention to 14% after 4 years. Mean CFU from positive samples also declined.</td>
<td>The use of chlorine dioxide was ineffective in eradicating colonization with 3 persistent strains of <em>L. pneumophila</em>. Chlorine susceptibilities remained unchanged during this period.</td>
<td>Water</td>
</tr>
<tr>
<td>6</td>
<td>Chaberny, I. F., &amp; Gastmeier, P. (2004). Should electronic faucets be recommended in hospitals? <em>Infection Control and Hospital Epidemiology</em>, 25(11), 997–1000.</td>
<td>Observational</td>
<td>Kitchen in a tertiary care teaching hospital over 6 months</td>
<td><em>Pseudomonas aeruginosa</em></td>
<td>Electronic faucets</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Initial water samples collected after installation of electronic faucets did not comply with the (German) drinking water regulation (&lt;100 CFU of coli-form bacteria). After flushing and chlorination, no evidence of <em>Pseudomonas</em> was found, compared to up to 15% at some periods.</td>
<td>Coliform (gut) bacteria were a greater issue in this study than <em>Pseudomonas</em>. Several interventions reduced water contamination. The potential risk of contamination with electronic faucets may outweigh its putative benefits as “no-touch” surfaces.</td>
<td>Water</td>
</tr>
<tr>
<td>7</td>
<td>Chen, Y. S., Lin, Y. E., Liu, Y. C., Huang, W. K., Shih, H. Y., &amp; Wann, S. R. (2008). Efficacy of point-of-entry copper-silver ionisation system in eradicating <em>Legionella pneumophila</em> in a tropical tertiary care hospital: Implications for hospitals contaminated with <em>Legionella</em> in both hot and cold water. <em>Journal of Hospital Infection</em>, 68(2), 152–158.</td>
<td>Case-control</td>
<td>3 buildings in a 1,266-bed Taiwanese medical center</td>
<td><em>Legionella pneumophila</em></td>
<td>Cu-Ag ionization system in the inpatient and outpatient buildings</td>
<td>No Cu-Ag ionization system in the emergency building</td>
<td>Environmental contamination (water)</td>
<td>Initially, there was no significant decrease in the rate of <em>Legionella</em> from baseline of 30%, but reduced to 0% after Cu-Ag concentration increased for 4 months in hospital wards. Effect persisted through end of study (11 months). In one ICU, <em>Legionella</em> persisted at low levels at month 11. No change in baseline for control site.</td>
<td>Helps to define minimal effective Cu-Ag concentration. Notably electrodes decreased in size by 50%, due to high flow, not electrolysis. Potential differences in buildings not discussed and could confound results. Reason for persistent <em>Legionella</em> may have been due to incorrect connection of tap water with waterline from purification system.</td>
<td>Water</td>
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</table>
### APPENDIX: WATER EVIDENCE TABLE (continued)

<table>
<thead>
<tr>
<th>Source</th>
<th>Study Type</th>
<th>Setting</th>
<th>Pathogen(s)</th>
<th>Intervention</th>
<th>Comparison</th>
<th>Endpoint</th>
<th>Results</th>
<th>Comments</th>
<th>Focus</th>
<th>Sub-focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chen, Y. S., Liu, Y. C., Lee, S. S. J., Tsai, H. C., Wann, S. R., Keo, C. H., Lin, Y. S. E. (2005). Abbreviated duration of superheat-and-flush and disinfection of taps for <em>Legionella</em> disinfection: Lessons learned from failure. <em>American Journal of Infection Control</em>, 33(10), 606–610.</td>
<td>Observational</td>
<td>1,070-bed Taiwanese medical center</td>
<td><em>Legionella</em></td>
<td>Superheat-and-flush for 5 minutes with replacement of faucets and shower heads followed by second superheat-and-flush 6 weeks later</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Percent of sites positive for <em>Legionella</em> transiently reduced after each episode of superheat and flush, but did not eliminate <em>Legionella</em> in ICUs and wards</td>
<td>Water systems were not isolated; a secondary line feeding ICU may have been the cause of the ineffectiveness of superheating. Duration may have been too short. Small numbers of wards (&lt;10) in each comparison group.</td>
<td>Water</td>
<td>Superheating</td>
</tr>
<tr>
<td>Ezzeddine, H., Vanossel, C., Delmee, M., &amp; Wauters, G. (1989). <em>Legionella</em> spp. in a hospital hot water system: Effect of control measures. <em>Journal of Hospital Infection</em>, 13(2), 121–131.</td>
<td>Observational</td>
<td>A 900-bed university hospital</td>
<td><em>Legionella</em> spp.</td>
<td>Sequential environmental controls (chlorine, heating to 80°C, accelerated flow) were implemented over 3 years</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Chlorination with 6 ppm free chlorine for 6 hours was ineffective. Disconnecting tank mixing hot and cold waters, maintaining high-temperature, and accelerating flow rate was the most successful. Dead ends were found, new maintenance program implemented for water tanks. Attempting to increase temperature in heating tanks lead to a 40°C temperature gradient in the tank.</td>
<td>This older study shows importance of maintenance of plumbing. Small sample size, but persistent positive cultures despite several interventions suggests that each of these older interventions may not work well alone.</td>
<td>Water</td>
<td>Chlorine</td>
</tr>
<tr>
<td>Franzin, L., Cabodi, D., &amp; Fantino, C. (2002). Evaluation of the efficacy of ultraviolet irradiation for disinfection of hospital water contaminated by <em>Legionella</em>. <em>Journal of Hospital Infection</em>, 51(4), 269–274.</td>
<td>Observational</td>
<td>A hospital with 6 separate buildings</td>
<td><em>Legionella</em></td>
<td>Before/after study of UVGI in water system</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>UVGI reduce <em>Legionella</em> burden to undetectable levels in sterilization chamber, but <em>Legionella</em> could not be completely controlled either before the UVGI lamp, or at distal sites despite efforts at hyperchlorination and superheating.</td>
<td>UVGI may be effective in small areas, but alone is insufficient to remove <em>Legionella</em> from a larger water system.</td>
<td>Water</td>
<td>UVGI</td>
</tr>
</tbody>
</table>
### APPENDIX: WATER EVIDENCE TABLE (continued)

<table>
<thead>
<tr>
<th>Source</th>
<th>Study Type</th>
<th>Setting</th>
<th>Pathogen(s)</th>
<th>Intervention</th>
<th>Comparison</th>
<th>Endpoint</th>
<th>Results</th>
<th>Comments</th>
<th>Focus</th>
<th>Sub-Focus</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>Observational</td>
<td>A new 700-bed hospital with anticipated increased transplant volume</td>
<td>Legionella</td>
<td>UVGI in water system of new construction</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>None of the 930 cultures of hospital water grew Legionella in the 13 years after moving to a new building with UVGI in water mains; the previous building had up to 27% of samples positive for Legionella. Only one patient had hospital-acquired Legionella pneumonia though tap water from that patient's room did not grow Legionella.</td>
<td>UVGI may be useful in new construction to preventing contamination of hospital water system serving high risk patients. Maybe cost-effective compared to reactive strategies but has high ongoing initial and ongoing costs including annual bulb replacement, continuous electronic monitoring and energy costs.</td>
<td>Water</td>
<td>UV</td>
</tr>
<tr>
<td>14</td>
<td>Observational</td>
<td>1,000-bed Welsh teaching hospital</td>
<td>Legionella</td>
<td>Chlorine dioxide</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Over 2 years despite high cost treatments with chlorine dioxide, persistent positive water cultures and ongoing hospital acquired Legionellosis, though these attributed to use of non-sterile water for patient care. Use of sterile water for patient care is challenging, but may be effective in minimizing acquisition of Legionella when efforts to eliminate it are successful.</td>
<td>Water</td>
<td>CLO2</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Observational</td>
<td>Patients in ICU and transplant units</td>
<td>Pseudomonas aeruginosa</td>
<td>Sink modification</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>A shallow sink adjacent to the patient bed resulted in exposure from splashes of contaminated water. The outbreak was eliminated by renovations, including sink modification that prevented splashing onto surrounding areas.</td>
<td>This is an unusual case highlighting that consideration of simple design elements, or omission of them, can have unanticipated and far reaching consequences.</td>
<td>Water</td>
<td>Sinks</td>
</tr>
<tr>
<td>16</td>
<td>Observational</td>
<td>Pediatric oncology unit</td>
<td>Acinetobacter junii</td>
<td>Aerators</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>After exchanging the conventional aerators were to a different device, no further cases were reported.</td>
<td>Questions the use of aerators in high risk areas in hospitals.</td>
<td>Water</td>
<td>Aerator</td>
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</tbody>
</table>
### APPENDIX: WATER EVIDENCE TABLE (continued)

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>STUDY TYPE</th>
<th>SETTING</th>
<th>PATHOGEN(S)</th>
<th>INTERVENTION</th>
<th>COMPARISON</th>
<th>ENDPOINT</th>
<th>RESULTS</th>
<th>COMMENTS</th>
<th>FOCUS</th>
<th>SUB-FOCUS</th>
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</thead>
<tbody>
<tr>
<td>Kusnetsov, J., Iivanainen, E., Bioma, N., Zachues, O., &amp; Martikainen, P. J. (2001). Copper and silver ions more effective against Legionella than against mycobacteria in a hospital warm water system. <em>Water Research</em>, 35(17), 4217–4225.</td>
<td>Observational</td>
<td>Warm water system of a hospital</td>
<td>Legionella</td>
<td>Cu-Ag ionization</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Copper-silver was successful in eradicating Legionella, whereas low copper and silver concentrations were not efficient against nontuberculous mycobacteria or other heterotrophic bacteria.</td>
<td>Regular use of water eradicated Legionella from the shower, emphasizing the role of stasis and biofilm formation.</td>
<td>Water</td>
<td>Sinks</td>
</tr>
<tr>
<td>La Forgia, C., Franke, J., Haoek, D. M., Thomson, R. B., Robicsek, A., &amp; Peterson, L. R. (2010). Management of a multidrug-resistant <em>Acinetobacter baumannii</em> outbreak in an intensive care unit using novel environmental disinfection: A 38-month report. <em>American Journal of Infection Control</em>, 38(4), 259-263.</td>
<td>Observational</td>
<td>ICU</td>
<td><em>Acinetobacter baumannii</em></td>
<td>Weekly full drainage chase cleansing protocol with sodium hypochlorite (bleach) solution</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>The reservoir for the <em>Acinetobacter baumannii</em> clone was detected in a sink trap within one of the ICU patient rooms and a bleaching protocol successfully decontaminated the reservoir.</td>
<td>The shared drainage system can transfer infection from connected hand washing basins.</td>
<td>Water</td>
<td>Sinks</td>
</tr>
<tr>
<td>Leoni, E., De Luca, G., Legnani, P. F., Sacchetti, R., Stampi, S., &amp; Zanetti, F. (2005). <em>Legionella</em> waterline colonization: Detection of <em>Legionella</em> species in domestic, hotel and hospital hot water systems. <em>Journal of Applied Microbiology</em>, 98(2), 373–379.</td>
<td>Observational</td>
<td>Local water distribution system</td>
<td><em>Legionella</em></td>
<td>—</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Highest colonization was found in the hot water systems of five hospitals studied, suggesting that the water recirculation system used by centralized boilers enhanced the spreading of <em>Legionella</em>.</td>
<td>Differences in <em>Legionella</em> colonization between types of buildings may be due more to other factors than variation in water supply.</td>
<td>Water</td>
<td></td>
</tr>
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<td>SOURCE</td>
<td>STUDY TYPE</td>
<td>SETTING</td>
<td>PATHOGEN(S)</td>
<td>INTERVENTION</td>
<td>COMPARISON</td>
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<td>Oliveira, M. S., Maximino, E., Lobo, R. D., Gobara, S., Sinto, S. I., Ianhez, L. E., … Levin, A. S. S. (2007). Disconnecting central hot water and using electric showers to avoid colonization of the water system by <em>Legionella pneumophila</em>: An 11-year study. <em>Journal of Hospital Infection</em>, 66(4), 327–331.</td>
<td>Observational</td>
<td>A 20-bed renal transplant unit</td>
<td><em>Legionella</em></td>
<td>Electric showers</td>
<td>Period before installing electric showers</td>
<td>Environmental contamination (water) and infection</td>
<td>67 months after installing electric showers, one of 686 cultures was <em>Legionella</em> positive. No nosocomial pneumonia by <em>L. pneumophila</em> was found.</td>
<td>The study was conducted in Brazil and the electric showers used are not common in other countries.</td>
<td>Water</td>
<td>Electric heaters for showers</td>
</tr>
<tr>
<td>SOURCE</td>
<td>STUDY TYPE</td>
<td>SETTING</td>
<td>PATHOGEN(S)</td>
<td>INTERVENTION</td>
<td>COMPARISON</td>
<td>ENDPOINT</td>
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<tr>
<td>Palmore, T. N., Stock, F., White, M., Bordner, M., Michelin, A., Bennett, J. E., … Henderson, D. K. (2009). A cluster of cases of nosocomial Legionnaires disease linked to a contaminated hospital decorative water fountain. Infection Control and Hospital Epidemiology, 30(8), 764–768.</td>
<td>Observational</td>
<td>Stem cell transplantation unit</td>
<td>Legionella pneumophila</td>
<td>Decorative fountains</td>
<td>—</td>
<td>Environmental contamination (water) and infection</td>
<td>Isolates from both patients and the fountain were identical, suggesting that the decorative fountain (equipped with a filter and ozone generator) was the source of the outbreak.</td>
<td>Pool supplemented unfiltered municipal water, with likely stagnant water in this pipe when fountain turned off for 4 months for construction.</td>
<td>Water</td>
<td>Decorative fountains</td>
</tr>
<tr>
<td>Reuter, S., Sigge, A., Wedeck, H., &amp; Traumann, M. (2002). Analysis of transmission pathways of Pseudomonas aeruginosa between patients and tap water outlets. Critical Care Medicine, 30(10), 2222–2228.</td>
<td>Observational</td>
<td>One surgical ICU and 12 peripheral wards.</td>
<td>Pseudomonas aeruginosa</td>
<td>Faucets in patient rooms</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Faucets in rooms may have served as the source of infection for 35% of patients whereas patients may have contaminated 10% of faucets.</td>
<td>Small study where timing of cultures was used to determine direction of transmission; this maybe a faulty assumption. Hand hygiene using alcohol hand rubs and using sterile water for patient care may minimize the risk of transmitting waterborne pathogens.</td>
<td>Water</td>
<td>Faucets</td>
</tr>
<tr>
<td>Rogues, A. M., Boulestreau, H., Lasheras, A., Boyer, A., Grison, D., Merle, C., Castaing, Y., … Gachie, J. P. (2007). Contribution of tap water to patient colonisation with Pseudomonas aeruginosa in a medical intensive care unit. Journal of Hospital Infection, 67(1), 72–78.</td>
<td>Observational</td>
<td>ICU</td>
<td>Pseudomonas aeruginosa</td>
<td>A disinfection program including chlorination, compared to before implementation</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>Following the implementation of a disinfection procedure, the proportion of tap water isolates with P. aeruginosa and the number of colonized patients decreased.</td>
<td>No isolated design intervention involved.</td>
<td>Water</td>
<td>Chlorination</td>
</tr>
<tr>
<td>SOURCE</td>
<td>STUDY TYPE</td>
<td>SETTING</td>
<td>PATHOGEN(S)</td>
<td>INTERVENTION</td>
<td>COMPARISON</td>
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<tr>
<td>32</td>
<td>Observational</td>
<td>A 750-bed university hospital</td>
<td><em>Legionella</em></td>
<td>Cu-Ag ionization over 4 years</td>
<td>Different concentrations of silver-copper</td>
<td>Environmental contamination (water)</td>
<td>A significant reduction in the first year, but increased in the third year.</td>
<td>Raises possibility that <em>Legionella</em> developed a tolerance to silver ions, which merits further investigation.</td>
<td>Water</td>
<td>Water</td>
</tr>
<tr>
<td>33</td>
<td>Case-control</td>
<td>A community hospital</td>
<td><em>Mycobacterium xenopi</em></td>
<td>Mixed methods including cleaning, heating, and water flushing for 15 minutes</td>
<td>—</td>
<td>Environmental contamination (water)</td>
<td>M. xenopi was eliminated from the water system.</td>
<td>Because emergence thought to be due to a decrease in water temperature, authors recommended keeping water temperature at 130°F.</td>
<td>Water</td>
<td>Water temperature</td>
</tr>
<tr>
<td>34</td>
<td>Observational</td>
<td>A 937-bed tertiary-care center</td>
<td><em>Legionella pneumophila</em></td>
<td>Superheat-and-flush for 30 minutes, and then chlorinated for 2ppm</td>
<td>—</td>
<td>Environmental contamination (water) and infection</td>
<td>67% of the sites were culture negative for <em>Legionella pneumophila</em> after 6 months, of the 33% positive it was at very low levels. No nosocomial cases.</td>
<td>—</td>
<td>Water</td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Observational</td>
<td>16 hospitals to install copper-silver ionization systems</td>
<td><em>Legionella</em></td>
<td>Cu-Ag ionization</td>
<td>Superheat and flush, ultraviolet light, and hyperchlorination</td>
<td>Environmental contamination (water) and infection</td>
<td>Copper-silver ionization was reported to be successful in eradicating <em>Legionella</em>, with no nosocomial cases reported.</td>
<td>Based on surveys answered by infection preventionists at designated facilities in an area (Pittsburgh) with endemicity and multiple outbreaks of <em>Legionella</em>.</td>
<td>Water</td>
<td>Cu-Ag</td>
</tr>
<tr>
<td>SOURCE</td>
<td>STUDY TYPE</td>
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<tr>
<td>Vonberg, R. P., Eckmanns, T., Brudernik, J., Ruden, H., &amp; Gastmeier, P. (2005). Use of terminal tap water filter systems for prevention of nosocomial legionellosis. Journal of Hospital Infection, 60(2), 159–162.</td>
<td>Observational</td>
<td>Bone marrow transplant unit</td>
<td>Legionella</td>
<td>Impregnated, disposable, terminal water filters with a pore size of 0.2 mm</td>
<td>Non-impregnated, disposable, terminal tap water filters</td>
<td>Environmental contamination (water)</td>
<td>Unfiltered tap water revealed growth of Legionella, but impregnated filter system was suitable for the prevention of nosocomial Legionellosis in high-risk patient care areas.</td>
<td>Education for appropriate use and maintenance of these filters is important. May provide a short term solution while more definitive measures are implemented, but probably not practical over the long run due to cost, maintenance.</td>
<td>Water</td>
<td>Filters</td>
</tr>
<tr>
<td>Vonberg, R. P., Rotermund-Rauchenberger, D., &amp; Gastmeier, P. (2005). Reusable terminal tap water filters for nosocomial legionellosis prevention. Annals of Hematology, 84(6), 403–405.</td>
<td>Observational</td>
<td>Pediatric oncological ward</td>
<td>Legionella spp.</td>
<td>Reusable water filters</td>
<td>Unfiltered splash water</td>
<td>Environmental contamination (water)</td>
<td>Water splash samples from filtered taps were Legionella free. Successful tests with the reusable filters which were required to be processed after 7 days.</td>
<td>May provide a short term solution while more definitive measures are implemented, but probably not practical over the long run due to cost, maintenance.</td>
<td>Water</td>
<td>Filters</td>
</tr>
<tr>
<td>Source</td>
<td>Study Type</td>
<td>Setting</td>
<td>Pathogen(s)</td>
<td>Intervention</td>
<td>Comparison</td>
<td>Endpoint</td>
<td>Results</td>
<td>Comments</td>
<td>Focus</td>
<td>Sub-focus</td>
</tr>
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<tr>
<td>40</td>
<td>Observational</td>
<td>ICUs in a 2,200-bed hospital</td>
<td>Gram-negative bacteria</td>
<td>Faucet aerators</td>
<td>Comparison of results from different ICU units</td>
<td>Environmental contamination (water)</td>
<td>54 (33%) of the faucets were contaminated with nonfermentative gram-negative bacilli. Strong positive correlation between tap water system contamination and the prevalence rate of waterborne pathogens in ICU patients.</td>
<td>Sterile water in ICUs for patient care (such as enteral feeding) may prevent nosocomial infection.</td>
<td>Water</td>
<td>Faucets</td>
</tr>
<tr>
<td>41</td>
<td>Observational</td>
<td>Surgical ICU in an acute care academic hospital</td>
<td>Stenotrophomonas maltophilia</td>
<td>Faucet aerators in patient rooms</td>
<td>—</td>
<td>Environmental contamination (water) and infection</td>
<td>After comprehensive environmental evaluation, aerators cultured positive, and remained so even after exchange. Low level contamination of potable water led to contamination of faucet aerators with subsequent which then served as a reservoir.</td>
<td>Little concordance between strain types found in patients and on aerators. Routine disinfection of aerators (challenging to do consistently) or removal (with increased splash and other issues) may be considered if aerators implicated in an outbreak.</td>
<td>Water</td>
<td>Faucets</td>
</tr>
<tr>
<td>42</td>
<td>Observational</td>
<td>NICU</td>
<td>Pseudomonas aeruginosa</td>
<td>Elbow-operated faucets</td>
<td>Electronic faucets</td>
<td>Environmental contamination (water) and infection</td>
<td>Water cultures from elbow-operated faucets were clean. P. aeruginosa outbreak resolved after replacement of the electronic faucets.</td>
<td>Elbow operative faucets offer a &quot;low touch&quot; alternative to the potential issues (contamination and potential increased colonization risk) of electronic faucets.</td>
<td>Water</td>
<td>Faucets</td>
</tr>
</tbody>
</table>
References


The Role of Facility Design in Preventing Healthcare-Associated Infection: Interventions, Conclusions, and Research Needs

Craig Zimring, PhD; Megan E. Denham, MAEd; Jesse T. Jacob, MD; Douglas B. Kamerow, MD, MPH; Nancy Lenfestey, MHA; Kendall K. Hall, MD, MS; Altug Kasali, MArch, PhD; David Z. Cowan, MS; and James P. Steinberg, MD

ABSTRACT

OBJECTIVE: To summarize the findings and provide recommendations based on the multidisciplinary literature review and industry scan, focusing on the links between the built environment and healthcare-associated infections. To propose a research agenda in order to increase informed design decisions and advance the evidence base.

BACKGROUND: The HAI-Design project explores the research linking a range of design interventions to healthcare-associated infection. The multidisciplinary team evaluated over 3,800 articles and conducted interviews with a range of stakeholders including CEOs, architects, designers, physicians and other healthcare experts, the results of which are featured in this special Supplement as topical papers.

TOPICAL HEADINGS: The four topical papers describing the role of the built environment in the acquisition of healthcare-associated infections are summarized. The evidence evaluating the strategies for intervention through the built environment is analyzed, and a research agenda is proposed.

CONCLUSIONS: While the evidence base supporting the efficacy of strategies and technologies continues to grow, there are currently few data that demonstrate a reduction in infection rates. The need for multidisciplinary collaboration and increased efforts to standardize the evaluation of environmental studies are essential to overcome the many challenges and improve the reliability of data.

KEYWORDS: Built environment, evidence-based design, healthcare-associated infection, hospital, infection control

AUTHOR AFFILIATIONS: Craig Zimring is a Professor at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Megan E. Denham is a Research Associate II at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. Jesse T. Jacob is an Assistant Professor in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia. Douglas B. Kamerow is a Chief Scientist in Health Services and Policy Research at RTI International in Washington, D.C. Nancy F. Lenfestey is a Public Health Policy Associate at RTI International in Research Triangle Park, North Carolina. Kendall K. Hall is a Medical Officer in the Center for Quality Improvement and Patient Safety at the Agency for Healthcare Research and Quality in Rockville, Maryland. Altug Kasali is a Research Assistant at SimTigrate Design Lab in the College of Architecture at Georgia Institute of Technology in Atlanta, Georgia. David Z. Cowan is a Senior Research Scientist for the Health Systems Institute at Georgia Institute of Technology in Atlanta, Georgia. James P. Steinberg is a Professor of Medicine in the Division of Infectious Diseases at Emory University School of Medicine in Atlanta, Georgia.

CORRESPONDING AUTHOR: Craig Zimring, PhD, Georgia Institute of Technology, 828 West Peachtree St. NW, Suite 334, Atlanta, GA 30332-0477; craig.zimring@coa.gatech.edu; (404) 385-8193; (404) 385-7452 (fax).

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stimulated by the healthcare quality movement, healthcare organizations and practitioners are increasing their efforts to prevent healthcare-associated infections (HAIs), which has led to a reduction in HAI rates in the United States. Much of this effort has focused on improving clinical practices (Pronovost, 2008). However, the built environment is gaining recognition for its role in decreasing, or increasing, the risk of infection.

The research evidence regarding the impact of the built environment on HAIs is scattered between design and infectious disease literature. This article provides recommendations based on a large multidisciplinary project, which included a literature review and industry scan, examining the associations between the built environment of hospitals and HAIs. This article summarizes a range of design interventions, their impact on transmission of pathogens, and how they are addressed in design guidelines. The complete results of the literature review can be found as topical reports available within this special Supplement to HERD. The challenges and opportunities for collaboration between design and infection prevention researchers and clinicians are discussed. We end with a discussion of strategies to improve research and action.

Design Interventions to Reduce Healthcare-Associated Infections

The project explored the research linking a range of design interventions to healthcare-associated infection. The team evaluated over 3,800 articles in peer-reviewed and non-peer-reviewed journals and conducted interviews with a range of stakeholders, including CEOs, architects, designers, physicians, and other healthcare experts. In order to provide sufficient depth, the project focused on acute care facilities, though many interventions are applicable to a range of settings. In addition to considering how design interventions can prevent environmental contamination and interrupt transmission of pathogens, the team also explored interventions that change behavior, such as improving hand hygiene compliance.

Table 1 provides an overview of the principal design interventions using the built environment, how they are addressed in two key guidelines, and comments about further action.

Expert Interviews

The experts interviewed in the areas of hospital administration, architecture, interior design, hospital epidemiology, infection prevention, and air and water quality showed keen interest in the impact of the environment on HAIs. Interventions such as single-patient rooms, increasing the number of sinks and alcohol rubs, improving air treatment and circulation, water filtration and treatment systems and improved material choices (including antimicrobial materials) were most commonly discussed. The experts were supportive of the concept of evidence-based design but expressed concerns regarding its definitions and inconsistent standards of evidence. The terminology that these experts preferred was
TABLE 1. DESIGN INTERVENTIONS AND GUIDELINES

<table>
<thead>
<tr>
<th>INTERVENTION/ DESIGN ELEMENT</th>
<th>MODE OF TRANSMISSION OR SOURCE/RESERVOIR</th>
<th>TARGETED PATHOGENS OR INFECTIONS</th>
<th>CDC*</th>
<th>FGI 2010**</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminar air flow (LAF)/ Unidirectional air flow</td>
<td>Air</td>
<td>SSI</td>
<td>Unresolved (U) for ORs, not recommended for Protective Environment (PE) rooms</td>
<td>NA</td>
<td>Field research and simulation shows that LAF and unidirectional flow are effective in reducing squames and droplets from entering wounds. However the impact on actual infections remains unresolved.</td>
</tr>
<tr>
<td>HEPA filters</td>
<td>Air</td>
<td>Airborne pathogens primarily Mycobacterium tuberculosis and Aspergillus spp.</td>
<td>(Ib) for portable filters, (Ib, IC) for point of use HEPA filters in PE rooms</td>
<td>Recommended in PE rooms</td>
<td>HEPA filtration alone may be insufficient, particularly during construction when Aspergillus poses an increased risk of infection. HEPA filters are costly to replace and maintain. There is no evidence of benefit for persons who are not immunocompromised.</td>
</tr>
<tr>
<td>In-Duct UVGI</td>
<td>Air</td>
<td>Mycobacterium tuberculosis</td>
<td>Recommended for environmental control as a supplemental measure for airborne infection isolation, based on risk assessment (II)</td>
<td>NA</td>
<td>UVGI alone is an insufficient mechanism for infection control, but may help increase efficiency and efficacy of filtration systems.</td>
</tr>
<tr>
<td>Positive pressure rooms</td>
<td>Air</td>
<td>Multiple</td>
<td>Recommended for use in all protective environments and operating rooms (Ib, IC)</td>
<td>Recommended for PE rooms.</td>
<td>Intent of positive pressure is to protect patient from pathogens external to room. Recommended air exchange rate to accompany positive pressure depends on room use.</td>
</tr>
<tr>
<td>Negative pressure rooms</td>
<td>Air</td>
<td>Multiple (e.g., Mycobacterium tuberculosis, rubeola (measles), varicella-zoster (chickenpox))</td>
<td>Recommended for use in airborne infection isolation rooms (Ib, IC)</td>
<td>Recommended for Airborne Infection Isolation (AII) rooms</td>
<td>Intent of negative pressure is to protect others from airborne pathogens harbored by infected patient in room. Recommended air exchange rate to accompany negative pressure depends on whether or not construction is new.</td>
</tr>
<tr>
<td>Safe plumbing practices</td>
<td>Water</td>
<td>Primarily Legionella and gram negative pathogens that can grow in water including P. aeruginosa</td>
<td>Maintain cold water &lt;68°F and hot water &gt;124°F to discourage bacteria growth. (IC)</td>
<td>Maintain cold water &lt;68°F and hot water &gt;124°F to discourage bacteria growth.</td>
<td>Proper design and maintenance of the hospital plumbing system is essential to reduce risk of pathogen growth leading to transmission; all water should be in regular use to avoid standing water in pipes.</td>
</tr>
</tbody>
</table>

continues...
### TABLE 1. DESIGN INTERVENTIONS AND GUIDELINES (continued)

<table>
<thead>
<tr>
<th>INTERVENTION/ DESIGN ELEMENT</th>
<th>MODE OF TRANSMISSION OR SOURCE/RESERVOIR</th>
<th>TARGETED PATHOGENS OR INFECTIONS</th>
<th>CDC*</th>
<th>FGI 2010**</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Chlorination</td>
<td>Water</td>
<td>Primarily Legionella</td>
<td>Remediation strategy after distribution system repair (IC, II)</td>
<td>NA</td>
</tr>
<tr>
<td>8</td>
<td>Hyperchlorination</td>
<td>Water</td>
<td>Primarily Legionella</td>
<td>Recommended when cases of Legionella are identified (IC)</td>
<td>NA</td>
</tr>
<tr>
<td>9</td>
<td>Superheat-and-flush</td>
<td>Water</td>
<td>Primarily Legionella</td>
<td>Recommended when cases of Legionella are identified (IC)</td>
<td>NA</td>
</tr>
<tr>
<td>10</td>
<td>Copper-silver ionization</td>
<td>Water</td>
<td>Primarily Legionella</td>
<td>(U)</td>
<td>Unresolved</td>
</tr>
<tr>
<td>11</td>
<td>UVGI</td>
<td>Water</td>
<td>Legionella</td>
<td>(U)</td>
<td>Unresolved</td>
</tr>
<tr>
<td>12</td>
<td>Point-of-use filters</td>
<td>Water</td>
<td>Legionella, Pseudomonas aeruginosa, and Acinetobacter spp.</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>13</td>
<td>UVGI</td>
<td>Contact</td>
<td>Multiple pathogens, including C. difficile</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

*continued…*
<table>
<thead>
<tr>
<th>INTERVENTION/DISIGN ELEMENT</th>
<th>MODE OF TRANSMISSION OR SOURCE/RESERVOIR</th>
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<th>CDC*</th>
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<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 Hydrogen peroxide mist or vapor</td>
<td>Contact</td>
<td>Multiple (e.g., MRSA, VRE, C. difficile)</td>
<td>NA</td>
<td>NA</td>
<td>Mostly being studied for terminal room cleaning. Patients and staff must be out of the room while in use, the room must be sealed; decontamination typically takes significantly longer than UVC. Hydrogen peroxide compared to UVC, however, has the advantages of being able to permeate the entire room, is not limited by line of sight for full efficacy, and produces greater microbial killing.</td>
</tr>
<tr>
<td>15 Copper surfaces</td>
<td>Contact</td>
<td>Multiple (e.g., MRSA, VRE, C. difficile)</td>
<td>NA</td>
<td>NA</td>
<td>Surfaces made of copper alloys resist contamination by common pathogens, demonstrated both in lab settings and in clinical settings with high-touch surfaces made of copper alloy. Impact on healthcare associated infection rates less clear. More research also needed to determine the impact of repeated cleaning on copper surfaces. Copper technology has advantage of having continuous antimicrobial activity that could lessen contamination of surfaces from ongoing contact during daily patient care.</td>
</tr>
<tr>
<td>16 Sinks and alcohol hand rub dispensers</td>
<td>Contact</td>
<td>Multiple</td>
<td>Provide hand hygiene products in all patient care areas. (IB,IC) Alcohol hand rubs preferred method for hand hygiene in most circumstances. (IB) Use soap and water when hands are visibly dirty or soiled. (IA)</td>
<td>NA</td>
<td>Recommended</td>
</tr>
<tr>
<td>17 Single-patient rooms</td>
<td>Contact</td>
<td>Multiple</td>
<td>NA</td>
<td>Recommended</td>
<td>Private room associated with decreased infection risk and other benefits in areas such as patient- and family-centered care and patient flow (minimized need for room transfers).</td>
</tr>
</tbody>
</table>

NOTES:
NA: Relatively new technology and/or not addressed in existing guidelines.
“evidence-influenced design.” The need for additional evidence addressing cost, return on investment, and, most importantly, efficacy in reducing infections was a recurring topic discussed in the interviews.

The experts stressed that multiple interventions are needed to mitigate HAI risk, including interventions that address human behavior, as noncompliance can undermine even the most effective designs. Greater multidisciplinary collaboration is also necessary to enhance the application of both evidence and experience in the design of healthcare facilities. For the complete report detailing the expert interviews, see Lenfestey et al. (2013).

**Summary of Findings: The Role of Surfaces**

Contact, either direct or indirect, between human or environmental sources and susceptible patients is recognized as the most common mode of transmission of pathogens causing HAIs. For the complete report and description of supporting evidence on which the following summaries are based, see Steinberg et al. (2013).

Many common pathogens, such as methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant *Enterococcus* (VRE), *Acinetobacter* spp., and *Clostridium difficile*, can survive for days to months on dry surfaces. Patients admitted to rooms in which the previous occupant was known to harbor MRSA, VRE, or *Clostridium difficile* are at an increased risk of acquiring these pathogens (Huang, Datta, & Platt, 2006; Nseir et al., 2011; Shaughnessy et al., 2011). This suggests that terminal cleaning (cleaning when the patient is transferred out of the room) as routinely performed by environmental services personnel may be inadequate.

Strategies to improve surface cleaning include feedback systems to alert staff as to the quality of manual cleaning, as well as technologies and materials that supplement manual cleaning. Touch-free cleaning technologies, including ultraviolet germicidal irradiation (UVGI) and hydrogen peroxide (HP) delivered as a vapor or mist, can significantly reduce environmental contamination of patient rooms. Because both of these technologies require that the room be vacated, they are useful primarily for terminal room cleaning and have limited impact on day-to-day room cleaning.

Antimicrobial surfaces, such as those made with copper, have the advantage of providing continuous antimicrobial activity and have been shown to actively resist microbial contamination in both clinical and laboratory settings. The long-term durability of copper surfaces is not yet known; copper is more reactive than stainless steel and is more difficult to clean, which can lead to a build-up of debris and cells following repeated cleaning.

Carpets have been shown to harbor pathogenic bacteria in patient rooms and have been implicated in at least one outbreak. Carpets are also more difficult to clean and take time to dry after becoming wet through traditional cleaning methods. More research is needed to determine the infection risk that carpets pose, especially since carpets also offer many potential benefits in certain areas.
of healthcare facilities. Carpeting, for example, is desirable in areas where noise reduction is needed, and it helps reduce fatigue for healthcare workers required to stand or walk. However, with the removal of carpets from patient care areas, this is not a priority area of research.

Hand hygiene is accepted as the most important infection prevention measure to reduce transmission of pathogens in hospitals. Hand hygiene compliance by healthcare workers is often low. While much effort has been devoted to education and to the monitoring of hand hygiene, the built environment can have an impact on compliance. In simulation-based testing, and in at least one study in an intensive care unit, placing hand rub dispensers in clear view of physicians as they observed patients significantly improved hand hygiene compliance. Automated or staffed reminder systems can also increase hand hygiene compliance.

Curtains are used in hospitals to provide privacy and to function as movable partitions in many multi-bed spaces and single rooms, including intensive care units. Although there is uncertainty about the role of curtains in transmission of pathogens, low-cost steps to minimize or eliminate contact with privacy curtains would be prudent.

A growing body of evidence supports the conclusion that single-patient rooms are linked to reduced HAIs and have other psychosocial benefits. Single-patient rooms have been linked to reduction of many HAIs, including MRSA sepsis, pneumonia, and catheter-related infections. The exact cause for the decrease in infection rates is unclear, although it is postulated that there are more opportunities to conduct thorough terminal cleaning of surfaces after patients are moved or discharged from single-patient rooms. Private rooms may also reduce direct or indirect contact transmission of pathogens between patients compared to multi-occupancy rooms. As a result, the Facilities Guidelines Institute (FGI) began to require single-patient rooms for new construction starting with the 2010 Edition.

The following are research opportunities regarding surface transmission:

- Develop and test design and operational strategies to reliably enhance performance of routine room cleaning.

- Establish the cost-effectiveness of HP and UVGI for terminal cleaning and improve these technologies to make them more practical and effective by decreasing time for decontamination.

- Establish the impact of HP and UVGI on equipment, fabrics, and plastics used in patient care areas.

- Determine the impact of copper and other “self-cleaning” surfaces on infection in daily use in hospitals, especially on high-touch surfaces.

- Investigate methods for decreasing the infection risks of carpets, such as using antimicrobial materials, though this is less significant if carpet is not used in patient care areas.
• Establish the impact of hand hygiene reminder systems anchored in the built environment on sustained hand hygiene compliance and especially on infection.

• Establish strategies that allow staff, patients, and families to interact with the environment without touching, such as by using voice or gesture control.

Summary of Findings: Air

Most research on the effects of ventilation system design on HAIs has focused on the effect of alternative airflow strategies in operating rooms, such as laminar airflow, displacement ventilation, or turbulent ventilation. Many studies, in laboratories, clinical settings, and simulations, demonstrate that unidirectional airflow, when combined with very clean air and frequent air changes, reduces bacterial counts in the air and on open culture plates, and discourages the phenomenon of cells shed by healthcare workers landing in wounds. The effect of ventilation system design on HAIs in public or other care areas of hospitals remains less clear and merits further rigorous investigation. For the complete report and description of supporting evidence on which the following summaries are based, see Jacob et al. (2013).

A high-efficiency particulate air (HEPA) filter removes almost all particles from the air and is used in protective environments. HEPA filtration is one of the strategies aimed at reducing the spread of airborne pathogens by cleaning air as it enters or leaves airborne infection isolation rooms, operating rooms, or other protective environments. While some hospitals use HEPA filters in public and general patient care areas, the impact of this broader application of HEPA filtering is not yet established. HEPA filtering brings additional costs for construction, operations and maintenance, and its impact on immunocompromised patients requires further study. Several studies show that UVGI can be an effective strategy to augment the performance of heating, ventilation and air conditioning (HVAC) systems by increasing filter efficacy and efficiency through controlling the growth of biofilm on filters.

The following are research opportunities regarding air:

• Assess the impact of laminar airflow and other unidirectional flow on infection rates.

• Compare the costs and benefits of laminar flow to other unidirectional flow technologies.

• Measure the impact of ventilation rates and flow strategies on operations and infections in patient care areas that are not protected environments.

• Evaluate the impact of HEPA filtering on patients and staff not in protected environments.

• Assess the costs and benefits of in-duct UVGI both to improve HVAC efficiency and to decontaminate air.
Summary of Findings: Water

Strategies for the prevention of infections from water sources include eliminating or reducing pathogens from a water reservoir or source and preventing contact with potentially contaminated water. For the complete report and description of supporting evidence on which the following summaries are based, see Denham et al. (2013). The primary method for inhibiting the growth of Legionella is to maintain an optimal temperature range (below 35°C and above 51°C). Additional measures, such as minimizing dead ends in pipes, can decrease pathogen growth. If the hospital water supply is implicated as a source of infection, it can be flushed with free chlorine or the water can be superheated and flushed. In cases of persistent contamination by Legionella, alternative strategies, such as copper-silver ionization and UVGI, can be used to augment water decontamination.

Faucets and aerators are known sources for pathogens, especially Pseudomonas aeruginosa, Acinetobacter spp., and other gram-negative bacteria. While some plumbing designs have been implicated in outbreaks, the impacts of faucet and sink design on endemic infection rates are not clear.

Decorative fountains have aesthetic appeal and can serve as a positive distraction for patients, family and staff. Two reported outbreaks have been linked to hospital fountains with suboptimal maintenance combined with flawed design. The Centers for Disease Control and Prevention’s (CDC) Hospital Infection Control Practices Advisory Committee recommends avoiding fountains in or near high-risk patient care areas because of the increased risk for legionellosis. The impact of well-designed and maintained fountains has not been established, but given the potential infection risks, the benefits and risks of water features should be carefully considered, especially near immunocompromised patients.

The following are research opportunities regarding water:

- Assess the cost-effectiveness of copper-silver ionization for long-term control of Legionella and other pathogens.
- Evaluate faucet, aerator, sink, and toilet designs on contamination of the adjacent environment and ultimately on infection risk.
- Examine the risk of infection versus the benefits of fountains and other positive distraction features, and explore the reduction in stress from other options that do not introduce additional risks, such as video or enclosed fountains.

Benefits and Challenges of Collaboration

The multidisciplinary nature of our project team, including hospital epidemiologists and researchers, health systems engineers, environmental psychologists, public health policy experts, architects, and clinical information specialists, provided a great deal of strength. The team was able to explore each of the steps in the translation process: identify questions from multiple perspectives, assess the quality and relevance of research, and assess applications of the research in guidelines and in infection prevention practice and design practice.
At the same time, the design team had multiple perspectives on what constituted the strength of evidence. The team considered at least two questions simultaneously:

- **Internal validity**—to what extent did the research allow the conclusion that a specific design intervention led to the result, rather than being due to other causes?

- **Practical impact**—to what extent did the research demonstrate that the intervention led to reductions in actual infection, rather than to intermediate results, such as reduction in contamination of surfaces or improvement in hand hygiene compliance?

Many studies looking at the impact of design interventions on infection risk are quasi-experimental in design, with measurement of outcomes before and after introduction of an intervention. Other interventions occur in the setting of outbreaks where multiple interventions are introduced simultaneously. There have been few randomized controlled trials, or other similar study designs, that provide a clear link between an individual intervention and outcomes demonstrating decreased infection.

With respect to practical impact of an intervention on infection risk, the team asked a series of questions. Does the intervention lead to a reduction of a pathogen in the laboratory? Does it lead to the reduction of a pathogen in a field test? Does it lead to the reduction of a pathogen in everyday hospital practice? Does it lead to reduced infection in actual clinical application? The last question was considered to be the gold standard and was seldom answered.

These questions highlight the complexity of conducting research in design and infection prevention. The team was committed to the use of evidence to help move to a practice based on an understanding of what actually works in the real world. Most of the team members are trained as scientists, with a healthy skepticism about causal claims. At the same time, both design and infection prevention require action no matter what the evidence base. A new hospital involves thousands of design decisions, despite a lack of empirical evidence. Infection prevention requires the coordination of the entire hospital staff, even if definitive evidence is not available.

To at least partially address this, we adopted a systems science view that became embedded in our conceptual model (Zimring, Jacob, et al., 2013). This model examines how a range of design interventions interacts with changes in behavior, in order to interrupt pathogens and ultimately reduce infection. The “chain of transmission interventions models” presented in this Supplement provide the framework by which to organize interventions aimed at interrupting the specific mechanisms of transmission (Denham et al., 2013; Jacob et al., 2013; Steinberg et al., 2013).
Conclusions

Strategies for research and development include:

1. Increase the number of multidisciplinary collaborations between infectious diseases/hospital epidemiology and quality improvement communities, designers, and evidence-based design researchers in order to develop and test evidence-based solutions. These collaborations are necessary to ensure that specific design interventions are subjected to rigorous evaluation and have practical applications. In addition, these collaborations encourage teams to re-examine basic functions and design new approaches. For example, while high-touch surfaces that are self-cleaning or easy to clean should be evaluated, multidisciplinary collaboration allows reasoning back to re-evaluate basic approaches: there is also the opportunity to consider if the self-cleaning surfaces can be replaced with equipment that requires no touch at all to operate (voice control, for example).

2. Improve the evidence base for design and infection prevention and clarify standards for evidence. The standards of rigor used in healthcare epidemiology can help increase rigor of evidence-based design as a field. Healthcare epidemiology has a longer history of moving from basic science and lab research to clinical trials and interventions.

3. Develop systems science approaches. Whereas in medical research, rigorous, tightly controlled studies, such as randomized controlled trials, can often be performed, most design interventions are multi-factorial and are deployed in settings with varying care cultures and care processes. It is difficult to isolate the impact of a single design intervention, and in many cases it might be more important to understand the contribution of design to a whole system of care.

4. Deploy proposed interventions in real healthcare settings. Currently, there are few data on the efficacy of seemingly promising strategies and materials developed by researchers in real-world settings. Antimicrobial surfaces seem to reduce bacteria on high-touch surfaces, but do they work in the practical context of a surface that receives regular cleaning, which entails moisture and potential corrosion or degradation? Do new touch-free cleaning strategies work for inpatient room cleaning, where patients stay for short periods and are replaced frequently? How do infection prevention strategies affect the care and experience of patients? How do strategies intended to improve the experience of patients, families, and staff, such as family areas in patient rooms, water features, gardens, and functional windows, influence the transmission of pathogens and impact infection rates? What is the business case for different intervention strategies?

5. Capitalize on this moment of extraordinary convergence. Both the infection prevention and design communities are recognizing the importance of design in controlling HAIs. This has created a unique opportunity for
collaborative research and practice, for designers and built environment researchers to be members of hospital epidemiology research projects, for hospital epidemiologists and infection prevention professionals to be members of infection prevention research teams and of built environment research teams, and particularly to be involved early and continuously in design projects.

Implications for Practice

• While there is growing acknowledgement that the built environment impacts healthcare-associated infection, evidence is scattered among disciplines, and causal links are actively being explored. Design professionals should continue to monitor emerging evidence.

• Healthcare organization decision makers should proactively involve infection prevention specialists and built environment research teams early and continuously in the design process. This will help prevent costly delays in construction due to overlooked or unintended infection control issues and can structure the applications of interventions or technologies in a way that they can be monitored and evaluated for their efficacy in real healthcare settings.

• Infectious disease and healthcare epidemiology researchers should consider built environment issues in their research, including design researchers as collaborators where appropriate.
References


Design and Infection: A Call for Greater Progress Through Research

D. Kirk Hamilton, FAIA, FACHA, EDAC

This special issue of HERD, commissioned by the Agency for Healthcare Research and Quality (AHRQ), part of the U.S. Department of Health and Human Services, focuses on infection and aspects of the physical environment that are related to infection. The articles included here offer important updates to the state of the evidence related to infection and the environment.

A clinical diagnostic term for infection is sepsis. The Sepsis Handbook reports that “Sepsis is a complex process that involves the interplay between a number of microbial and host factors” (Balk, Ely, & Goyette, 2004, p. 188). It goes on to tell us that, “Severe sepsis is a common, frequently fatal, and expensive disease” (p. 4). Prevention of sepsis or infection is a major goal for every healthcare organization, and in each individual and unique clinical encounter.

To a hospital patient at risk, there are few topics more important than hospital- or healthcare-associated infection (HAI). We know that the frequency of HAIs in the American health system is shameful (Gordin et al., 2005; Larson, 1988; Scott, 2004). Infection is transmitted by direct human contact (Pittet, Allegranzi, & Boyce, 2009), or as a result of contact with airborne (Tang et al., 2011) or waterborne (Sinclair, Jones, & Gerba, 2009) bacterial, viral, or fungal organisms in the environment. The infections are increasingly related to drug resistant strains (Capriotti, 2003). We know that proper hand hygiene on the part of caregivers is the single most important contribution to protection from infection organisms (Albert & Condie, 1981), yet the adherence to hand hygiene guidelines is poor (Pittet, 2001). In addition to thoughtful behavior on the part of caregivers and visitors, design decisions also play an important role in controlling the spread of infections in healthcare settings. More research into the role of design decisions is needed.
There also is a need for more research on the organisms that cause these infections. Infectious bacterial, viral, and fungal organisms have different characteristics, and have different means of survival and propagation in healthcare environments. We are discovering new technologies to destroy infectious organisms, such as hydrogen peroxide aerosol, and we are relearning the use of older cleaning methods like chlorine solutions or ultraviolet light. We are only at the beginning of knowing how to protect patients, staff, and visitors from these threats.

More research is needed in the area of contact transmission, in which objects and humans can be both hosts and carriers. We need to understand more about the materials used in the design of healthcare settings and medical equipment. Much research and investigation is taking place to develop materials with antimicrobial properties, for example, the current interest in the properties of copper alloy surfaces. More research along these lines is needed, in addition to studies to confirm or challenge the effectiveness of materials purported to be antimicrobial.

There is a need for additional research in the area of airborne transmission of infectious organisms. We need to have a better understanding of the effectiveness of HEPA filtration and mechanical systems that re-circulate air. Although filtration and UV-light treatment appear to be effective, in situations involving the presence of avian flu or SARS, for example, we may need greater ability to isolate patients and the air systems that serve them. We need to have better studies about the relative protective value of 100% outside air that is 110% exhausted as compared with the cost of such systems and the energy required to operate them. I know an engineer who, with his colleagues, is using promising computer simulations to study and understand the distribution of airborne particles from a sneeze or cough in the patient room, and of infectious or contagious organisms from the surgical site on the operating table. One question I think should be addressed is whether the ceiling height in patient rooms plays a role in air movement that might be better understood.

There is a need for more research in the area of moisture and waterborne organisms and their role in transmission of infection. Water is required for handwashing, bathing, drinking, and cleaning in healthcare settings. Reservoirs of water exist in sinks, drains, ice, toilets, and showers. Water can be spilled from pitchers, cups, or glasses, or can condense on the surface of cold containers. Many infectious organisms thrive in the presence of moisture and warm temperatures, environments which are often found in healthcare settings.

As an architect, I am convinced that much more investigation of designs that contribute to controlling infection is needed. We must better understand the role of engineering systems for heating, ventilation, and air conditioning and their features. We must better understand plumbing systems and the ways to prevent colonization of drains or aerosol spray from sinks. We must design convenient and effective handwashing sinks and locate them where proper use is encouraged. We need to explore the options for antimicrobial materials and finishes that will not harbor moisture. We need to understand how transmission happens with cubicle curtains, window blinds, keyboards, television controls, door
handles, and other frequently touched objects. We must rigorously measure the HAI results obtained in completed projects.

It is time for the development of a useful and effective theory, or theories, of design for infection control. We need sophisticated and evidence-based hypotheses on how to address airborne, waterborne, and contact infection through design interventions. We need better information on what will destroy the bacterial, viral, and fungal organisms that cause these infections. We need experimental test sites where innovative design solutions can be tested.

I am herewith making a global call for researchers and practitioners from many disciplines to work together to address infection control with new research. A comprehensive research agenda can be proposed and monitored by an organization such as the Association of Professionals in Infection Control and Epidemiology (APIC). Important potential sources of funding including foundations like the Robert Wood Johnson Foundation and government agencies like the National Institutes for Health and AHRQ must be called upon to help support this important research. The healthcare organizations that stand to benefit from this research agenda must permit their facilities to be used in this research initiative.

References


Introduction to Systematic Reviews for Healthcare Design

Margaret J. Foster, MS, MPH, AHIP

This methods column focuses on the systematic review, a method used to respond to a research question(s) that can be answered by studying studies. The column defines and contrasts systematic reviews with narrative review, provide an overview of the process focusing on the search methods, and list resources for further guidance.

What Is a Systematic Review?

A systematic review “uses explicit and rigorous methods to identify, critically appraise, and synthesize relevant studies” (Mulrow and Cook, 1998). When defining reviews, it is useful to think of them on a spectrum, going from very subjective (narrative review) to the very objective (meta-analysis). However, all reviews are susceptible to bias, especially in the selection of inclusion criteria and search process. Table 1 describes the differences between the traditional narrative review and the systematic review. The five main steps are described in overview below with figures and tables to provide examples and more information. When planning to conduct a systematic review, it is important to consider the entire review, perhaps even writing a formal protocol, before starting.

Step 1: Define and Plan

In defining the review there are three characteristics to be defined: the research question, the inclusion criteria, and the scope of the review. In developing the
research question, consider framing your question using the PICO format. “PICO” stands for Population, Intervention, Comparison, and Outcomes, a question format commonly used in evidence-based medicine. By including these four components, the question, and thus the review itself, becomes more clear and precise. The PICO format has been discussed in Brown and Ecoff (2011). An example PICO question is shown in Figure 1, which shows the evolution of the research question through the systematic review process to the final product—the evidence table. Next, transform the research question into the inclusion criteria. Finally, determine the scope of the review, which can vary based on the breadth of the question asked, the comprehensiveness of the search, and the amount of detail in the studies to be analyzed (Gough, Oliver, & Thomas, 2012).

There are two searches to conduct during the planning stage: scoping search and a search for relevant reviews. A scoping search is a quick search run in the most relevant database (usually Medline) to get an estimate of the number of articles matching the criteria. The criteria may then need to be altered, to be made either more specific or more general. The search for related reviews ensures that a systematic review on the exact question has not been published and to find related reviews to your topic to show previous research. There are two main places to search for reviews—databases of reviews and bibliographic databases. There are several free review databases, such as PubMed Health, Cochrane Library, TRIP database, and Health Evidence, which collect or produce systematic reviews (full text may be limited). A search in a bibliographic database such as PubMed can be limited to systematic reviews. The search needs to be broad enough to find reviews concerning the most important concept(s) of the proposed review. In this example, systematic reviews on sunlight should be sought. If a review is located that is exactly like the proposed review, then research question may need to be altered, unless the review found in the database search was not well done, is not recent, or the search was not comprehensive. Related reviews need to evaluated and included in the introduction of the review to provide readers with previous research. These reviews will be utilized throughout the systematic review as discussed in later sections.

Table 1. Comparing Review Types

<table>
<thead>
<tr>
<th>PROCESS/STEP</th>
<th>NARRATIVE REVIEW</th>
<th>SYSTEMATIC REVIEW</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Research question</td>
<td>Usually not explicitly stated or goal is general, to summarize a topic</td>
<td>Specific research question</td>
</tr>
<tr>
<td>2. Search for studies</td>
<td>Usually not reported</td>
<td>Comprehensive and methods reported</td>
</tr>
<tr>
<td>3. Selection of studies</td>
<td>Criteria not provided, process often biased</td>
<td>Selection process is reported</td>
</tr>
<tr>
<td>4. Evaluation of quality and coding</td>
<td>Quality is not assessed, all studies are not treated the same</td>
<td>All studies are treated the same, including assessment of quality</td>
</tr>
<tr>
<td>5. Synthesis</td>
<td>Qualitative and non-systematic</td>
<td>Systematic</td>
</tr>
</tbody>
</table>

**Figure 1.** Evolution of research question through systematic review process.

**STEP 1: PICO FORMAT OF QUESTION**

Do the published studies show that sunlight reduces length of stay for children in critical care?

- **Population:** children in critical care
- **Intervention:** sunlight
- **Comparison:** room without sunlight
- **Outcome:** reduced length of stay

**STEP 2: STUDY CRITERIA**

Article will be included if it:

- Is about children in critical care.
- Is an evaluation of hospital design with increased sunlight.
- Reports length of stay.
- Uses appropriate methods.
- Is in English and published from 1990 on.

**STEP 3: SCREENING**

Screening questions:

1. Is this article in English?
2. Is it published after 1989?
3. Is it about children in critical care?
4. Does it describe a hospital design project with increased sunlight?
5. Does it report length of stay?

Labels:

- Included: yes to all questions
- Maybe: unsure
- No 1: if no to question 1, stop screening
- No 2: if no to question 2, stop screening
- And so on.

**STEP 4: DATA ABSTRACTION**

Quality of methods:

1. Was the study design appropriate?
2. Was the sampling correct?
3. Were exposures/outcomes measured correctly?
And so on.

Coding form:

- Population (hospital, region, number of children)
- Method of study
- Quality of methods
- Design to increase sunlight
- Length of stay measurement

**STEP 5: SYNTHESIS (evidence table)**

<table>
<thead>
<tr>
<th>Author (Year)</th>
<th>Population</th>
<th>Study Design</th>
<th>Design Intervention</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Garza et al. (2008)</td>
<td>25 children, rural hospital; U.S.</td>
<td>Cohort</td>
<td>Window in 12 children’s rooms, others without</td>
<td>Those with windows had decreased stay by 0.4 days.</td>
</tr>
</tbody>
</table>
Before moving forward, it is important to consider building a team, the timeline, standards to be followed, documentation needs, and software. Even if you plan on working on the review alone, you should seek out advisors as appropriate, including a subject expert on the review topic, a search expert, and a biostatistician. The amount of time it takes to complete a review will depend on the amount of literature to sort through, the depth of assessment performed once studies are located and the number people on the team. While considering the ultimate audience of the review, select the standards or guidelines to be followed. I usually follow the *Cochrane Handbook* and Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines, better known as PRISMA (Higgins, Green, & Cochrane Collaboration, 2008; Liberati et al., 2009). Documentation needs will vary depending on selected standard. There are several processes throughout the review that can be expedited with software. Bibliographic managers vary in usefulness during a review; examples include EndNote, RefWorks, Mendeley, Zotero, to name a few. Software designed specifically for systematic reviews include Agency for Healthcare Research and Quality (AHRQ), Systematic Review Data Repository (SRDR), Cochrane’s Review Manager (Revman), or the Joanne Briggs Institute SUMARI software. See “Resources” at the end of this article for links on review software.

Research Instruction Guide On Reviews (RIGOR) is a freely available spreadsheet created by the author that provides a guide to documenting the review methods and results. See “Resources” at the end of article.

**Step 2: Search and Document**

The search process is at the center of the systematic review and choices made during the search process can result in bias, which can be minimized by following guidelines. It is also recommended that an expert searcher be consulted, and it is required by some standards (Institute of Medicine, 2001; Weller, 2004). Reporting bias is the most common bias to effect results in systematic reviews and occurs when the nature and direction of its results affect the publication or non-publication of a study. It has been shown that it is more likely that significant positive findings will be published in a timely manner (time lag bias), in English (language bias), in multiple places (duplicate publication bias), cited more often (citation bias), and in journals that are widely indexed (location bias) (Higgins, Green, & Cochrane Collaboration, 2008).

The first step is to create a list of databases to be searched, listed in order of relevance. Each database will be searched once, using the most effective search techniques. It is recommended that reviewers search Medline and at least one more database, as limiting to only those articles in Medline may bias the results (Savoie, Helmer, Green, & Kazanjian, 2003). Table 2 lists bibliographic databases and includes estimated number of articles on hospital design for most of those listed.

The second step is to design the search in the most relevant database on the list. The goal of the search is to balance sensitivity with specificity. If the search is too...
sensitive, too many irrelevant articles will be retrieved. However, if it is too specific, relevant articles maybe missed. Table 3 shows the steps to develop a comprehensive search in PubMed (Medline). The Cochrane Handbook requires that each concept in the search be searched through both keywords and thesaurus terms, if available in the database (Higgins, Green, & Cochrane Collaboration, 2008). For example, in PubMed, thesaurus terms are called MeSH (Medical

Table 2. Databases of Primary Study, Listed by Perspective (estimated number of articles on hospital design)

<table>
<thead>
<tr>
<th>PRESPECTIVE</th>
<th>DATABASES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architectural</td>
<td>Avery Index (125), Arts Full Text (200)</td>
</tr>
<tr>
<td>Business/Administrative</td>
<td>Business Source Complete (2,200), ABI/Inform (500), ProQuest Health Management (832)</td>
</tr>
<tr>
<td>Clinical medicine</td>
<td>Medline (10,500), EMBASE (12,500), CINAHL (3,000)</td>
</tr>
<tr>
<td>Engineering</td>
<td>Compendex (3,000), ProQuest Engineering Collection (1,552)</td>
</tr>
<tr>
<td>Environment</td>
<td>GreenFILE (100), TOXLINE (150), ProQuest Environmental Science Collection (520)</td>
</tr>
<tr>
<td>Pharmacy</td>
<td>International Pharmaceutical Abstracts (210), ProQuest Pharmacollection (1,278)</td>
</tr>
<tr>
<td>Social sciences</td>
<td>PsycINFO (600), Sociological Abstracts (100), Social Services Abstracts (25)</td>
</tr>
<tr>
<td>Sports medicine/rehabilitation</td>
<td>SportDISCUS (200–300)</td>
</tr>
<tr>
<td>Veterinary</td>
<td>CAB Abstracts (318), Zoological Record (2)</td>
</tr>
</tbody>
</table>

Table 3. Developing the Search in Medline

<table>
<thead>
<tr>
<th>STEP</th>
<th>EXAMPLE</th>
</tr>
</thead>
</table>
| 1. Define concepts to be searched | Concept 1: Population = children  
| | Concept 2: Health issue = intensive care  
| | Concept 3: Intervention = sunlight |
| 2. Find synonyms for each | Concept 1: child* or infant* or newborn* or preschool* or toddler* or adolescen* or teen*  
| | Concept 2: intensive care or critical care or ICU or CCU or NICU  
| | Concept 3: Sunlight or natural light or sunlit or sunny |
| 3. Consider truncation and alternate spelling | Concept 1: infant* or newborn* or preschool* or toddler* or child* or adolescen* or teen* or pediatric* |
| 4. Find thesaurus terms for each concept | Concept 1: exp child or exp infant or exp adolescent  
| | Concept 2: exp intensive care unit/for exp critical care  
| | Concept 3: sunlight |
| 5. Combine terms | (child* or infant* or newborn* or preschool* or toddler* or adolescen* or teen* OR exp child or exp infant or exp adolescent) AND (intensive care or critical care or or ICU or CCU or NICU) or exp intensive care unit/or exp critical care) AND (sunlight or natural light or sunlit or sunny or sunlight) |

NOTES:  
[*] is a truncation symbol, teen* retrieves teen, teens, teenager, teenagers.  
MeSH terms are shown in italics.  
“exp” stands for “explode”, meaning to search for the MeSH term and all terms on its lower branch.
Subject Heading) terms. The concept of “sunshine” will be searched with the keywords and with the MeSH term. Figure 2 shows the number of articles with concept of sunshine in different fields and what would be missed by searching just one. To view MeSH terms in PubMed, use the dropdown menu next to the search box, change to MeSH, then type in a word. MeSH terms are put into trees or hierarchies so that one can select a broad term such as “architecture” and all subtopics by selecting explode. See Figure 3 for an example of the MeSH term architecture as topic.

**TIP:** Before designing the search, it is helpful to look to previous searches available in the previous reviews. In addition, find search filters that have been evaluated, such as at InterTASC, BMJ’s Clinical Evidence, and others. Also, look at primary studies that you found through the scoping search. Consider terms in titles and abstracts as well as MeSH terms. To see these, locate the article in PubMed, and click on MeSH terms link (listed below abstract).

Once the search is considered complete, retrieve all records, move into bibliographic software, and check for duplicates. Next translate the search for all other databases. The keywords should stay the same between the databases, with only the thesaurus/index terms changing. However, not all databases have a thesaurus of terms.

Step 3: Study Selection

After retrieving studies from the database searches, the screening process begins, which usually has two steps—first by title and abstract, then by full text. The goal of screening is determine if the article will be included and if not, to label

![Figure 2. Number of articles sunshine as concept in various fields.](chart.png)

**Figure 2.** Number of articles sunshine as concept in various fields.

| 6,307 in keywords only* | 3,185 in both | 8,158 as MeSH** terms only |

In title/abstract or MeSH term = 1,7650

**NOTES:**
* Keywords: sunlight or natural light or sunlit or sunny.
** MeSH term used was “sunlight.”
why it is not included. There are several questions that need to be answered when planning screening methods: what are the screening questions? Who will screen and how will articles be divided? How will disagreements be handled? Screening questions are yes/no questions based on criteria that should be available in the abstract. See Figure 1, above, for an example of questions and labels for articles. Different approaches may be taken in using available software to label articles. My preferred method is using a customized RefWorks database, while others prefer EndNote (King, Hooper, & Wood, 2011). In my guide (see “Resources”), I provide a handout that discusses step-by-step how I utilize RefWorks during the screening and coding process of the review. Next, articles need to be divided among the screeners, such as two screeners for every article or one screener for every article, divided evenly among the group. Once abstract screening is completed, review disagreements if multiple screeners were used and the inter-rater reliability of screening could be evaluated with Cohen’s kappa. All articles labeled “included” or “maybe” will move onto full text screening. The same
questions, plus possible additional questions, will be used. All articles need to be labeled as either in or out, reporting numbers as shown in Figure 4.

Depending on how comprehensive the search is intended to be, there are several ways to expand the search beyond the bibliographic databases search. Expanding the search after the selection process allows the included articles to inform the most effective expansion of the search. The one approach that all reviews should include is to search the reference lists of all included articles and relevant reviews. In addition, using citation tracking databases such as Scopus or Web of Science, articles that have cited the included articles or relevant reviews can also be browsed for selection. It is also important to search grey literature—research outside the control of commercial publishers, such as conference proceedings, blogs, dissertations and theses, government documents, guidelines, trial registries, and grants. Internet searches can be aimed at professional organizations, government sites, and similar sites to find reports and other grey literature that may otherwise have been missed. Non-database approaches include requesting studies from researchers in the field, hand searching, and Internet searches.
Studies can be requested by posting the inclusion criteria on listservs, blogs, professional sites, and/or contacting authors of included studies. Hand searching is conducted by selecting a list of journals, then browsing those parts of the journals least likely to be well indexed, such as supplements, special issues, and abstracts of conferences (Armstrong, Jackson, Doyle, Water, & Howes, 2005).

When should you stop searching? Cooper, Hedges, and Valentine list six questions to consider when determining if it is time to stop searching (2009). The main question to consider is: during the last resource searched, how many unique, relevant citations were found? If you continue to see significant numbers of new, included articles, continue searching. As the review process continues, the search may need to be updated from time to time. The *Cochrane Handbook* recommends that searches be updated within 6 months of publication (Higgins, Green, & Cochrane Collaboration, 2008).

**Step 4: Data Abstraction**

Step 4 concerns appraisal and coding eligible studies. In another methods column published in *HERD*, Stichler (2010) provided guidance on appraising articles. In addition, there are several appraisal tools available such as the Critical Appraisal Skills Programme (CASP) (2011). In general the questions included in these appraisals are:

- Was the study design appropriate for the research question?
- Was the sampling correct (source, time, size, representative of study population)?
- Were exposures/outcomes measured correctly?
- Were biases/confounders taken into consideration?
- Were the results valid, reliable, significant, and interpreted appropriately? (Heller, Verma, Gemmell, Harrison, Hart, & Edwards, 2008)

Coding is the process of reading each article/study and systematically coding characteristics onto a form, which can be done by hand, a Microsoft Access database, or the systematic review software mentioned during Step 1. The *Cochrane Handbook* provides a recommended list divided into six sections: methods, participants, interventions, outcomes, results, and miscellaneous (Higgins, Green, & Cochrane Collaboration, 2008). Other examples can be found on The Community Guide website or on the Agency for Healthcare Research and Quality’s website in the Evidence-Based Reports section. These examples provide a template which can be customized to match the need of the review. It is important that all studies be treated in a similar way, with variations only due to differences in methods.

**Step 5: Synthesize and Write**

There are a variety of ways that the evidence can be synthesized, depending on types of evidence found during the review. Usually coded information is
arranged into tables called “evidence tables” (see Figure 1) in ways appropriate for the data. Three types of synthesis will be defined here. Framework synthesis is used when the review was conducted to determine the model of a particular phenomenon. Thematic synthesis is conducted by determining categories for studies either with pre-determined categories or after reviewing all of the studies. Mixed methods synthesis combines findings from qualitative and quantitative studies by utilizing the strengths of both types (Gough, Oliver, & Thomas, 2012).

During the interpretation of the synthesis, several questions should be discussed. First, describe the consistency of the studies’ outcomes, including the reliability or quality of the outcomes. Next, discuss whether the result answered the review’s research question(s) and compare these results with related reviews. Finally, describe in what contexts your results could be applied and other implications for practitioners (Gough, Oliver, & Thomas, 2012).

A standard structure for the reporting of review was developed by PRISMA, which provides a checklist and order of items to include in the review as well as a flowchart depicts the flow of articles through the study. Figure 4, above, provides an example (Liberati et al., 2009).

**Conclusion**

Systematic reviews are an important part of the evidence base in a discipline or field. By providing a systematic approach to locating, evaluating, and synthesizing evidence, systematic reviews can provide valuable insight to intervention effectiveness, assist in developing conceptual frameworks, and pointing out gaps in the body of knowledge.

**Resources**

The following links are resources mentioned in the article.

**Systematic Review Guides and Standards**

- Cochrane Handbook: www.cochrane-handbook.org
- Systematic Review Guide by Margaret Foster: guides.library.tamu.edu/systematicreviews
- PRISMA standards: www.prisma-standard.org
- The Community Guide: www.thecommunityguide.org
- AHRQ Evidence-Based Reports: www.ahrq.gov/research/findings/evidence-based-reports

**Systematic Review Databases**

- Cochrane Library: www.thecochranelibrary.com
- TRIP: www.tripdatabase.com
• Health Evidence: www.healthevidence.org
• PubMed Health: www.pubmedhealth.com

**Systematic Review Software/Tools**

• Agency for Healthcare Research and Quality (AHRQ) Systematic Review Data Repository (SRDR): srdr.ahrq.gov/
• Cochrane’s Review Manager (Revman): imscochrane.org/revman
• Joanna Briggs Institute (SUMARI): www.joannabriggs.org/SUMARI
• RIGOR spreadsheet by Margaret Foster: guides.library.tamu.edu/rigor

**Implications for Practice**

• The systematic review process is a research method that is a study of studies with five main steps: define, search, select, data abstraction, and synthesis.

• When conducted following appropriate standards, systematic reviews provide valuable evidence based syntheses with minimal bias.

• Understanding how to critically analyze a systematic review article is an important skill in evidence-based practice.

• This article describes the process of systematic reviews as well as example and resource lists to guide review authors through the steps.

**References**


Eden, J., Levit, L., Berg, A., Morton, S. (Eds.), Committee on Standards for Systematic Reviews of Comparative Effectiveness Research, & Institute of Medicine. (2011). *Finding what works in


