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REVIEW

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Hand and environmental hygiene: respective roles for MRSA, multi-resistant gram negatives, *Clostridioides difficile*, and *Candida* spp.

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Abstract

Healthcare-associated infections (HAIs) caused by multidrug-resistant organisms (MDROs) represent a global threat to human health and well-being. Because transmission of MDROs to patients often occurs via transiently contaminated hands of healthcare personnel (HCP), hand hygiene is considered the most important measure for preventing HAIs. Environmental surfaces contaminated with MDROs from colonized or infected patients represent an important source of HCP hand contamination and contribute to transmission of pathogens. Accordingly, facilities are encouraged to adopt and implement recommendations included in the World Health Organization hand hygiene guidelines and those from the Society for Healthcare Epidemiology of America/Infectious Diseases Society of America/Association for Professionals in Infection Control and Epidemiology. Alcohol-based hand rubs are efficacious against MDROs with the exception of *Clostridiodes difficile*, for which soap and water handwashing is indicated. Monitoring hand hygiene adherence and providing HCP with feedback are of paramount importance. Environmental hygiene measures to curtail MDROs include disinfecting high-touch surfaces in rooms of patients with *C. difficile* infection daily with a sporicidal agent such as sodium hypochlorite. Some experts recommend also using a sporicidal agent in rooms of patients colonized with *C. difficile*, and for patients with multidrug-resistant Gram-negative bacteria. Sodium hypochlorite, hydrogen peroxide, or peracetic acid solutions are often used for daily and/or terminal disinfection of rooms housing patients with *Candida auris* or other MDROs. Products containing only a quaternary ammonium agent are not as effective as other agents against *C. auris*. Portable medical equipment should be cleaned and disinfected between use on different patients. Detergents are not recommended for cleaning high-touch surfaces in MDRO patient rooms, unless their use is followed by using a disinfectant. Facilities should consider using a disinfectant instead of detergents for terminal cleaning of floors in MDRO patient rooms. Education and training of environmental services employees is essential in assuring effective disinfection practices. Monitoring disinfection practices and providing personnel with performance feedback using fluorescent markers, adenosine triphosphate assays, or less commonly cultures of surfaces, can help reduce MDRO transmission. No-touch disinfection methods such as electrostatic spraying, hydrogen peroxide vapor, or ultraviolet light devices should be considered for terminal disinfection of MDRO patient rooms. Bundles with additional measures are usually necessary to reduce MDRO transmission.

Keywords Hand hygiene, Environmental hygiene, Multidrug-resistant organisms, Alcohol-based hand rub, Cleaning, Disinfection

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Introduction

Infections caused by multidrug-resistant organisms (MDROs) represent a significant public health burden throughout the world, resulting in an estimated 1.27 million deaths attributable directly to MDROs [1]. Deaths attributable to MDROs were frequently caused by methicillin-resistant *Staphylococcus aureus* (MRSA), third-generation cephalosporin-resistant *Escherichia coli*, carbapenem-resistant *Acinetobacter baumannii* (CRAB), fluoroquinolone-resistant *E. coli*, carbapenem-resistant *Klebsiella pneumoniae* (CRKP), and third-generation cephalosporin-resistant *K. pneumoniae* [1]. Equally concerning is the increased prevalence in recent years of multidrug-resistant (MDR) *Pseudomonas aeruginosa*, extended spectrum ß-lactamase producing *Enterobacterales*, and MDR *C. auris* [2–11].

Although some progress had been made in reducing infections caused by MRSA, MDR *P. aeruginosa*, and carbapenem-resistant *Acinetobacter* in the years prior to the COVID-19 pandemic [2, 12], data from the United States revealed that MDRO infections among hospitalized patients increased considerably from 2019 to 2020 due to the pandemic [13]. The purpose of this paper is to review the respective roles of hand hygiene and environmental disinfection on prevention of infections caused by MRSA, multidrug-resistant Gram-negative bacteria, *C. difficile*, and *C. auris*.

Modes of hand transmission

Limiting transmission of MDROs to susceptible patients is the cornerstone of preventing infections due to these pathogens. Transmission of pathogens from one patient to another via contaminated hands of healthcare personnel (HCP) is a common means by which patients acquire nosocomial pathogens, and as a result, hand hygiene is considered the most important measure for preventing healthcare-acquired infections (HAIs) [14–16].

Indirect transmission of pathogens from one patient to another requires that several events must occur [15].

(1) Patients colonized or infected with healthcare-associated pathogens must have the organisms on their skin or in their secretions or excretions, or shed them onto environmental surfaces in their immediate vicinity.
(2) Pathogens on contaminated surfaces must survive for some time, often persisting for days to several weeks.
(3) Pathogens must be transferred from the patient or environmental surfaces to the hands or gloves of HCP and remain viable for at least several minutes.
(4) HCP must perform hand hygiene using suboptimal technique, use an ineffective antiseptic agent, or fail to perform hand hygiene when indicated.
(5) Contaminated hands of HCP must come in direct contact with another patient, or with an environmental surface that will subsequently come in contact with another patient.

Patients cared for in hospitals and post-acute care facilities are frequently colonized or infected with MDROs due to previous exposures to antibiotics [2, 9, 17–31]. Frequent colonizers include MRSA, vancomycin-resistant enterococci (VRE), multidrug-resistant Gram-negative bacteria (MDR-GNB); *C. difficile*, and *Candida* spp., with *C. auris* becoming common in recent years.

Affected patients/residents are usually colonized at multiple body sites with MDROs such as MRSA [17, 21, 32–34], MDR-GNB [17], *C. difficile* infection (CDI) [35, 36], and *Candida* spp. [4, 7, 29, 30, 37]. Common sites include the groin, rectum, abdomen, chest, forearms and hands.

Patients colonized or infected with MDROs shed skin squames containing pathogens and contaminate objects in their immediate surroundings that are frequently touched by HCP (so-called high-touch surfaces [HTSs]), the floor in the vicinity of their bed, their toilet, and portable reusable equipment [3, 7, 8, 15, 17, 28, 34, 36, 38–47]. Commonly contaminated sites include bedside rails, bedside tables, intravenous pumps, and supply carts [37, 38, 41, 42, 48–52]. The greater the level of MDRO colonization of a patient's skin and other body sites, the greater the degree of environmental contamination with MDROs such as MDR-*Acinetobacter* and *C. auris* [24, 37, 53]. Patients whose hands are colonized with MDROs may serve as a reservoir for environmental contamination [17, 34].

The level of surface contamination is often greatest in contact precautions (isolation) rooms housing patients with MDROs: some studies reported a frequency of 9.8–90% [34, 36, 38, 41, 43, 54]. Lower contamination rates occur in non-contact precaution patient rooms and other patient care areas [43, 44, 46, 54]. The percentage of contact precautions rooms contaminated with one or more MDROs was 40–71% in several studies [38, 41, 42, 55]. Mobile patient care equipment may also become contaminated with MDROs, including *C. auris* [7, 8, 45, 56, 57]. Asymptomatic *C. difficile* carriers are significantly less likely to have skin colonization and/or shed organisms into their environment [58], but can still be a source of transmission to other patients [59]. Rectal, perianal or stool colonization alone can increase the risk of transmission of pathogens such as *A. baumannii* and MRSA [52, 60, 61]. Patients with diarrhea and concomitant gastrointestinal colonization or infection with pathogens such as *C. difficile*, MRSA, or VRE are especially likely to contaminate their immediate environment and the gloves of HCPs [38, 58, 62–65].

Clostridiodes difficile spores and MRSA often cause extensive contamination of dry surfaces [21, 28, 34, 38, 43, 63]. Some studies cite low rates of environmental contamination by MDR-GNB, [66] while others have documented substantial environmental contamination by carbapenem-resistant Enterobacteriaceae (CRE) and MDR-AB [41, 67, 68]. MDR-GNB such as *P. aeruginosa* are frequently recovered from moist surfaces such as sinks, which are increasingly recognized as a source of MDR-GNB colonization and infection [69–72]. *Candida* spp., including *C. auris*, have also been recovered from environmental surfaces in healthcare settings [3, 7, 73, 74].

MDROs including MRSA, MDR-GNB (especially *A. baumannii*), *C. difficile*, and *Candida* spp. (including *C. auris*) can survive on dry surfaces for varying time periods, ranging from several days to weeks or months [73, 75–81]. As a result, contaminated surfaces can be a source of pathogen transmission to patients [28].

Hands and/or gloves of HCP frequently become contaminated during patient care activities [15, 27, 82–84]. This can occur following either contact with the patient's skin or with surfaces near the patient. Direct contact with a patient's colonized skin can transfer pathogens including Gram-negative bacteria, MRSA and *C. difficile* to the hands of HCP [35, 38, 50, 84–89]. Hand contacts with other surfaces also occur frequently, as often as every 4.2 s in some intensive care unit settings, with touching mobile objects or immobile surfaces accounting for a majority of the hand-to-surface contacts [90]. Not surprisingly, contact with contaminated environmental surfaces can also result in contamination of the hands or gloves of HCP [15, 27, 42, 47–49, 51, 83, 91–96]. Wolfensberger et al. [83] found that the average rates of transfer of MDROs following contact with patients or their environment to hands and gloves were 33% and 30%, respectively.

A review of 59 studies by Montoya et al. [84] found that the frequency of hand contamination among HCP varies by pathogen, with following pooled prevalence rates [and ranges] having been reported: MRSA (4.3% [0–39.5%]), vancomycin-resistant enterococci (9.0% [0–55.3%]), *Pseudomonas* spp. (4.6% [0–28.3%]) and *Acinetobacter* spp. (6.2% [0.6–28.6%]), with hand contamination by *C. difficile* varying from 0 to 10.7%.

Others have reported higher rates of *C. difficile* hand contamination among HCP, varying from 14 to 59% [38, 62, 87, 92]. *Candida spp*. not uncommonly contaminates the hands of HCP [97–100]. HCP hand contamination by *C. auris* has been reported, but may not be as common as with other species [6, 101, 102]. The risk of HCP hand contamination depends on part on the type and duration of patient care provided, the presence of invasive devices, and the extent of environmental contamination [27, 38, 103, 104]. The greater the extent of environmental contamination, the greater the risk of contamination of HCP hands [38]. Caring for patients colonized or infected with MDROs also frequently results in contamination of the gloves of HCP [82, 83, 105–108]. Hands may become contaminated despite wearing gloves, and may occur during glove removal, with a frequency ranging from 2.6 to 29% [65, 87, 105–107, 109].

Staphylococcus aureus, Gram-negative bacteria, *C. difficile* and *Candida* spp. can survive on human skin for enough of time to permit possible transmission from contaminated hands. Some pathogens survive on skin for at least several minutes, while others survive for 1 h or longer [77, 110–116]. Transmission from contaminated hands to patients or environmental surfaces may occur if HCP do not perform appropriate hand hygiene when indicated [16], fail to perform hand hygiene, or if contaminated gloves are not removed after contact and are used when caring for a subsequent patient. Evidence of transmission of pathogens from contaminated hands is exemplified by outbreaks due to multidrug-resistant *Staphylococcus epidermidis*, *Citrobacter diversus*, *Pseudomonas aeruginosa*, *Serratia marcescens*, *K. pneumoniae*, and *C. tropicalis* [15, 117–126]. Most of the above-mentioned outbreaks were due to persistent colonization of HCP fingernails or hand dermatitis. Although transient contamination of HCP hands is infinitely more common, documenting individual instances of transmission is much more difficult.

When patients are mobile, modeling studies utilizing silicon nanoparticles with encapsulated DNA provide evidence that pathogens colonizing a patient's skin can be transmitted indirectly to another patient following mutual contact with contaminated surfaces, such as toilet seats [127]. Pathogens can also be transmitted indirectly from one patient to another if contaminated surfaces are not adequately disinfected. Multiple studies have demonstrated that inadequate disinfection of rooms following a patient's discharge puts patients subsequently admitted to the same room at increased risk of acquiring pathogens harbored by the preceding occupant [128].

Measures to prevent hand transmission of MDROs

Prevention and control of MDROs requires implementing a bundle of measures, with bundles varying in content depending on the target pathogens, as outlined in published guidelines and review articles [8, 129–135]. Strategies to improve hand hygiene are frequently included in such bundles, since poor hand hygiene compliance often contributes to transmission of MDROs [11, 135–137].

The 2009 WHO hand hygiene guidelines and those recently published by the Society for Healthcare Epidemiology of America (SHEA)/Infectious Diseases Society of America (IDSA)/Association for Professionals in Infection Control and Epidemiology (APIC) both outline policies and practices designed to reduce transmission of healthcare-associated pathogens of all types, including MDROs [16, 138]. Accordingly, healthcare facilities are encouraged to adopt and implement recommendations included in the WHO or SHEA/IDSA/APIC hand hygiene guidelines [16, 138]. The combination of implementing the WHO multimodal strategy, promoting the use of alcohol-based hand rub (ABHR) as the preferred method of hand hygiene, and promoting the WHO 5 Moments for Hand Hygiene indications for hand hygiene have been shown to yield higher compliance rates [139, 140]. And implementing multimodal hand hygiene strategies has been shown to contribute to the reduction of HAIs due to MDROs [141–145].

ABHR is preferred method for hand hygiene against almost all pathogens, including MDROs such as MRSA, MDR-GNB, and *C. auris* [16, 138, 146, 147]. For preventing infections caused by pathogens with reduced susceptibility to ABHR (e.g., *C. difficile* and norovirus), there remains some debate regarding the role of AHBR due to mixed data regarding ABHR efficacy against norovirus based on product formulation and test methodology [148], and because the relative difference in the effectiveness between approved ABHRs and soap and water handwashing on *C. difficile* or norovirus is based solely on laboratory data. Routine use of gloves followed by hand hygiene after glove removal are recommended when caring for patients with *C. difficile* infection [138]. During outbreaks of *C. difficile* or norovirus infections, washing with soap and water is preferred when caring for patients with known or suspected infections [16, 138, 149]. However, ABHR should continue to be readily available when caring for patients with *C. difficile* or norovirus infections during outbreaks [138], and can be useful when used as an adjunct to soap and water handwashing during outbreaks [148, 150]. A few outbreaks of norovirus in hospitals have been controlled by using primarily ABHR with 80–95% ethanol for hand hygiene in conjuction with other measures [151, 152]. A large number of studies provide a solid evidence base showing that long-term use of ABHR is associated with reductions in HAIs [142, 153–156]. Despite its poor activity against *C. difficile* spores, prolonged use of ABHR has not been associated with an increase *C. difficile* infections [154, 157–160].

Based on in vitro data, it may be prudent to avoid hand antiseptics containing 1% chloroxylenol or chlorhexidine (without alcohol) when caring for patients with *C. auris* [146]. Although there is some concern about whether ABHR gel and foam products are sufficiently efficacious [161–165], several studies have concluded that well-formulated ABHR gel and foam products that meet efficacy standards are acceptable for use in healthcare settings [166–169]. A recent literature review failed to identify evidence demonstrating that one format (rinse, gel, or foam) is significantly more effective in preventing transmission of healthcare-associated pathogens or HAIs [170]. The updated SHEA/IDSA/APIC guidance states that liquid, gel and foam ABHRs with at least 60% alcohol are acceptable for use [138]. Facilities should identify and correct deficiencies in hand hygiene infrastructure, such as lack of adequate numbers of readily accessible ABHR dispensers [171, 172]. Increasing the availability of ABHR dispensers and increasing ABHR consumption have been associated with reduction of MDROs [8, 173, 174].

Facilities should also devote greater attention to hand hygiene technique [175]. Errors in hand hygiene technique include applying an inadequate (i.e., low) volume of ABHR on hands, rubbing hands together for too short a time, failure to cover all surfaces adequately, failure to perform hand hygiene after glove removal, and applying ABHR to gloves [11, 175]. Some facilities may choose to promulgate a simplified 3-step procedure (versus the WHO six-step method) for performing hand hygiene using an ABHR as an approach to improving technique and increasing hand hygiene compliance [176]. Additional research is needed to identify the optimum method for applying ABHR on hands [177].

Monitoring HCP performance combined with timely feedback is an essential element of multimodal programs to improve hand hygiene, and can identify trends in compliance rates and areas of suboptimal compliance [16, 138, 142]. Direct observation of HCP by validated observers continues to be the gold standard method, although there is some evidence that automated hand hygiene monitoring systems may be a useful adjunctive strategy [138, 175, 177]. Practical methods for specifically monitoring hand hygiene technique during routine patient care activities are needed [175].

Environmental hygiene strategies for prevention of MDRO infections

The important role of the environment in transmission of HAIs and the need for cleaning and disinfection of environmental surfaces are well-established [72, 178–182]. There is substantial evidence that cleaning and disinfecting environmental surfaces (often accompanied by additional interventions) can reduce patient colonization and/or HAIs in general, and importantly, infections caused by MDROs [11, 183–186]. Despite the availability of guidance on environmental hygiene programs, considerable variability in implementation exists between different facilities [187, 188]. General elements of a multimodal program, as outlined in several articles, are listed below [182, 184, 189, 190].

Policies/procedures

Daily application of a disinfectant to HTSs in contact precautions/isolation rooms of patients with MDRO infections is recommended in acute care settings [131, 132, 147, 182, 183, 191, 192]. Because surfaces are frequently contaminated in rooms of patients colonized with MDROs and in rooms without known MDRO patients [54, 193], some experts recommend daily disinfection of HTSs in all patient rooms [54, 182, 183, 190, 192, 194]. Daily use of disinfectants has been shown to reduce MDRO contamination of HCP hands [91], has contributed to reducing MDRO infections in several studies and may reduce MDRO prevalence in long-term care facilities [183, 195]. Policies should state if disinfection of HTSs in MDRO patient rooms should be performed more than once/day [196], a practice adopted in some hospitals [183, 197–199].

Instructions for daily and terminal cleaning and disinfection should include recommendations regarding the number of cloths or wipes to be used per room and when to change mop heads [182]. Reusable buckets used to contain liquid disinfectants should be cared for following manufacturer recommendations to avoid contamination with Gram-negative bacteria [200–202]. Portable equipment such as digital thermometers, temperature probes, ultrasound probes and wheelchairs should be disinfected between use on different patients [7, 45, 183].

Lack of clarity among HCP regarding who is responsible for cleaning and disinfection of HTSs and portable equipment is a relatively common problem. It has been identified as a potential cause of suboptimal environmental hygiene [147, 179]. Accordingly, engaging EVS staff and nursing personnel in formulating detailed policies regarding who is responsible for cleaning various surfaces and products to be used can help rectify misconceptions among personnel [183, 184, 203, 204].

Terminal cleaning and disinfection of rooms vacated by patients with MDROs is recommended to reduce the risk of MDRO infection among patients subsequently admitted to the rooms [128, 131, 182, 183, 191]. Facility policies should address whether "no-touch" disinfection devices (e.g., ultraviolet (UV) light and automated hydrogen peroxide systems) are to be used, an issue of ongoing debate [192, 205, 206]. Administrators need to provide adequate financial resources, sufficient EVS staff, and appropriate personal protective equipment, and foster a culture that recognizes the essential services provided by EVS personnel. Providing EVS staff with incentives, opportunities for certification, higher pay may improve morale and personnel retention [207, 208].

Cleaning & disinfection products and procedures

Physical wiping surfaces with a neutral detergent can remove some microorganisms, including *C. difficile* spores [209]. However, detergents are not only less effective than disinfectants in reducing MDROs [210, 211], but can transfer MDROs (including *C. difficile*) from one surface to another [212].

Detergents have commonly been used for cleaning floors, in part because floors have not been considered potential sources of transmission [182, 187]. However, there is continuing debate about whether floors should be cleaned with a detergent or a disinfectant [192, 213]. Evidence in favor of using disinfectants instead of detergents on floors include the following: use of detergents may actually increase colony counts on floors [214, 215]; floors are frequently contaminated with MDROs and can be a potential source of transmission to patients [38, 41, 46, 213, 216], and that using a disinfectant with two or more disposable mop heads per room reduced MRSA, *C. difficile* and *Candida* spp. on floors [45]. As a result, facilities may want to consider using a disinfectant for terminal cleaning of floors in patient rooms [45, 192].

Disinfectants available for use in healthcare settings include products containing alcohol, chlorine-releasing agents (e.g., sodium hypochlorite "bleach", sodium dichloroisocyanurate), quaternary ammonium compounds alone or combined with alcohol, improved hydrogen peroxide, phenolics, peracetic acid/hydrogen peroxide, dodecylbenzenesulfonic acid, and glucoprotamin [101, 217, 218]. Factors to be considered when selecting disinfectants for use in healthcare facilities have been summarized by Rutala et al. [182]. In-use concentrations of common disinfectants are effective against most healthcare-associated pathogens, with a few notable exceptions [182, 192, 219]. Sporicidal agents are recommended for disinfection of *C. difficile* infection patient rooms [191, 192, 220]. Facility policies should also stipulate if sporicidal agents are also used for daily and/or terminal cleaning of rooms of patients colonized with *C. difficile*, and patients colonized or infected with MDR-GNB or *C. auris* [3]. Some disinfectants with quaternary ammonium compounds as the only active agent are not as effective as other disinfectants against *C. auris* [146, 221], suggesting that products with demonstrated high potency against *C. auris* may be preferable for disinfection of rooms housing patients with *C. auris*. Sodium hypochlorite, hydrogen peroxide, and peracetic acid solutions are commonly used for decontaminating surfaces contaminated with *C. auris*. In the United States, the Environmental Protection Agency has posted a list of disinfectants (List P) that are appropriate for use against *C. auris* [222]. Exposing *C. auris* to 1000 ppm sodium hypochlorite yielded suboptimal reduction (e.g., 1.3–1.6 $\log_{10}$) in several studies, suggesting that higher concentrations should be considered [146, 223].

Pre-impregnated disinfectant wipes have been shown to be effective in reducing total colony counts and MDRO bioburden on surfaces [218, 224–227]. A prospective cluster-controlled crossover trial found that a pre-impregnated hydrogen peroxide-based wipe was significantly better than a quaternary ammonium-based disinfectant at reducing total colony counts on surfaces, and reduced colonization and infection by MDRO pathogens to a greater extent, although the difference between disinfectants did not reach statistical significance [228].

Education and training

Education and training of HCP regarding environmental cleaning and disinfection of HTSs, common areas, mobile equipment and reusable equipment are essential elements of multimodal strategies to reduce transmission of healthcare-associated pathogens, including MDROs [130, 147, 190, 229]. EVS staff should receive specific education and training regarding the types of disinfectant in use, methods of application, frequency and sequence of disinfection, list of HTSs, and the importance of following manufacturers' instructions regarding contact times and dilutions, if warranted [185, 190, 195].

One hospital implemented standardized education of EVS staff, validating the knowledge and cleaning competency of new EVS personnel, annual assessment of room-cleaning skills of all EVS personnel and other quality improvement measures, resulting in a significant increase in surface cleaning performance and a sustained reduction of *C. difficile* infection rates over a period of 10 years [230]. Hospital staff involved in use of "no-touch" devices must be adequately trained on how to operate the devices, and ideally receive periodic competency evaluations [231].

Monitoring cleaning and disinfection and feedback

Monitoring the effectiveness of cleaning/disinfection procedures and providing EVS and nursing personnel with feedback are essential for preventing infections caused by MDROs and other pathogens [130, 135, 147, 185, 232]. Methods for monitoring the effectiveness of cleaning and disinfection practices include visual assessments of cleanliness, the use of overt or covert direct observation of EVS staff, fluorescent markers, adenosine triphosphate (ATP) assays, and culture methods [181, 233, 234]. The advantages and limitations of the various methods are summarized in the following Table 1.

When using either fluorescent markers or ATP assays, involving infection prevention personnel in assessment of disinfection practices is advisable, since having EVS personnel monitor performance may yield exaggerated compliance rates [230, 233, 245].

No-touch technologies

The rationale for considering the use of supplemental no-touch methods include that fact that up to 55% of surfaces in rooms vacated by patients with MRDOs may still be contaminated following terminal disinfection, and that such residual contamination puts subsequent patients at increased risk of acquiring an MDRO [28, 128]. Recently, electrostatic spray devices used to deliver liquid disinfectants to an area have been shown to reduce healthcare-associated pathogens on fixed surfaces and mobile equipment [206]. Automated decontamination systems include devices that emit hydrogen peroxide vapor (HPV), aerosols of hydrogen peroxide (aHP) or peracetic acid, continuous ultraviolet light (UV-C), or pulsed broad-spectrum UV light [246]. All the above types of devices have been shown to reduce the bioburden of pathogens on surfaces. However, they vary in terms of their ability to reduce pathogens on all surfaces in hospital rooms and pathogen-specific $\log_{10}$ reductions achieved [247]. Although several reviews have concluded that these devices can reduce transmission of healthcare-associated pathogens and/or reduce HAIs, controversy still exists regarding their effectiveness (and cost-effectiveness) and the practicality of their use [147, 205, 206, 246–248].

Of the methodologies mentioned above, HPV produces the greatest $\log_{10}$ reductions of pathogens and yields the most homogeneous levels of disinfection [247]. HPV has been shown to reduce *C. difficile* infection and VRE acquisition, and appears to have contributed to control of outbreaks due to MRSA, CRE, MDR *Enterobacter cloacae* and *C. auris* [3, 249–251]. A prospective controlled trial found that terminal disinfection of patient rooms reduced patient acquisition of MDROs by 64% [247, 252]. Systems using aHP have been shown to reduce the bioburden of MDR-GNB, MRSA, VRE, *C. difficile* and *C. auris* on environmental surfaces, and when used in conjunction with other measures, resulted in a significant reduction in MRSA infections [247]. Currently, no randomized controlled trials have evaluated the efficacy of HPV or aHP to reduce HAIs.

Continuous or pulsed xenon UV light devices reduced hospital-associated *C. difficile* infection (HA-CDI) and HAIs due to MRSA,VRE and MDR Gram-negatives in most before-after studies [247, 253]. In a

Table 1 Advantages and limitations of strategies for monitoring environmental hygiene

Method	Advantages	Limitations
Visual assessments [181, 233, 234]	Possible in all facilities; does not require special equipment; requires less time than other methods; direct observation of and feedback to EVS personnel are possible	Cannot detect residual surface contamination
Direct observation of EVS personnel [229, 235–237]	Can identify suboptimal technique; has contributed to reduction of MDRO transmission	Time consuming; not feasible in some circumstances
Fluorescent markers [46, 179, 181, 190, 230, 233–235, 238, 239]	Multiple studies support its use. Has been shown to improve cleaning compliance rates, reduce surface contamination, nosocomial transmission, and HAIs caused by MDROs. Can provide useful feedback to EVS staff	Complete marker removal does not assure elimination of MDROs from surface; EVS staff occasionally use black light to identify marked surfaces and prioritize those surfaces. Somewhat time-consuming, unless a representative sample of surfaces is selected
Adenosine triphosphate (ATP) assays [179, 181, 233, 234, 236, 240–243]	Can provide immediate feedback to EVS staff and identify variations in cleaning practices. Associated with improved cleaning practices during CRE and CRAB outbreaks; may be useful in monitoring disinfection of CDI patient rooms. Associated with greater reduction of MDRO colonization/infection than fluorescent markers in a cluster-randomized trial	Detects both microorganisms and other organic material; poor correlation between ATP readings and level of microbial contamination; results may vary depending on microbe present. Some disinfectants may cause falsely low assay results. Relatively expensive
Culturing surfaces [8, 28, 46, 54, 67, 181, 229, 233, 241, 244]	Can identify pathogens, including MDROs, on surfaces before and after routine disinfection. Swabs, sponges, contact plates and dip slides can be used to sample surfaces	Requires additional laboratory capabilities; results not available for 24–72 h; relatively expensive; requires the use of a neutralizer if surfaces have been disinfected with a product with residual activity

ATP—adenosine triphosphate; CDI—*C. difficile* infection; CRE—carbapenem-resistant Enterobacteriaceae; CRAB—carbapenem-resistant *Acinetobacter baumannii*; EVS—environmental services personnel; HAIs—healthcare-associated infections; MDRO—multidrug-resistant organisms multicenter cross-over cluster-randomized controlled trial that compared adding UV-C disinfection to standard disinfection methods, terminal room disinfection using UV-C reduced the incidence of hospital-wide *C. difficile* and VRE, but not *Acinetobacter* spp. or MRSA [254]. In contrast, in a single-center crossover cluster-randomized controlled trial performed in a hospital's four cancer and one solid organ transplant units, daily and terminal room UV-C disinfection did not significantly reduce *C. difficile* or VRE infection rates [248].

Limitations of no-touch technologies include their acquisition costs, cycle time impact on room turnaround times, ease of use, personnel time required to deploy them, the inability to use them in occupied patient rooms, and limited evidence of their ability to reduce HAIs. Accordingly, facilities need to consider the level of their standard cleaning/disinfection proficiency, costs and operational issues of using no-touch systems, and level of MDRO transmission in making decisions regarding their use [192, 206].

Enhanced environmental hygiene strategies include sporicidal disinfectants for MDR-GNB or *C. auris*, increased disinfection frequency (e.g., 2–3 times/day), adding EVS staff, use of specific check lists, removal of implicated contaminated equipment, certification of terminal room disinfection by infection control personnel, which may be combined with antimicrobial stewardship [7, 135, 199, 240, 255–257].

Additional strategies frequently combined with measures to improve hand hygiene and environmental hygiene include contact precautions for patients infected (and in some instances colonized) with MDROs, placing affected patients in isolation or cohorting them, and bathing them with chlorhexidine soap [7, 137, 194, 240, 255]. Surveillance cultures are used to identify patients with unrecognized colonization with certain MDROs such as MDR-GNRs and *C. auris* [7, 101, 137, 255].

In conclusion, implementing bundles that have improved hand hygiene and environmental hygiene has been successful in reducing transmission of MDROs and related HAIs [7, 135, 194, 199, 240, 256].

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Author informations
The author was lead co-author of the CDC Guideline for Hand Hygiene in Health-care Settings, and a contributor to the WHO Guidelines on Hand Hygiene in Health Care, and has published numerous articles dealing with hand hygiene, environmental disinfection, and methods for monitoring cleaning/disinfection of surfaces in hospitals.

Author contributions
JMB conducted searches of the PubMed and Google Scholar databases for relevant articles, and reviewed all articles cited in the bibliography, which included many which were accumulated over a period of several decades while serving as an infectious diseases specialist and hospital epidemiologist. He prepared all versions, including the final version, of the manuscript.

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