The role of the healthcare environment in the spread of multidrug-resistant organisms: update on current best practices for containment

Roy F. Chemaly, Sarah Simmons, Charles Dale, Jr, Shashank S. Ghantoji, Maria Rodriguez, Julie Gubb, Julie Stachowiak and Mark Stibich

Therapeutic Advances in Infectious Disease published online 28 July 2014
DOI: 10.1177/2049936114543287

Ther Adv Infect Dis
(2010) 0(0) 1–12
DOI: 10.1177/2049936114543287

The role of the healthcare environment in the spread of multidrug-resistant organisms: update on current best practices for containment

Roy F. Chemaly, Sarah Simmons, Charles Dale, Shashank S. Ghantoji, Maria Rodriguez, Julie Gubb, Julie Stachowiak and Mark Stibich

***Abstract*:** The role of the environment in harboring and transmitting multidrug-resistant organisms has become clearer due to a series of publications linking environmental contamination with increased risk of hospital-associated infections. The incidence of antimicrobial resistance is also increasing, leading to higher morbidity and mortality associated with hospital-associated infections. The purpose of this review is to evaluate the evidence supporting the existing methods of environmental control of organisms: environmental disinfection, contact precautions, and hand hygiene. These methods have been routinely employed, but transmission of multidrug-resistant organisms continues to occur in healthcare facilities throughout the country and worldwide. Several new technologies have entered the healthcare market that have the potential to close this gap and enhance the containment of multidrug-resistant organisms: improved chemical disinfection, environmental monitoring, molecular epidemiology, self-cleaning surfaces, and automated disinfection systems. A review of the existing literature regarding these interventions is provided. Overall, the role of the environment is still underestimated and new techniques may be required to mitigate the role that environmental transmission plays in acquisition of multidrug-resistant organisms.

***Keywords*:** Disinfection, Environmental Cleaning, MDROs, No-Touch Disinfection, Best Practices

Correspondence to:
Roy F. Chemaly, MD, MPH, FIDSA, FACP
Department of Infectious Diseases, Infection Control and Employee Health, Unit 402, The University of Texas MD Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, TX 77030-4009, USA
rfchemaly@mdanderson.org

Sarah Simmons, MPH
Charles Dale, Jr, BA
Xenex Healthcare Services, San Antonio, TX, USA

Shashank S. Ghantoji, MD, MPH
Department of Infectious Diseases, Infection Control, and Employee Health, The University of Texas MD Anderson Cancer Center, Houston, TX, USA

Maria Rodriguez, RN, BSN
Julie Gubb, BS
Julie Stachowiak, MIA MPH, PhD
Mark Stibich, MHS, PhD
Xenex Healthcare Services, San Antonio, TX, USA

The patient environment in healthcare settings has continually proven to harbor a reservoir of potentially harmful, and even lethal multidrug-resistant organisms (MDROs). Increased interest in the prevention of hospital-acquired infections has led to a renewed interest in tackling this growing problem for three primary reasons: a number of studies have been published not only describing the contamination of patient environments, but also linking that contamination to an increase in the risk of healthcare-associated infections (HAIs) [Fisher *et al.* 2012; Weinstein, 1991; Carling and Huang, 2013; Otter *et al.* 2013]; pathogens associated with HAIs are causing increases in mortality and morbidity due to antimicrobial resistance [Harris, 2008]; and changes in reimbursement for HAIs have caused healthcare facilities to explore environmental interventions for the reduction of HAIs [McGlone *et al.* 2012; Stone *et al.* 2010].

In this review, we summarize the data linking contamination in the environment to an increased risk of HAIs, the issues in current practices addressing the environment and the spread of MDROs, and finally, we examine emerging technologies that address enhanced environmental cleaning and outcomes. It is not meant to be a comprehensive review, but rather to shed some light on the breadth of complexity when considering the role of the environment in the spread and control of MDROs and the issues with current practices.

The link between the environment and the risk of HAIs

Survival in the environment

It is well established that pathogens can survive in healthcare environments for long periods of time [Otter and French, 2009; Kramer *et al.* 2006;

Table 1. Summary of survival time *versus* prior room occupancy risk for healthcare-associated infections.

Organism	Survival time*	Prior room occupancy risk increase[$]
MRSA	7 days to >12 months	1.5
VRE	5 days to >46 months	2.25
Pseudomonas aeruginosa	6 h to 16 months	1.75
Clostridium difficile	>5 months (spores)	2.5
Acinetobacter baumannii	3 days to 11 months	3.5
CRE	19 days	
Norovirus (feline calicivurus)	8 h to 7 days	Limited data
Rotavirus	6–60 days	Limited data

Adapted from Kramer *et al.* [2006], Otter *et al.* [2013], and Havill *et al.* [2014].
*Survival times of multidrug-resistant organisms (MDROs) on dry inanimate objects. Range depends on experimental design and methods of assessing contamination.
[$]Ratio of increased risk associated with the room being previously occupied by patients infected with common MDROs.

Smith *et al.* 1996]. The exact survival times of different pathogens vary depending on the conditions being tested, with factors such as temperature and humidity playing a role. Under conditions likely to occur in healthcare facilities, *Clostridium difficile* spores, vancomycin-resistant *Enterococcus* (VRE), methicillin-resistant *Staphylococcus aureus* (MRSA) and *Acinetobacter baumannii* have been recovered after 4–5 months [Otter *et al.* 2011], with endospores typically lasting longer than vegetative bacteria [Otter and French, 2009]. Additional studies on the survival time of MDROs in the environment are available [Wendt *et al.* 1998; Huang *et al.* 2006a; Jawad *et al.* 1998; Havill *et al.* 2014], with a summary in Table 1.

Presence of MDROs in the patient care environment

There are numerous studies demonstrating the presence of MDROs in the patient care environment. These studies typically focus on MRSA, VRE, and *C. difficile*; however, *Acinetobacter* and norovirus are also frequently sampled. Contamination levels have been found that exceed the number of bacteria or virons necessary for the transmission of the organisms [Otter *et al.* 2013]. While it is not known whether the contamination levels on any individual surface will exceed the number of organisms necessary to be transmitted or cause disease, the summation of contamination in a room can pose a significant hazard to the next patient. This summation of contamination is particularly relevant when considered in conjunction with extended survival times of MDROs on hard surfaces. Multiple studies have demonstrated the presence of pathogens in the environment [Getchell-White *et al.* 1989; French *et al.* 2004; Dubberke *et al.* 2007; Dumford *et al.* 2009]; in one, MRSA was cultured from 43% of beds of individuals not known to be MRSA positive [French *et al.* 2004], and in another, VRE was cultured from 13% of surfaces in rooms of patients not known to be colonized with VRE [Trick *et al.* 2002]. Byers and colleagues concluded that 16% of hospital room surfaces contained VRE-positive samples, even though standard terminal cleaning protocols for rooms with a previous VRE-positive occupant had been followed [Byers *et al.* 1998]. Most likely, this contamination of rooms of unaffected patients is due to viability of organisms shed by previous occupants [French *et al.* 2004; Drees *et al.* 2008; Hardy *et al.* 2006], but it could also be due to horizontal transmission from healthcare workers, visitors or asymptomatic carriers [Riggs *et al.* 2007], as well as migration of the organisms through air flow or other means [Creamer *et al.* 2014; Edmiston *et al.* 2005]. For patients with clinical infection with MRSA or VRE, the frequency of environmental contamination with these organisms correlates with the number of culture-positive body sites [Rohr *et al.* 2009; Bonten *et al.* 1996; Boyce *et al.* 2007]. These patients may also shed more pathogens than those who are only colonized, especially if they have diarrhea, which may result in widespread contamination [Boyce *et al.* 1997, 2007; Boyce, 2007].

Prior room occupancy risk

Prior room occupancy risk is defined as the risk conferred to a new patient based on the characteristics of the patient who occupied the room before. As expected, the presence of a positive

culture for a given pathogen from the prior occupant of the room places the subsequent occupant at higher risk for acquisition of the same pathogen [Otter *et al.* 2013; Drees *et al.* 2008; Huang *et al.* 2006b; Nseir *et al.* 2011; Shaughnessy *et al.* 2011]. Since there is no direct contact between the two patients, this risk is associated with the environment. The VRE colonization status of the prior occupant, for example, is predictive for an increase in VRE colonization risk to the subsequent occupant [Drees *et al.* 2008; Nseir *et al.* 2011]. In a 14-month surveillance study across two intensive care units (ICUs), patients in rooms with previous VRE-colonized occupants were three times more likely to acquire VRE as those whose rooms did not house a colonized patient [Drees *et al.* 2008]. This pattern is also true for MRSA. Among 10,000 patients with a previous MRSA-positive infected or colonized room occupant, 3.9% acquired MRSA colonization compared with 2.9% for non-MRSA-positive rooms [Huang *et al.* 2006b]. Of patients who acquired *C. difficile* infection (CDI) after ICU admission, 11% had a CDI-positive prior room occupant compared with 4.6% who did not ($p = 0.002$) [Shaughnessy *et al.* 2011]. Furthermore, Huang *et al.* [2006c] found that admission to a room previously occupied by a patient with an MDRO increased the risk of the next patient by 40%. It is important to note that this increase in risk can affect not only patients admitted to rooms in which the prior occupants tested positive for a pathogen but also other patients in the facility and even patients in other facilities in a network [Lee *et al.* 2011]. Table 1 shows a summary of the additional risk attributed to the prior room occupant for a number of organisms.

These risks identified above represent vertical transmission of pathogens within an institution. Methods of assessing horizontal transmission continue to evolve with new applications of existing technologies. New tools are deployed to understand the interrelation between HAIs, the environment, and the sources of risk. For example, using molecular epidemiologic techniques, such as polymerase chain reaction, the identification of clonal types within species can be quantified [Bhalla *et al.* 2004]. This has led to the discovery of outbreaks in situations in which no indications were present by using standard infection control surveillance and definitions [Carling and Bartley, 2010].

The use of these techniques to explore clonal repetition can potentially provide new insight into the spread of pathogens within a healthcare facility over time in addition to infection control practices. It is expected that, at some point, molecular epidemiological techniques will be deployed in a routine fashion to provide insight into the transmission of organisms within a facility.

Impact of enhanced cleaning on HAIs

The risk of disease transmission attributable to contaminated surfaces in the patient environment such as bed rails, handles, and grab bars has been well defined, and there has been a clear demonstration that enhancing environmental disinfection of high-touch surfaces can lead to a decrease in HAI rates. Improved cleaning thoroughness and enhanced cleaning methods can lead to a reduction in the acquisition of HAIs. These methods include utilizing checklists to ensure that high-touch surfaces are cleaned first, double cleaning of rooms, and the addition of cleaners dedicated to high-touch surfaces [Boyce, 2007; Donskey, 2013; Dancer, 2009]. Many infection prevention guidelines have recommended the use of routine hypochlorite disinfection in place of standard disinfection to prevent transmission of *C. difficile*. A study of two medical wards treating older people found that the use of hypochlorite was associated with a significant decrease in hospital-associated *C. difficile* [Wilcox *et al.* 2003]. Furthermore, a study looking at the use of hypochlorite in ICUs found that it was effective at reducing infection rates when used for all discharge cleaning, and when used only for cleaning *C. difficile* isolation rooms [McMullen *et al.* 2007].

Issues with current practices

Compliance with routine and terminal cleaning

In multiple studies, researchers marked high-touch surfaces in rooms with a marker visible only under ultraviolet (UV) light in order to determine whether the surfaces had been cleaned [Carling *et al.* 2008a, 2008b, 2010]. In one of those studies, 1404 surfaces in 157 patient rooms were checked after routine cleaning, and only 47% of the surfaces had actually been cleaned [Carling *et al.* 2006b]. This result reflects the inability of hospital cleaning staff to consistently and systematically clean a room owing to time pressure, training issues, high turnover rate and other difficulties.

Equipment

The impact of the contamination of mobile medical equipment such as intravenous poles, carts, and documentation stations has not been well studied. Best-practice guidelines related to portable medical equipment recommend disinfection between uses [Healthcare Infection Control Practices Advisory Committee, 2003]. The contamination of these types of equipment and the recovery of MDROs such as MRSA on the equipment's surfaces have been documented [Havill *et al.* 2011]. A systematic review of 23 studies showed that 86.8% of equipment was found to be contaminated, with an average of 82.1 colonies per surface, with known pathogens such as MRSA, *Pseudomonas* spp. and *Acinetobacter* spp. [Schabrun and Chipchase, 2006]. Furthermore, environmental sampling for *C. difficile* spores revealed that around 20% of mobile equipment was contaminated, including pulse oximeters, medication carts, and barcode scanners [Dumford *et al.* 2009]. Interestingly, contamination of medical equipment has also been tied to outbreaks of MDRO infections. For example, VRE outbreaks have been linked to contamination of rectal thermometers, ear thermometers, and electrocardiogram leads [Falk *et al.* 2000; Livornese *et al.* 1992; Porwancher *et al.* 1997], and an MRSA outbreak in a head and neck surgery center in the Netherlands was linked to contamination of ultrasonic nebulizers [Schultsz *et al.* 2003].

Current cleaning practices are often inconsistent for mobile medical equipment, with uncertainty between the nursing and environmental staff on cleaning roles, cleaning frequency, and cleaning methods. Recently, the Joint Commission has placed an increased focus on identifying clean and dirty equipment [Joint Commission, 2010].

Clothing and hand-held electronics

The clothing of healthcare workers (i.e. white coats, ties, and jackets) and gadgets (i.e. pagers, tablets, and other devices) may play a role in the spread of microorganisms, mainly MDROs. The presence of microorganisms on these items has been well documented [Munoz-Price *et al.* 2012; Singh *et al.* 2002; Goldblatt *et al.* 2007; Lopez *et al.* 2009]. Recently, the Society for Healthcare Epidemiology of America issued new guidelines to reduce the use of white coats in the clinical setting [Bearman *et al.* 2014]. Like mobile medical equipment, current cleaning practices for garments are often infrequent and inconsistent. However, the link between contamination on these items and HAIs has not yet been established.

Cloth surfaces

Upholstered furnishings are becoming increasingly common in patient-care areas as hospitals seek to reduce the patient's perception of the hospital as a clinical environment. As a result, many surfaces have been introduced to patient rooms without adequate training or processes in place to assure the successful disinfection or cleaning of those surfaces. For example, curtains are often only laundered when visibly soiled. It is still unknown how much the contamination of these materials can cause horizontal spread of organisms through the hands of healthcare workers or act as a reservoir for these organisms [Trillis *et al.* 2008].

Solution/wipe contamination and improper application

Components of the cleaning process can rapidly become contaminated themselves. Bucket-based cleaning tools and fluids become contaminated rapidly and potentially serve as a point of transfer of pathogens from one surface to another [Healthcare Infection Control Practices Advisory Committee, 2003]. Additionally, many disinfectants require the mixing of different chemicals on site. Errors in the process lead to reduced efficacy and potential hazard for cleaning staff [Sarwar *et al.* 2004; Singer *et al.* 2006]. Mop heads and wipes, if not used correctly, also become contaminated and potentially spread pathogens from surface to surface. This has led to adoption of disposable cleaning items, such as disposable wipes. However, some studies have shown that wipes themselves can become contaminated, especially if not used according to manufacturer's instructions. This often occurs when environmental workers use one wipe to disinfect multiple surfaces, or a greater surface area than recommended by the manufacturer [Sattar, 2010].

There is also the risk of contamination of hands when performing hand hygiene. Contamination of soap has been reported [Sartor *et al.* 2000], as well as contamination of the sink area [Doring *et al.* 1996]. One academic center removed all automatic faucets from their facility because of contamination of the aerators [Hargreaves *et al.* 2001].

Acquired resistance to disinfectants

The persistent pressure of disinfectants on the microorganisms present in the environment may lead to the development of resistance. Many organisms already possess intrinsic resistance to common disinfectants and acquired resistance through plasmid mediated transmission is becoming more common [McDonnell and Russell, 1999]. Recurrent exposure of bacteria to chlorhexidine has been linked to higher levels of resistance [Block and Furman, 2002]. Concern about resistance to triclosan, as well as unsupported marketing claims, has led to a US Food and Drug Administration ban of the chemical [Halden, 2014]. With the rapid emergence of resistance to disinfectant, it may be prudent to assess efficacy of the disinfectant used in the facility against common clinical isolates [Kawamura-Sato *et al.* 2010].

Contact precautions

Contact precautions and using personal protective equipment for patients on isolation have long been a primary means of containing pathogens to a limited environment within a facility. Recent controversy suggests that contact precautions isolation may have no impact on hospital-associated MRSA infections [Gasink and Brennan, 2009; Abad *et al.* 2010], but other data contradict that finding [Healthcare Infection Control Practices Advisory Committee, 2007]. Patients in contact isolation are significantly less likely to have interactions with their healthcare providers for the duration of their isolation [Evans *et al.* 2003]. This decrease in provider contact is an additional argument for reassessing the routine use of isolation precautions. Additional strategies, such as decolonization of patients with chlorohexidine bath [Climo *et al.* 2013], can reduce the risk of transmission of MDROs potentially by reducing the bioburden of pathogens in the environment. Additional research into the cost effectiveness of contact precautions, routine screening, and decolonization is merited.

Hand hygiene/environment connection

International guidelines recommend performing hand hygiene procedures after coming into contact with surfaces in the patient environment [Boyce and Pittet, 2002; WHO, 2009]. In one study, hand imprint cultures were positive for one or more pathogens after contacting surfaces near 34 of 64 patients (53%) in occupied rooms and in 6 of 25 rooms (24%) that had been cleaned after patient discharge. *S. aureus* and VRE were the most common organisms isolated. All 12 of the VRE isolates were identified as *Enterococcus faecium* and 7 (35%) of the *S. aureus* isolates were MRSA strains [Bhalla *et al.* 2004].

The addition of antimicrobial chemicals to hand hygiene products was an effective method for enhancing bacteriostatic activity. However, over time, organisms have developed resistance to chemicals such as chlorhexidine and triclosan [Block and Furman, 2002; Goroncy-Bermes and Schouten, 2001]. While alcohol-based hand rubs are effective and have not shown any evidence of inducing bacterial resistance [Kampf and Kramer, 2004], they are not as effective as soap and water for hand washing for elimination of bacterial spores from the skin [Weber *et al.* 2003].

Suboptimal compliance with appropriate hand hygiene has been well documented. Overall, healthcare worker compliance with hand hygiene is around 40% [Boyce and Pittet, 2002]. Studies have also shown that the average hand hygiene event does not last for the recommended 15–20 s [WHO, 2009]. To better track and administer hand hygiene programs, electronic monitoring systems have been implemented. These systems use a variety of techniques to assess compliance, and reporting and behavior correction can occur in real time [Boyce, 2011]. The accuracy of electronic monitoring systems continues to improve and their use in hospitals may become more appealing.

Beyond the guidelines: emerging technologies

As more attention is focused on HAI reduction and the role of the environment in transmission, a number of technologies are emerging to reduce the risk derived from the microbial reservoir in patient care areas. Many of these technologies have been proven effective in the laboratory setting, but have an unknown impact on facility-wide HAI rates.

New disinfectant claims

Multiple products have emerged with new disinfectant claims, mostly centered on *C. difficile* spore kill times. Special consideration should be given to the mechanism of delivery of the disinfectant to the targeted surface and the required contact time for the chemical. Some application methods may not adequately moisten a surface for the entire contact time and long contact

times may not be achievable due to the time pressures in the healthcare environment [Carling and Huang, 2013]. As we have seen above, human factors result in a high percentage of high-touch surfaces being missed in typical disinfection; that fact and the compliance of housekeeping with the use of any disinfectant, including the correct mixing of chemicals, are important factors when evaluating new products.

Environmental monitoring

Improving manual disinfection compliance can be accomplished, to a degree, through enhanced monitoring of the environmental workers [Carling and Huang, 2013]. Many facilities have deployed these technologies to comply with Joint Commission Standards 2013 EC.04.01.03.EP2: 'results of data analysis [are used to] identify [and correct] opportunities to resolve environmental safety issues'. Available from http://www.jointcommission.org/Standards/ (accessed March 19, 2014).

Such practice has relied on a visual assessment of cleanliness; however, studies have identified no correlation between the visual assessment and a significant decrease in the microbiological contamination level [Carling, 2008; Carling *et al.* 2006a]. As a result, the visual assessment is considered an inadequate measure of monitoring environmental contamination.

More commonly accepted measures for environmental monitoring include environmental surface sampling, fluorescent marking systems and adenosine triphosphate (ATP) monitoring [Guh and Carling, 2010; Rutala and Weber, 2008]. These methods are effective because they provide immediate feedback and educational opportunities for the cleaning staff. Continuing education and reinforcement of cleaning techniques, in conjunction with environmental monitoring, is critical for providing a clean healthcare environment [Carling and Huang, 2013].

Environmental surface sampling is the current Centers for Disease Control and Prevention recommendation; however, this sampling is limited to times of outbreak rather than part of a routine practice [Sehulster and Chinn, 2003]. This protocol may change as specific sampling techniques, such as a polymerase chain reaction based system, become affordable and quick to identify. A third measure for assessment of cleanliness is ATP monitoring; however, more evidence that effectively correlates ATP levels and environmental contamination is needed [Carling and Huang, 2013].

Self-disinfecting surfaces

Surfaces with self-disinfecting properties have been emerging in the marketplace. These surfaces use a variety of approaches to achieve disinfection, including antimicrobial copper, titanium dioxide coatings, and other technologies [Salgado *et al.* 2013; Schmidt *et al.* 2013; Li *et al.* 2006]. The efficacy of these surfaces has been demonstrated in the laboratory, but the slow kill times and selective use of antimicrobial surfaces in hospitals have yet to show a proven impact on HAIs. Additionally, there is concern that resistance to these surfaces may develop over time as organisms are exposed to the antimicrobial mechanism over long periods. As more of these surfaces are used in healthcare settings, data will indicate whether they are effective or cost effective.

Automated disinfection systems

Enhanced environmental disinfection has been shown to have a significant impact on HAI rates [Donskey, 2013]. These enhanced cleaning methods have typically relied on additional manpower or a change in cleaning chemicals. Over the past several years, a number of automated disinfection systems that use hydrogen peroxide or UV light have entered the market. These systems vary greatly in their disinfection methods and application in the healthcare environment.

There are three commercially available technologies for the automated disinfection of rooms in healthcare environments: hydrogen peroxide vapor, mercury UV light and pulsed xenon UV light. All three technologies have been deployed in hospitals.

Economic justifications for facilities considering these types of systems should be based not only on the capital cost of the systems, but also on projected avoided costs associated with prevented infections. These projections and their costs should be based on the available medical literature. As pay for performance metrics for hospitals continue to change, the cost effectiveness of these systems may increase.

Hydrogen peroxide vapor

Hydrogen peroxide is an effective antimicrobial agent that functions by generating hydroxyl

Table 2. Reductions of healthcare-associated infections associated with automated room disinfection systems.

Disinfection technology	Organism	Reported reduction	Reference
Hydrogen peroxide vapor with additional bleach cleaning	*C. diff.*	37% ($p < 0.0001$)	Manian *et al.* [2013]
Hydrogen peroxide vapor	VRE	0.20 IRR ($p < 0.001$)	Passaretti *et al.* [2013]
	MRSA	No significant reduction	Passaretti *et al.* [2013]
	MDR-GNB	No significant reduction	Passaretti *et al.* [2013]
	C. diff.	No significant reduction	Passaretti *et al.* [2013]
Pulsed xenon UV	MRSA	57% ($p = 0.001$)	Simmons *et al.* [2013]
Pulsed xenon UV	*C. diff.*	53% ($p = 0.01$)	Levin *et al.* [2013]
Pulsed xenon UV	MDROs	15% ($p = 0.04$)	Haas *et al.* [2014]

C. diff., *Clostridium difficile*; IRR, incidence rate ratio; MDR-GNB, multidrug-resistant gram-negative bacilli; MDRO, multidrug resistant organism; MRSA, methicillin-resistant *Staphylococcus aureus*; VRE, vancomycin-resistant enterococcus.

radicals and other cytotoxic oxygen species. These reactive molecules interact with the cell walls and DNA of organisms, leading to irreparable damage or cell lysis. Hydrogen peroxide systems are placed in empty patient rooms; they discharge a vapor of hydrogen peroxide, which fills the room, disinfecting on contact with surfaces. There is ample evidence of the efficacy of HPV on common hospital environmental organisms [Otter and French, 2009; Boyce *et al.* 2008]. However, existing literature on the reduction of HAIs is limited (Table 2).

This vapor poses a potential health risk to humans; exposure can lead to irritation of the eyes, nose, throat, and lungs [BioQuell, 2010]. Because of this risk, certain measures need to be taken to appropriately seal the room prior to use of the disinfection system. This preparation includes sealing of doors and windows, as well as ventilation intakes and returns. Failure to appropriately seal the room can result in leakage of the product that exceeds recommended short-term exposure limits [Fu *et al.* 2012]. In addition, the time required completing the sealing and disinfection process ranges from 1.5 to 4 h, depending on the size of the room [Passaretti *et al.* 2013; Boyce *et al.* 2008; Havill *et al.* 2012; Holmdahl *et al.* 2011; Manian *et al.* 2013].

Mercury ultraviolet

Mercury systems generate monochromatic UV light, with the majority of the emitted light occurring at a wavelength of 254 nm [Harm, 1980; Rutala *et al.* 2010]. This wavelength of light is able to induce pyrimidine dimers in the DNA of organisms [Harm, 1980; Wang, 1976]. However, the optimum wavelength for producing pyrimidine dimers is 265 nm [Harm, 1980; Wang, 1976], which means that mercury systems induce dimers at a slower rate than the lower frequency light [Kowalski, 2009]. Published data regarding efficacy and disinfection times for mercury systems have shown reductions in vegetative organisms such as MRSA and VRE with approximately 15 min of exposure and reductions in *C. difficile* spores with approximately 100 min of exposure [Rutala *et al.* 2010; Boyce *et al.* 2011]. As with hydrogen peroxide systems, there are safety concerns associated with the use of UV light. Direct, prolonged exposure to UV light can result in a temporary irritation of the cornea and conjunctiva of the eye [Kowalski, 2009; Cullen, 2002]. The risk of exposure is mitigated by the use of motion sensors that shut off the device.

Pulsed xenon ultraviolet

The alternative method for production of UV light is through pulsed xenon flash lamps. These lamps utilize xenon gas to generate broad-spectrum, high-intensity UV light. Pulsed xenon technology emits light throughout the germicidal spectrum, ranging from 200 to 280 nm [Boyce *et al.* 2011]. As with mercury-based systems, xenon systems achieve deactivation of pathogens by inducing thymine dimers [Boyce *et al.* 2011]. Because pulsed xenon emits UV throughout the germicidal spectrum, it is able to induce dimers with optimum efficiency. This broad-spectrum light also allows pulsed xenon light to deactivate bacteria with three unique mechanisms: photosplitting, the creation of single- or double-strand breaks in the DNA; photohydration, the addition of a water molecule across a carbonyl group of a DNA base; and

photocrosslinking, which causes abnormal bonding activity in proteins [Harm, 1980; Wang, 1976; Kowalski, 2009]. These additional mechanisms of action allow for more rapid deactivation of pathogens. Studies on the disinfection times for pulsed xenon UV show reductions for *C. difficile* spores and vegetative organisms within 5 min [Simmons *et al.* 2013; Stibich *et al.* 2011]. Safety concerns related to pulsed xenon UV are the same as those for mercury systems. As with the mercury systems, these risks are mitigated by implementing motion sensors that shut off the device.

When utilizing UV light for disinfection, regardless of type, it is critical to consider the enhanced efficacy associated with direct line of sight. Reflected light has been found to be substantially less effective than direct light at eliminating pathogens [Rutala *et al.* 2010; Boyce *et al.* 2011]. Separate areas such as bathrooms have been found to receive insufficient levels of disinfection when the only disinfection cycle occurs in the main patient room [Boyce *et al.* 2011]. To account for the poorer disinfection efficacy of reflected light, multiple positions are necessary when utilizing a UV system.

All of these systems have demonstrated an ability to reduce contamination levels in the environment. Of interest is whether this environmental reduction translates into a reduction in HAI rates. Table 2 summarizes the published data regarding infection reductions associated with use of automated disinfection systems.

Conclusion

It has been demonstrated that pathogens can survive in and be recovered from healthcare environments. Further, the risk of HAIs can be linked to the prior room occupant and lessened through environmental interventions. The issues with current practices identified here are not meant to be a comprehensive list of gaps, but rather to broaden and stimulate thinking about how the environment interacts with pathogens to produce risk for patients.

The patient environment has not received the same level of focused attention from infectious diseases researchers and infection preventionists as other areas. Now that many facilities have established good infection control practices, it is likely that additional HAI reductions will come from outside the current practices, through interventions such as automated room disinfection or molecular epidemiological investigations of clonal spread of specific pathogens.

The environment should be considered a substantial factor in infection control practices, and resources should be directed to improving our understanding of the interaction of pathogen survival, disinfection, hand hygiene, and HAI risk.

Funding

This research is supported in part by the National Institutes of Health through MD Anderson's Cancer Center Support Grant CA016672.

Conflict of interest statement

RFC is a consultant for Xenex Healthcare Services; SS, CDJ, MR, JG, JS and MS are employees of Xenex Healthcare Services; SSG has no competing financial interest to declare.

Acknowledgment

The authors thank Ms Sunita C. Patterson of MD Anderson Cancer Center for editorial support.

References

Abad, C., Fearday, A. and Safdar, N. (2010) Adverse effects of isolation in hospitalised patients: a systematic review. *J Hosp Infect* 76: 97–102.

Bearman, G., Bryant, K., Leekha, S., Mayer, J., Munoz-Price, L., Murthy, R. *et al.* (2014) Healthcare personnel attire in non-operating-room settings. *Infect Control Hosp Epidemiol* 35: 107–121.

Bhalla, A., Pultz, N., Gries, D., Ray, A., Eckstein, E., Aron, D. *et al.* (2004) Acquisition of nosocomial pathogens on hands after contact with environmental surfaces near hospitalized patients. *Infect Control Hosp Epidemiol* 25: 164–167.

BioQuell. (2010) *Material Safety Data Sheet*, 1st edition edn, BioQuell: Andover.

Block, C. and Furman, M. (2002) Association between intensity of chlorhexidine use and microorganisms of reduced susceptibility in a hospital environment. *J Hosp Infect* 51: 201–206.

Bonten, M., Hayden, M., Nathan, C., van Voorhis, J., Matushek, M., Slaughter, S. *et al.* (1996) Epidemiology of colonisation of patients and environment with vancomycin-resistant enterococci. *Lancet* 348: 1615–1619.

Boyce, J. (2007) Environmental contamination makes an important contribution to hospital infection. *J Hosp Infect* 65: 50–54.

Boyce, J. (2011) Measuring healthcare worker hand hygiene activity: current practices and emerging technologies. *Infect Control Hosp Epidemiol* 32: 1016–1028.

Boyce, J., Havill, N. and Moore, B. (2011) Terminal decontamination of patient rooms using an automated mobile UV light unit. *Infect Control Hosp Epidemiol* 32: 737–742.

Boyce, J., Havill, N., Otter, J. and Adams, N. (2007) Widespread environmental contamination associated with patients with diarrhea and methicillin-resistant Staphylococcus aureus colonization of the gastrointestinal tract. *Infect Control Hosp Epidemiol* 28: 1142–1147.

Boyce, J., Havill, N., Otter, J., McDonald, L., Adams, N., Cooper, T. *et al.* (2008) Impact of hydrogen peroxide vapor room decontamination on Clostridium difficile environmental contamination and transmission in a healthcare setting. *Infect Control Hosp Epidemiol* 29: 723–729.

Boyce, J. and Pittet, D. (2002) Guideline for hand hygiene in health-care settings. *Am J Infect Control* 30: 1–46.

Boyce, J., Potter-Bynoe, G., Chenevert, C. and King, T. (1997) Environmental contamination due to methicillin-resistant Staphylococcus aureus: possible infection control implications. *Infect Control Hosp Epidemiol* 18: 622–627.

Byers, K., Durbin, L., Simonton, B., Anglim, A., Adal, K. and Farr, B. (1998) Disinfection of hospital rooms contaminated with vancomycin-resistant Enterococcus faecium. *Infect Control Hosp Epidemiol* 19: 261–264.

Carling, P. (2008) Evaluating the thoroughness of environmental cleaning in hospitals. *J Hosp Infect* 6: 273–274.

Carling, P. and Bartley, J. (2010) Evaluating hygienic cleaning in health care settings: what you do not know can harm your patients. *Am J Infect Control* 38: S41–S50.

Carling, P., Briggs, J., Hylander, D. and Perkins, J. (2006a) An evaluation of patient area cleaning in 3 hospitals using a novel targeting methodology. *Am J Infect Control* 34: 513–519.

Carling, P., Briggs, J., Perkins, J. and Highlander, D. (2006b) Improved cleaning of patient rooms using a new targeting method. *Clin Infect Dis* 42: 385–388.

Carling, P. and Huang, S. (2013) Improving healthcare environmental cleaning and disinfection: current and evolving issues. *Infect Control Hosp Epidemiol* 34: 507–513.

Carling, P., Leander, J., Bartley, J. and Herwaldt, L. (2010) Identifying opportunities to improve environmental hygiene in multiple healthcare settings. In: *Public Health and Community Medicine Papers*. SHEA 2010 Decennial, Atlanta, GA, USA.

Carling, P., Parry, M., Rupp, M., Po, J., Dick, B. and Von Beheren, S. (2008a) Improving cleaning of the environment surrounding patients in 36 acute care hospitals. *Infect Control Hosp Epidemiol* 29: 1035–1041.

Carling, P., Parry, M. and Von Beheren, S. (2008b) Identifying opportunities to enhance environmental cleaning in 23 acute care hospitals. *Infect Control Hosp Epidemiol* 29: 1–7.

Climo, M., Yokoe, D., Warren, D., Perl, T., Bolon, M., Herwaldt, L. *et al.* (2013) Effect of daily chlorhexidine bathing on hospital-acquired infection. *N Engl J Med* 368: 533–542.

Creamer, E., Shore, A., Deasy, E., Galvin, S., Dolan, A., Walley, N. *et al.* (2014) Air and surface contamination patterns of methicillin-resistant Staphylococcus aureus on eight acute hospital wards. *J Hosp Infect* 86: 201–208.

Cullen, A. (2002) Photokeratitis and other phototoxic effects on the cornea and conjunctiva. *Int J Toxicol* 21: 455–464.

Dancer, S. (2009) The role of environmental cleaning in the control of hospital-acquired infection. *J Hosp Infect* 73: 378–385.

Donskey, C. (2013) Does improving surface cleaning and disinfection reduce health care-associated infections? *Am J Infect Control* 41: S12–S19.

Doring, G., Jansen, S., Noll, H., Grupp, H., Frank, F., Botzenhart, K. *et al.* (1996) Distribution and transmission of Pseudomonas aeruginosa and Burkholderia cepacia in a hospital ward. *Pediatr Pulmonol* 21: 90–100.

Drees, M., Snydman, D., Schmid, C., Barefoot, L., Hansjosten, K., Vue, P. *et al.* (2008) Prior environmental contamination increases the risk of acquisition of vancomycin-resistant enterococci. *Clin Infect Dis* 46: 678–685.

Dubberke, E., Reske, K., Noble-Wang, J., Thompson, A., Killgore, G., Mayfield, J. *et al.* (2007) Prevalence of Clostridium difficile environmental contamination and strain variability in multiple health care facilities. *Am J Infect Control* 35: 315–318.

Dumford, D. 3rd, Nerandzic, M., Eckstein, B. and Donskey, C. (2009) What is on that keyboard? Detecting hidden environmental reservoirs of Clostridium difficile during an outbreak associated with North American pulsed-field gel electrophoresis type 1 strains. *Am J Infect Control* 37: 15–19.

Edmiston, C., Seabrook, G., Cambria, R., Brown, K., Lewis, B., Sommers, J. *et al.* (2005) Molecular epidemiology of microbial contamination in the operating room environment: is there a risk for infection? *Surgery* 138: 573–579, discussion 579-582.

Evans, H., Shaffer, M., Hughes, M., Smith, R., Chong, T., Raymond, D. *et al.* (2003) Contact isolation in surgical patients: a barrier to care? *Surgery* 134: 180–188.

Falk, P., Winnike, J., Woodmansee, C., Desai, M. and Mayhall, C. (2000) Outbreak of vancomycin-resistant

enterococci in a burn unit. *Infect Control Hosp Epidemiol* 21: 575–582.

Fisher, C., Fiorello, A., Shaffer, D., Jackson, M. and McDonnell, G. (2012) Aldehyde-resistant mycobacteria bacteria associated with the use of endoscope reprocessing systems. *Am J Infect Control* 40: 880–882.

French, G., Otter, J., Shannon, K., Adams, N., Watling, D. and Parks, M. (2004) Tackling contamination of the hospital environment by methicillin-resistant Staphylococcus aureus (MRSA): a comparison between conventional terminal cleaning and hydrogen peroxide vapour decontamination. *J Hosp Infect* 57: 31–37.

Fu, T., Gent, P. and Kumar, V. (2012) Efficacy, efficiency and safety aspects of hydrogen peroxide vapour and aerosolized hydrogen peroxide room disinfection systems. *J Hosp Infect* 80: 199–205.

Gasink, L. and Brennan, P. (2009) Isolation precautions for antibiotic-resistant bacteria in healthcare settings. *Curr Opin Infect Dis* 22: 339–344.

Getchell-White, S., Donowitz, L. and Groschel, D. (1989) The inanimate environment of an intensive care unit as a potential source of nosocomial bacteria: evidence for long survival of Acinetobacter calcoaceticus. *Infect Control Hosp Epidemiol* 10: 402–407.

Goldblatt, J., Krief, I., Klonsky, T., Haller, D., Milloul, V., Sixsmith, D. *et al.* (2007) Use of cellular telephones and transmission of pathogens by medical staff in New York and Israel. *Infect Control Hosp Epidemiol* 28: 500–503.

Goroncy-Bermes, P. and Schouten, M. (2001) Voss A: in vitro activity of a nonmedicated handwash product, chlorhexidine, and an alcohol-based hand disinfectant against multiply resistant gram-positive microorganisms. *Infect Control Hosp Epidemiol* 22: 194–196.

Guh, A. and Carling, P. (2010) *Options for Evaluating Environmental Cleaning*, Environmental Evaluation Workgroup, Centers for Disease Control and Prevention: Atlanta, GA.

Haas, J., Menz, J., Dusza, S. and Montecalvo, M. (2014) Implementation and impact of ultraviolet environmental disinfection in an acute care setting. *Am J Infect Control* 42: 586–590.

Halden, R. (2014) On the need and speed of regulating triclosan and triclocarban in the United States. *Environ Sci Technol* 48: 3603–3611.

Hardy, K., Oppenheim, B., Gossain, S., Gao, F. and Hawkey, P. (2006) A study of the relationship between environmental contamination with methicillin-resistant Staphylococcus aureus (MRSA) and patients' acquisition of MRSA. *Infect Control Hosp Epideiol* 27: 127–132.

Hargreaves, J., Shireley, L., Hansen, S., Bren, V., Fillipi, G., Lacher, C. *et al.* (2001) Bacterial contamination associated with electronic faucets: a new risk for healthcare facilities. *Infect Control Hosp Epidemiol* 22: 202–205.

Harm, W. (1980) *Biological Effects of Ultraviolet Radiation*, Cambridge University Press: Cambridge.

Harris, A. (2008) How important is the environment in the emergence of nosocomial antimicrobial-resistant bacteria? *Clin Infect Dis* 46: 686–688.

Havill, N., Boyce, J. and Otter, J. (2014) Extended survival of carbapenem-resistant Enterobacteriaceae on dry surfaces. *Infect Control Hosp Epidemiol* 35: 445–447.

Havill, N., Havill, H., Mangione, E., Dumigan, D. and Boyce, J. (2011) Cleanliness of portable medical equipment disinfected by nursing staff. *Am J Infect Control* 39: 602–604.

Havill, N., Moore, B. and Boyce, J. (2012) Comparison of the microbiological efficacy of hydrogen peroxide vapor and ultraviolet light processes for room decontamination. *Infect Control Hosp Epidemiol* 33: 507–512.

Healthcare Infection Control Practices Advisory Committee. (2003) *Guidelines for Environmental Infection Control in Health-Care Facilities*, US Department of Health and Human Services Centers for Disease Control and Prevention: Atlanta, GA.

Healthcare Infection Control Practices Advisory Committee. (2007) *Guideline for Isolation Precautions: Preventing Transmission of Infectious Agents in Healthcare*, US Department of Health and Human Services Centers for Disease Control and Prevention: Atlanta, GA.

Holmdahl, T., Lanbeck, P., Wullt, M. and Walder, M. (2011) A head-to-head comparison of hydrogen peroxide vapor and aerosol room decontamination systems. *Infect Control Hops Epidemiol* 32: 831–836.

Huang, R., Mehta, S., Weed, D. and Price, C. (2006a) Methicillin-resistant Staphylococcus aureus survival on hospital fomites. *Infect Control Hosp Epidemiol* 27: 1267–1269.

Huang, S., Datta, R. and Platt, R. (2006b) Risk of acquiring antibiotic-resistant bacteria from prior room occupants. *Arch Intern Med* 166: 1945–1951.

Huang, S., Datta, R. and Platt, R. (2006c) Risk of acquiring antibiotic-resistant bacteria from prior room occupants. *Arch Intern Med* 166: 1945–1951.

Jawad, A., Seifert, H., Snelling, A., Heritage, J. and Hawkey, P. (1998) Survival of Acinetobacter baumannii on dry surfaces: comparison of outbreak and sporadic isolates. *J Clin Microbiol* 36: 1938–1941.

Joint Commission. (2010) It's all on the surface: establishing protocols for cleaning and disinfecting environmental surface areas. *Environment of Care News* 13: 6–11.

Kampf, G. and Kramer, A. (2004) Epidemiologic background of hand hygiene and evaluation of the most important agents for scrubs and rubs. *Clin Microbiol Rev* 17: 863–893.

Kawamura-Sato, K., Wachino, J., Kondo, T., Ito, H. and Arakawa, Y. (2010) Correlation between reduced susceptibility to disinfectants and multidrug resistance among clinical isolates of Acinetobacter species. *J Antimicrob Chemother* 65: 1975–1983.

Kowalski, W. (2009) *Ultraviolet Germicidal Irradiation Handbook: UVGI for Air and Surface Disinfection*, Springer: Berlin, Heidelberg.

Kramer, A., Schwebke, I. and Kampf, G. (2006) How long do nosocomial pathogens persist on inanimate surfaces? A systematic review. *BMC Infect Dis* 6: 130.

Lee, B., McGlone, S., Wong, K., Yilmaz, S., Avery, T., Song, Y. *et al.* (2011) Modeling the spread of methicillin-resistant Staphylococcus aureus (MRSA) outbreaks throughout the hospitals in Orange County, California. *Infect Control Hosp Epidemiol* 32: 562–572.

Levin, J., Riley, L., Parrish, C., English, D. and Ahn, S. (2013) The effect of portable pulsed xenon ultraviolet light after terminal cleaning on hospital-associated Clostridium difficile infection in a community hospital. *Am J Infect Control* 41: 746–748.

Li, Y., Leung, P., Yao, L., Song, Q. and Newton, E. (2006) Antimicrobial effect of surgical masks coated with nanoparticles. *J Hosp Infect* 62: 58–63.

Livornese, L. Jr, Dias, S., Samel, C., Romanowski, B., Taylor, S., May, P. *et al.* (1992) Hospital-acquired infection with vancomycin-resistant Enterococcus faecium transmitted by electronic thermometers. *Ann Intern Med* 117: 112–116.

Lopez, P., Ron, O., Parthasarathy, P., Soothill, J. and Spitz, L. (2009) Bacterial counts from hospital doctors' ties are higher than those from shirts. *Am J Infect Control* 37: 79–80.

Manian, F., Griesnauer, S. and Bryant, A. (2013) Implementation of hospital-wide enhanced terminal cleaning of targeted patient rooms and its impact on endemic Clostridium difficile infection rates. *Am J Infect Control* 41: 537–541.

McDonnell, G. and Russell, A. (1999) Antiseptics and disinfectants: activity, action, and resistance. *Clin Microbiol Rev* 12: 147–179.

McGlone, S., Bailey, R., Zimmer, S., Popovich, M., Tian, Y., Ufberg, P. *et al.* (2012) The economic burden of Clostridium difficile. *Clin Microbiol Infect* 18: 282–289.

McMullen, K., Zack, J., Coopersmith, C., Kollef, M., Dubberke, E. and Warren, D. (2007) Use of hypochlorite solution to decrease rates of Clostridium difficile-associated diarrhea. *Infect Control Hosp Epidemiol* 28: 205–207.

Munoz-Price, L., Arheart, K., Mills, J., Cleary, T., Depascale, D., Jimenez, A. *et al.* (2012) Associations between bacterial contamination of health care workers' hands and contamination of white coats and scrubs. *Am J Infect Control* 40: e245–e248.

Nseir, S., Blazejewski, C., Lubret, R., Wallet, F., Courcol, R. and Durocher, A. (2011) Risk of acquiring multidrug-resistant Gram-negative bacilli from prior room occupants in the intensive care unit. *Clin Microbiol Infect* 17: 1201–1208.

Otter, J. and French, G. (2009) Survival of nosocomial bacteria and spores on surfaces and inactivation by hydrogen peroxide vapor. *J Clin Microbiol* 47: 205–207.

Otter, J., Yezli, S. and French, G. (2011) The role played by contaminated surfaces in the transmission of nosocomial pathogens. *Infect Control Hosp Epidemiol* 32: 687–699.

Otter, J., Yezli, S., Salkeld, J. and French, G. (2013) Evidence that contaminated surfaces contribute to the transmission of hospital pathogens and an overview of strategies to address contaminated surfaces in hospital settings. *Am J Infect Control* 41: S6–S11.

Passaretti, C., Otter, J., Reich, N., Myers, J., Shepard, J., Ross, T. *et al.* (2013) An evaluation of environmental decontamination with hydrogen peroxide vapor for reducing the risk of patient acquisition of multidrug-resistant organisms. *Clin Infect Dis* 56: 27–35.

Porwancher, R., Sheth, A., Remphrey, S., Taylor, E., Hinkle, C. and Zervos, M. (1997) Epidemiological study of hospital-acquired infection with vancomycin-resistant Enterococcus faecium: possible transmission by an electronic ear-probe thermometer. *Infect Control Hosp Epidemiol* 18: 771–773.

Riggs, M., Sethi, A., Zabarsky, T., Eckstein, E., Jump, R. and Donskey, C. (2007) Asymptomatic carriers are a potential source for transmission of epidemic and nonepidemic Clostridium difficile strains among long-term care facility residents. *Clin Infect Dis* 45: 992–998.

Rohr, U., Kaminski, A., Wilhelm, M., Jurzik, L., Gatermann, S. and Muhr, G. (2009) Colonization of patients and contamination of the patients' environment by MRSA under conditions of single-room isolation. *Int J Hyg Environ Health* 212: 209–215.

Rutala, W., Gergen, M. and Weber, D. (2010) Room decontamination with UV radiation. *Infect Control Hosp Epidemiol* 31: 1025–1029.

Rutala, W. and Weber, D. (2008) *Guideline for Disinfection and Sterilization in Healthcare Facilities*, Centers for Disease Control and Prevention: Atlanta, GA.

Salgado, C., Sepkowitz, K., John, J., Cantey, J., Attaway, H., Freeman, K. *et al.* (2013) Copper surfaces reduce the rate of healthcare-acquired infections in the intensive care unit. *Infect Control Hosp Epidemiol* 34: 479–486.

Sartor, C., Jacomo, V., Duvivier, C., Tissot-Dupont, H., Sambuc, R. and Drancourt, M. (2000) Nosocomial Serratia marcescens infections associated with extrinsic contamination of a liquid nonmedicated soap. *Infect Control Hosp Epidemiol* 21: 196–199.

Sarwar, G., Olson, D., Corsi, R. and Weschler, C. (2004) Indoor fine particles: the role of terpene

emissions from consumer products. *J Air Waste Manag Assoc* 54: 367–377.

Sattar, S. (2010) Promises and pitfalls of recent advances in chemical means of preventing the spread of nosocomial infections by environmental surfaces. *Am J Infect Control* 38: S34–S40.

Schabrun, S. and Chipchase, L. (2006) Healthcare equipment as a source of nosocomial infection: a systematic review. *J Hosp Infect* 63: 239–245.

Schmidt, M., Attaway, H. III, Fairey, S., Steed, L., Michels, H. and Salgado, C. (2013) Copper continuously limits the concentration of bacteria resident on bed rails within the intensive care unit. *Infect Control Hosp Epidemiol* 34: 530–533.

Schultsz, C., Meester, H., Kranenburg, A., Savelkoul, P., Boeijen-Donkers, L., Kaiser, A. *et al.* (2003) Ultrasonic nebulizers as a potential source of methicillin-resistant Staphylococcus aureus causing an outbreak in a university tertiary care hospital. *J Hosp Infect* 55: 269–275.

Sehulster, L. and Chinn, R. (2003) CDC, HICPAC: Guidelines for environmental infection control in health-care facilities. Recommendations of CDC and the Healthcare Infection Control Practices Advisory Committee (HICPAC). *MMWR Recomm Rep* 52: 1–42.

Shaughnessy, M., Micielli, R., DePestel, D., Arndt, J., Strachan, C., Welch, K. *et al.* (2011) Evaluation of hospital room assignment and acquisition of Clostridium difficile infection. *Infect Control Hosp Epidemiol* 32: 201–206.

Simmons, S., Morgan, M., Hopkins, T., Helsabeck, K., Stachowiak, J. and Stibich, M. (2013) Impact of a multi-hospital intervention utilising screening, hand hygiene education and pulsed xenon ultraviolet (PX-UV) on the rate of hospital associated methicillin resistant Staphylococcus aureus infection. *J Infect Prev* 14: 172–174.

Singer, B., Destaillats, H., Hodgson, A. and Nazaroff, W. (2006) Cleaning products and air fresheners: emissions and resulting concentrations of glycol ethers and terpenoids. *Indoor Air* 16: 179–191.

Singh, D., Kaur, H., Gardner, W. and Treen, L. (2002) Bacterial contamination of hospital pagers. *Infect Control Hosp Epidemiol* 23: 274–276.

Smith, S., Eng, R. and Padberg, F. Jr (1996) Survival of nosocomial pathogenic bacteria at ambient temperature. *J Med* 27: 293–302.

Stibich, M., Stachowiak, J., Tanner, B., Berkheiser, M., Moore, L., Raad, I. *et al.* (2011) Evaluation of a pulsed-xenon ultraviolet room disinfection device for impact on hospital operations and microbial reduction. *Infect Control Hosp Epidemiol* 32: 286–288.

Stone, P., Glied, S., McNair, P., Matthes, N., Cohen, B., Landers, T. *et al.* (2010) CMS changes in reimbursement for HAIs: setting a research agenda. *Med Care* 48: 433–439.

Trick, W., Temple, R., Chen, D., Wright, M., Solomon, S. and Peterson, L. (2002) Patient colonization and environmental contamination by vancomycin-resistant enterococci in a rehabilitation facility. *Arch Phys Med Rehabil* 83: 899–902.

Trillis, F. 3rd, Eckstein, E., Budavich, R., Pultz, M. and Donskey, C. (2008) Contamination of hospital curtains with healthcare-associated pathogens. *Infect Control Hosp Epidemiol* 29: 1074–1076.

Wang, S. (1976) *Photochemistry and Photobiology of Nucleic Acids*, Elsevier: Amsterdam.

Weber, D., Sickbert-Bennett, E., Gergen, M. and Rutala, W. (2003) Efficacy of selected hand hygiene agents used to remove Bacillus atrophaeus (a surrogate of Bacillus anthracis) from contaminated hands. *JAMA* 289: 1274–1277.

Weinstein, R. (1991) Epidemiology and control of nosocomial infections in adult intensive care units. *Am J Med* 91: 179S–184S.

Wendt, C., Wiesenthal, B., Dietz, E. and Ruden, H. (1998) Survival of vancomycin-resistant and vancomycin-susceptible enterococci on dry surfaces. *J Clin Microbiol* 36: 3734–3736.

Wilcox, M., Fawley, W., Wigglesworth, N., Parnell, P., Verity, P. and Freeman, J. (2003) Comparison of the effect of detergent versus hypochlorite cleaning on environmental contamination and incidence of Clostridium difficile infection. *J Hosp Infect* 54: 109–114.

World Health Organization. (2009) *WHO Guidelines on Hand Hygiene in Health Care*, WHO: Geneva.