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Touchless Technologies for Decontamination in the Hospital: a Review of Hydrogen Peroxide and UV Devices

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Abstract Reduction of microbial contamination of the hospital environment is a challenge, yet has potential impacts on infection prevention efforts. Fumigation and UV light devices for environmental cleaning have expanded into the health care setting with the goal of decontamination of difficult to clean or overlooked surfaces. In an era of increased scrutiny of hospital-acquired infections, increasingly, health care centers are adopting these "touchless" cleaning techniques as adjuncts to traditional manual cleaning. The evidence for improved clinical outcomes is lacking; yet, the experience with these devices continues to accumulate in the literature. We review the recently published data related to the use of hydrogen peroxide and UV light-based decontamination systems for cleaning of hospital rooms. Touchless cleaning technologies may provide an incremental benefit to standard practices by limiting cross-transmission of pathogens via environmental surfaces, though evidence of prevention of infections remains limited.

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Introduction

Reduction of microbial contamination in the hospital environment is an important component of an infection prevention strategy. This is especially true in an era of increased scrutiny on hospital-acquired infections and multidrug-resistant organisms. The burden of microbial contamination as identified in the literature depends on a variety of factors including culture methods, sites cultured, occupant characteristics, and cleaning practices used at the hospital; however, over 50 % of sites may remain untouched by conventional manual cleaning [1]. Flaws in traditional cleaning methods are more than aesthetic and can translate into very real patient risks. A patient admitted to a hospital room whose previous occupant had methicillin-resistant *Staphylococcus aureus* (MRSA), *Clostridium difficile*, or certain multidrug-resistant gram negative rods has a significantly increased risk of acquiring each of these pathogens [2–4]. Similar to many hospital-acquired infections, the absolute overall risk of acquisition remains low, though this may be of little comfort to patients who assume that a room is clean when they are admitted to it.

Touchless technologies attempt to overcome some of the deficiencies of manual cleaning by taking the human element out of the process. Touchless technologies encompass a wide range of products including self-disinfecting surfaces and fumigation methods. Self-disinfecting surfaces have been reviewed recently by Humphreys, and application in the clinical setting has been scantly reported in the literature to date [5].

Fumigation with gases or aerosolized compounds has long been employed as a decontamination strategy to protect food and water supplies [6]. More recent advances in delivery systems have allowed for the expansion of this technology to the health care system including patient care areas. Application of vapors for decontamination overcomes many of the limitations of traditional manual cleaning within the hospital environment, because of its ability to permeate or penetrate complex surfaces [7, 8], albeit with varying levels of uniformity [9]. While other gases such as chlorine dioxide and ozone are also potent decontamination agents, there is a decreased safety margin for both gases compared to hydrogen peroxide (HP) methods; limits of acceptable exposures in case of residual gas or room leakage are 1 ppm for HP compared to <0.1 ppm for chlorine dioxide and ozone [6, 8, 10, 11]. In addition, both chlorine dioxide and ozone require carefully controlled humidity and have corrosive properties that are problematic for hospital furnishings and equipment [6].

Thus, in general, hospitals using touchless technologies have used UV light and hydrogen peroxide, both of which have been reviewed in the literature previously [6–8, 12, 13]. However, as more health care centers gain experience with various devices, the body of evidence on these technologies continues to increase. We review the recently published data regarding UV light and hydrogen peroxide usage in cleaning the health care environment.

Search Strategy

PubMed was searched using the terms (UV-C OR UVC OR pulsed xenon OR UV light OR hydrogen peroxide) AND (cleaning OR disinfection OR infection OR decontamination). This search produced >7000 articles that were screened for relevance by title. Sixty-eight articles were selected as relevant to the use of HP or UV technologies in clinical settings; 47 of these were original research. Original research articles were further reviewed by abstract; bibliographies were also considered. Thirty-one studies published between 2012 and March 2015 were selected for full review, and 28 are included in the analysis below based on pertinence to application of UV/HP technologies in environmental cleaning of hospital rooms. Articles published prior to 2012 were selectively included in order to provide context to this review of the recent literature.

Killing Efficacy

UV light and HP systems have distinct properties (Table 1). In general, UV-based systems require less time and manual effort for set up and monitoring, at the cost of decreased efficacy of "in vitro" killing of bacteria.

Efficacy of UV light and HP touchless technologies are measured in two main ways: (1) in vitro experiments using carefully quantitated samples of experimentally placed bacteria and measuring log reductions in the colonies posttreatment and (2) "in vivo" experiments using actual patient rooms postdischarge. Surfaces are cultured before and after treatments to determine reduction in site contamination. It is important to note whether a reduction in contamination is being compared to a dirty room, or to the residual contamination in a room cleaned by standard methods. Some investigations employed both methods (Table 2). The devices and their corresponding studies are grouped in four main categories to facilitate the organization of the discussion that follows; however, each category contains distinct machine models, manufacturers, and protocols for use that are important to bear in mind in any attempt to compare these technologies.

Of the devices under study, vaporized HP, or HP vapor, produces the best log reduction in colony-forming units (CFUs) achieving essentially complete eradication of experimentally placed bacteria in a test space [14–16]. However, even with superior efficacy compared to other methods, evidence of residual contamination of site is present in the real-life setting [11, 17]. Of note, the study by Havill et al. demonstrates residual contamination of actual patient rooms even when the authors found complete eradication of experimentally placed *C. difficile* spores, calling into question whether experimentally inoculated surfaces are comparable to the results required in real contaminated patient rooms [17].

Aersolized HP can produce >5 log reductions, though a wide range (1 to >5) has been reported depending on the organism of interest and the experimental design [9, 18]. There is evidence of unequal dispersion of the aerosols through a space, such as dramatic variations of log reductions even in the same room [9] and increased time requirements to permeate certain spaces [18]. In addition, Fu et al. found decreased levels of aerosolized HP during cycles compared with vaporized HP at <50 ppm vs >100 pm at peak levels [9]. The decreased levels of aerosolized HP along with the distribution variations may be responsible for the decreased efficacy when compared to vaporized HP [9].

UV devices produce 3–5 log reductions depending on the type of organism and the experimental set up [19–23]. Some studies of UVC devices use clinically present bioburden as opposed to experimentally placed bacteria to measure log reductions with device usage. Such a design produces notably lower log reductions than those seen with experimentally placed bacteria, because the starting concentrations are vastly different. For example, UVC produced 1.1–1.7 log reductions in clinically contaminated rooms where starting CFUs were 3.2–4.5 log [24]. Position of device in relation to the room and equipment is of great importance, as one study found that only 2.2 log reductions overall, and 53 % of sites still contaminated after a cycle due largely to the failure of the UVC device to

Table 1 Comparison of hydrogen peroxide and UV light methods

Name and common abbreviations	Active formulation	Examples of commercially available units and manufacturers	Time per cycle	Advantages	Limitations[a]
Aerosolized hydrogen peroxide (aHP or aHPP)	Colloidal suspension of small particles: generally 1–10 μm depending on device, silver or peracetic acid additives	Glosair, Advanced Sterilization Products Deprox system, Deprox DXC-pert, Braincon Nocospray aHPP, Anios	3–4 h[b] [11, 18]	1–5 log reductions in bacterial colonies [9, 18], depending on organism	Rooms must be sealed with tape to prevent leakage of gas Ventilation systems must be disabled to prevent dispersion to other locations Evidence of nonuniform distribution of the aersol in a space [9], and potential for residual [11] Wide variation in log10 killing efficacy reported
Hydrogen peroxide vapor (HPV or VHP)	Pressure vaporized 30–35 % hydrogen peroxide	HPV, Bioquell VHP, Steris	1.5–4 h[c] [11, 14] device dependent[d]	>5–6 log10 reductions in bacterial colonies (near complete) [14–17, 9] Achieves uniformity in distribution in room for equal exposures of surfaces [9]	Rooms must be sealed with tape to prevent leakage of gas Ventilation systems must be disabled to prevent dispersion to other locations One report of 8 h for aeration of a VHP system when not using a catalyzer [15]
UV-C radiation (UVC)	Mercury UV lamps produce germicidal spectrum of UVC light 240–280, aiming for peak DNA disruption at 260 nm, at doses of 12,000–36,000 μWs/cm^2 [8]	TruD, Lumalier Pathogon, Steris V-360+, Ultraviolet Devices, Spectra254	20–40 min[e] [19–23]	2–4 log 10 reductions in bacterial colonies [19–23]	Requires moving of furniture and devices to optimize their exposure to UV [22-23] Exposures of surfaces in room dependent on proximity to device and shading and time [22-23]
Pulsed Xenon UV light (PX-UV)	Rapid millisecond pulses of broad spectrum light 200–320 nm [26]	Xenex	15–20 min [25].	<1 log 10 reductions in bacterial colonies [25].	Requires moving of furniture and devices to optimize their exposure to UV [25] Exposures of surfaces in room dependent on proximity to device and shading [25]

aHP aerosolized hydrogen peroxide, *aHPP* aerosolized hydrogen peroxide and peracetic acid, *HPV* hydrogen peroxide vapor, *VHP* vaporized hydrogen peroxide, *UVC* ultraviolet-C, *PX-UV* pulsed xenon ultraviolet

[a] In all cases, the room must be empty of people during the decontamination process

[b] These devices require additional time to allow natural decomposition of HP into H_2O as an uncatalyzed process

[c] Times assuming use of catalyzers as an aerator component

[d] Typically, HPV faster than VHP and aHP/aHPP

[e] Shorter cycles are possible for vegetative bacteria, but longer cycles needed for spores (Cdiff)

Table 2 Efficacy in reducing bacterial colonies or site contamination

Author	Device type	Organisms of interest	Average log reductions for experimentally placed organisms	Reductions in site contamination of patient rooms postdischarge	Other findings
Steindl [18]	aHP	Cdiff	>5-6 log (complete)	N/A	Items placed inside open drawers had decreased killing, but this improved with increased HP treatment time
Galvin [15]	VHP	Cdiff, Staph aureus, ACB, other GNRs, Aspergillus	>6–7 log (complete) for all organisms of interest	N/A	8 h needed for cycle and complete aeration
Barbut [14]	HPV	Cdiff	>4.7–6.9 log (complete)	N/A	PVC and laminate surfaces evaluated
Doan [48]	HPV	Cdiff	2.3 log	N/A	Efficacy was similar to a chlorine releasing agent, which was found to be more cost effective
Lemmen [16]	HPV	MRSA, VRE, ACB	>4–5 log (complete) for all organisms of interest	N/A	Porous surfaces (textiles) saw equal reductions
Mitchell [34]	HPV	MRSA	N/A	24 % reduction in MRSA contamination when HPV arm compared to standard cleaning	HPV arm included topical HP- used instead of HPV in 20 % of rooms Decreased MRSA acquisitions during study in both arms
Rutala [19–21]	UVC	Cdiff, MRSA	4.5–4.6 log for MRSA 2.91–3.05 for Cdiff	N/A	Reflective coating was used with decreased cycle times (5–10 min), Results represent a combination of direct and indirect sites
Nerandzic [22, 23]	UVC	Cdiff, MRSA, VRE	2-3 log for MRSA at 6–10 feet 2–3 log for Cdiff at 6–10 feet 3–4 log for VRE at 6–10 feet 3 log for Cdiff at 4 feet >4 for MRSA at 4 feet >5 log for VRE at 4 feet	93 % reduction in contaminated site for MRSA and VRE, 80 % reduction for Cdiff Compared to baseline no cleaning	No difference in presence of soiling or position in one study [22], decreased killing with distance and soiling in a second study [23]
Anderson [24]	UVC	Cdiff, VRE, ACB	N/A	1.07 log reduction for all organisms, 1.68 log for VRE, 1.16 log for Cdiff	Starting CFUs only 4.46 and 3.17 log for all organisms and organisms of interest, respectively Results represent a combination of direct and indirect sites
Ghantoji [26]	PX-UV	Cdiff	N/A	94 % reduction in Cdiff site contamination, Compared to baseline no cleaning, vs 70 % decrease using bleach alone	Overall difference in residual contamination using PX-UV compared to bleach was not significant
Jinadatha [27]	PX-UV	MRSA	N/A	99 % reduction in MRSA site contamination, Compared to baseline no cleaning (aesthetic wipe only), vs 91 % decrease using bleach alone	Overall difference in residual contamination using PX-UV compared to bleach was significant

Table 2 (continued)

Author	Device type	Organisms of interest	Average log reductions for experimentally placed organisms	Reductions in site contamination of patient rooms postdischarge	Other findings
Fu [9]	aHP and HPV	Cdiff, MRSA, ACB	>6 log for MRSA, ACB, Cdiff (near complete) using HPV 2–5 log for MRSA using aHP, 1–4 log for ACB using aHP, 3.6–5.6 log for Cdiff using aHP, except for one outlier at 0.6 log	N/A	Soiling decreased HPV killing of MRSA, and aHP killing of MRSA and ACB, HPV achieved greater concentration of HP in the room at >100 ppm vs <50 for aHP
Blazejewski [11]	aHPP and HPV	MRSA, VRE, ACB, other GNRs	N/A	No significant difference between aHPP and HPV efficacy, so results reported together: 33 % reduction in contamination and 5.5 % reduction in organisms of interest (MRSA, VRE, ACB, GNRs) Compared to standard cleaning	aHPP levels in room at end did reach >3 ppm, there were reports of respiratory and eye irritation on entry
Havill [17]	HPV and UVC	Cdiff	>6 log (complete) for Cdiff using HPV, 2.2 log for Cdiff using UVC	92 % decrease in colony counts for HPV vs 46 % decrease in colony counts for UVC Compared to baseline no cleaning	2/3 positive sites were in the bathroom where UVC was not set to penetrate
Nerandzic [25]	UVC and PX-UV	Cdiff, MRSA, VRE	0.55 log for Cdiff using PX-UV 1.85 log for MRSA using PX-UV 0.6 log for VRE using PX-UV 1 log for Cdiff using UVC 3 log for MRSA using UVC 3.5 log for using UVC All results at 4 feet and 10-min cycles	80–91 % decrease in MRSA contaminated sites using PX-UV 83 % decrease in C diff contaminated sites using PX-UV 76–100 % decrease in VRE contaminated sites using PX-UV Compared to baseline no cleaning	UVC was as effective as PX-UV at a 10-min cycle time Killing decreases with distance from UV device

Cdiff Clostridium difficile, *MRSA* methicillin-resistant *Staphylococcus aureus*, *ACB* Acinetobacter, *VRE* vancomycin-resistant Enterococcus, *GNRs* gram-negative rods, *MDR* multidrug resistant, *MDRO* multidrug-resistant organisms, *HAI* hospital-acquired infection, *aHP* aerosolized hydrogen peroxide, *aHPP* aerosolized hydrogen peroxide and peracetic acid, *HPV* hydrogen peroxide vapor, *VHP* vaporized hydrogen peroxide, *UVC* ultraviolet-C, *PX-UV* pulsed xenon ultraviolet

penetrate into the adjoining bathroom [17]. The pulsed xenon UV (PX-UV) device attempts to overcome this issue by placing the machine at 3 different positions for 5 min at each site. Yet, Nerandzic et al. still found killing efficacy to be so distance dependent that they had to move mobile furniture and equipment into positions close to the PX-UV device to optimize performance [25]. PX-UV has the shortest time requirements of any of the touchless devices studied to date, yet also the lowest efficacy, with 0.5–1.85 log reductions found in one study [25]. The majority of studies of PX-UV have instead looked at reductions in patient room contamination, finding dramatic reductions when compared to baseline precleaned room contamination [26, 27].

Comparing Devices

Several studies have evaluated HP or UV devices in a head-to-head comparison. The first such study was done with vaporized HP (HPV) and aerosolized HP (aHP) tested against experimentally placed biological indicators at a concentration of 6 log. The HPV inactivated 100 % of the biological indicators while the aHP inactivated 10-79 % [28]. Fu et al. also evaluated HPV and aHP devices but used experimentally placed MRSA, *C. difficile*, and *Acinetobacter*; they found complete killing with the HPV device and incomplete, variable killing with the aHP device [9]. Interestingly, when HPV and an aerosolized HP device were applied in a clinical setting to perform terminal cleaning at patient discharge, no difference in efficacy was found by culturing sites within the room [11]. HPV has also been compared to a UVC device and found to be more efficacious in terms of log reductions in experimentally placed bacteria and also residual contaminated sites in patient rooms; UVC was not able to effectively penetrate some areas in the patient room [17]. Last, UVC has been compared to PX-UV and found to be superior in efficacy despite using a 10-min run time for both devices, which is half the usually recommended run time for UVC [25].

Effects of Organic Soiling

Discordant results have been reported when simulated soiling with organic material is used to mimic body fluids in the hospital environment. Many studies evaluating device efficacy included a soiling component; yet, the effect of soiling on killing efficacy remains unclear. Some studies find no difference in log reduction of bacteria when using an aerosolized HP device [18], and others find decreased killing depending on organism type with both vaporized HP and aerosolized HP devices [9]. One group reported disparate results even when using the same UVC devices, finding that a heavier soiling did decrease killing, while a more moderate soiling did not make a difference [22, 23]. Similarly, Zhang et al. found that heavy experimental soiling reduced efficacy of UVC devices against *C. difficile*, as well as heavy nonexperimental soiling though to a lesser extent. They further demonstrated that routine soiling of hospital rooms did not affect UVC cleaning and argue that precleaning of rooms is likely unnecessary when using these devices [29].

Clinical Efficacy and Infection Prevention

Although touchless technologies do not result in complete eradication of microbes from the patient environment, they further reduce residual contamination following standard room disinfection. Additionally, several published reports now support the clinical efficacy of touchless technologies (Table 3). Haas et al. reported their experience with a PX-UV device while obtaining a usage rate of 76 % of opportunities for terminal discharge cleaning of contact precaution rooms. They found a decrease of incident multidrug-resistant acquisitions and infections from 2.67 cases per 1000 patients days to 2.14 cases per 1000 patient days, albeit using a retrospective, quasi-experimental design evaluating times before and after a hospital-wide roll-out of the device. They employed PX-UV not only in terminal discharges, but also end of day OR suite and dialysis unit cleaning, and any other room on staff request [30]. Another study of *C. difficile* rates before and after hospital-wide roll-out of PX-UV demonstrated 54 % reduction in rates, from a stable 0.92 per 1000 patient days in the 2 years previous, to 0.45 per 1000 patient days in the year after its introduction. The authors collected data on antibiotic usage and other infection prevention practices to evaluate for possible confounding. They also noted a nonsignificant decrease in colectomy and death rates [31]. Passaretti et al. prospectively observed three cohorts before and after roll-out of vaporized HP in their institution. Two of the three cohorts did not use vaporized HP and thus allowed some control of confounding across different time periods. The authors succeeded in using vaporized HP in 74 % of opportunities in their "multidrug-resistant vaporized HP" arm and found a 64 % decrease in acquisitions of multidrug-resistant organisms by the next room occupants, largely driven by vancomycin-resistant *Enterococcus* (VRE). All other studied organisms revealed a trend toward reduction that was nonsignificant due to the low overall rate of patient acquisitions [32]. Another study evaluating vaporized HP in a quasi-experimental design found decreased *C. difficile* rates from 0.88 to 0.55 per 1000 patient days, though this study was limited by vaporized HP use in only 54 % of the discharges in the HP arm; all double occupancy rooms were cleaned with bleach four times instead of vaporized HP. The efficacy of repeated bleach cleanings could not be separated out from the vaporized HP in the outcome data; however, the authors argued that vaporized HP is much more tolerable to staff than four rounds of bleach cleaning [33]. While Mitchell et al. also found decreased MRSA acquisitions over time in their quasi-

Table 3 Efficacy in reducing health care associated acquisitions or infections

Author	Device type	Organisms	Study design	Findings	Comments
Passaretti [32]	HPV	Cdiff, MRSA, VRE, MDR GNRs	Prospective cohort	64 % decrease in acquisitions of organisms of interest combined, driven largely by VRE	Apart from VRE, individual organism acquisitions failed to reach significance due to low overall rates of nosocomial acquisition
Haas [30]	PX-UV	Cdiff, MRSA, VRE, MDR GNRs	Retrospective, quasi experimental	20 % decrease in acquisitions of nosocomial organisms from 2.67 to 2.14 per 1000 patient days	Significant overall and for each individual organism studied
Levin [31]	PX-UV	Cdiff	Retrospective, quasi experimental	Cdiff rates fell 0.95 to 0.45 per 1000 patient days, a 53 % decrease	A potential confounder was overall decrease in fluoroquinolone usage over the same time period
Manian [33]	HPV	Cdiff	Retrospective, quasi experimental	Cdiff rates fell 0.88 to 0.55 per 1000 patient days, a 38 % decrease	Bleach clean ×4 used in place of HPV in cases of room double occupancy
Mitchell [34]	HPV	MRSA	Retrospective, quasi experimental	MRSA rates fell 0.90 to 0.53 per 1000 patient days, a 41 % decrease	MRSA rates appear to have been downtrending both before and after the interventions, and results heavily confounded by increased screening for MRSA during the study period
Barbut [35]	HPV	MRSA, ACB	Retrospective, quasi experimental, in the setting of an outbreak	MRSA rates fell 7.22 to 0.77 per 1000 patient days and ACB rates fell from 6.92 to 0.77 per 1000 patient days, both decreases of 89 %	High baseline rates consistent with reported outbreak

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experimental study of vaporized HP, this was seriously confounded by lower rates of screening for MRSA in the period before roll-out. In addition, their HP data period included a combination of topical HP and vaporized HP usage for terminal cleaning, depending on single or double occupancies. Data for vaporized HP alone was not reported [34]. Last, while the study by Barbut has been cited to decrease clinical rates of MRSA and *Acinetobacter*, from 7.22 to 0.77 cases per 1000 patient days and 6.92 to 0.77, respectively, their addition of vaporized HP was one part of an infection prevention bundle implemented in response to an outbreak of MRSA in a burn unit, and is better categorized as an example of efficacy in outbreak settings [35].

Control of Outbreaks

Experience using touchless technologies in outbreak settings is limited to aerosolized HP and vaporized HP. Organism type may be important in outcomes. While previous studies reported successes in terminating outbreaks due to MRSA [35, 36], *Serratia* [37], and *C. difficile* [38, 39], outbreaks due to *Acinetobacter* are often problematic despite the employment of touchless HP [40–42]. Success with control of a *C. difficile* outbreak was reported by Best et al., when they decontaminated an entire closed stroke rehab unit with aerosolized HP, halting an outbreak with a peak prevalence of 10.8 %. Unfortunately, the authors noted that by 20-week postdecontamination, 3.5 % of room sites were again *C. difficile* positive. Of note, the study used aerosolized HP as a one-time intervention on the entire unit, and it was never integrated into routine terminal cleaning, where perhaps it may have helped suppress rates over a longer time period [38]. In contrast, Chmielarczyk et al. used vaporized HP on a closed unit to stop an outbreak of *Acinetobacter* that had affected 20 patients, only to have a second Acinetobacter outbreak occur 8 months later. An environmental reservoir was never found on extensive surveillance swabs collected by the investigators [40]. Landelle et al. reported an 18-month outbreak of *Acinetobacter* in multiple ICUs in which they used aerosolized HP for cleaning after terminal discharges without success, then vaporized HP on an entire closed unit only to have *Acinetobacter* recurrence upon reopening, then aerosolized HP again on two additional closed units. They reported that HP methods were unsuccessful, and only by cohorting patients with intensive infection control measures was the outbreak halted [41]. Last, another *Acinetobacter* outbreak offers clues as to why touchless methods may fail to eliminate certain environmental reservoirs. Alfandari et al. found *Acinetobacter* contaminating Velcro of blood pressure cuffs in their ICU, which suffered repeated cases of *Acinetobacter* infections despite use of aerosolized HP as one of many unsuccessful interventions to eradicate the bacteria from the environment. Only replacement of the cuffs ended the outbreak [42]. Aersolized HP is unlikely to penetrate a mesh at levels sufficient to eradicate *Acinetobacter*, which may be one major limitation of such technologies. Yet, even *Acinectobacter* outbreaks have been halted by vaporized HP in some instances [35, 43] (Table 4).

Other Applications

Recognition that the patient room is an open system allowing for the constant movement of objects in and out has prompted the use of UV and HP technologies to interrupt other presumed routes of transmission. UVC had previously been used for successful decontamination of portable medical equipment [44]. More recently, another group investigated the effectiveness in vaporized HP decontamination of unused medical supplies in patient rooms. They were able to completely eradicate a baseline contamination rate of 7–9 % of supplies. Of note, they took each item out of the cart and placed it on a metal rack to maximize exposure to the vaporized HP, a step not typically performed at terminal discharge [45]. A portable pulsed UV light device being developed in Japan was used to decontaminate commonly touched surfaces outside of the patient room. They found the portable UV device superior to ethanol wipes in time (43 vs 22 min) and efficacy on complex surfaces such as phones, paper, and keyboards [46].

Safety

Safety concerns when using aerosolized HP devices were raised in some studies. The presence of residual HP in the room at the end of the cycle has been noted and resulted in complaints of irritation and odor [11]. Leakage of HP into adjacent areas has also been reported when the room was not taped and sealed during the cycle [9]. However, the other studies reviewed here make no mention of leakage or residual when rooms are taped and sufficiently aerated after the cycle.

Damage to surfaces or electronics is another concern often raised regarding touchless cleaning technologies. Few such incidents have been reported, though one study did note an "incompatibility" of wall paint in one of the units with vaporized HP employed in the study; this paint had to be replaced [32]. No studies in this review mention damage to electronics or medical equipment. One group specifically studied the maintenance records before and after the initiation of vaporized HP in their institution and did not find an increase in service calls over this time, but rather an unexplained decrease [47].

Cost-Effectiveness

The issue of cost-effectiveness is often raised in discussions of UV and HP devices for environmental disinfection and decontamination of the health care system. One study attempting to

Table 4 Efficacy in outbreaks

Author	Device	Organisms	Setting	Outcomes
Barbut [35]	HPV	Cdiff	Burn unit, acute care HPV implemented in terminal cleaning as part of an infection prevention bundle	Successful termination of outbreak: MRSA rates fell 7.22 to 0.77 per 1000 patient days and ACB rates fell from 6.92 to 0.77 per 1000 patient days, both decreases of 89 %
Best [38]	aHP	Cdiff	Stroke unit, subacute care Ward closed and decontaminated using aHP	Successful termination of outbreak: Cdiff site contamination fell from 10.8 % to 0–0.9 %, though climbed to 3.5 % by 20 weeks postintervention
Alfandari [42]	aHP	ACB	Intensive care unit aHP one of multiple interventions including deferment of new admissions	Unsuccessful in outbreak termination, as ACB incidents recurred four weeks post intervention, contaminated blood pressure cuffs ultimately implicated in ACB persistence
Chmielarczyk [40]	VHP	ACB	Two intensive care units Both wards closed and VHP decontamination employed for both the initial outbreak and the recurrence	Successful termination of initial outbreak, however, ACB recurred in a second outbreak eight months later, also terminated with VHP, extensive environmental sampling was unable to identify a reservoir
Landelle [41]	aHP and HPV	ACB	Multiple intensive care units aHP for cleaning after terminal discharges, then HPV for closed ward decontamination, then aHP for two additional closed wards	Unsuccessful in outbreak termination; ACB continued to recur until patient cohorting and intensive infection control practices ended the outbreak

Cdiff Clostridium difficile, *ACB* Acinetobacter, *aHP* aerosolized hydrogen peroxide, *HPV* hydrogen peroxide vapor, *VHP* vaporized hydrogen peroxide

calculate cost-effectiveness of vaporized HP compared to various manual cleaning methods found that the increased cost was not justified by the slight increase in efficacy by log reductions in experimentally placed bacteria [48]. The real test of cost-effectiveness will likely depend on whether or not these methods will be conclusively shown to decrease hospital-acquired infections. When the cost estimates for surgical site infections, ventilator-associated pneumonias, and catheter-associated bloodstream infections reach $20,000 per event [49] and hospitals are strongly incentivized to decrease rates, touchless technologies may be poised for cost-effectiveness if used judiciously.

Limitations of Current Data on Touchless Technologies for Hospital Disinfection

Of the studies reviewed, the vast majority are either prospective observational studies using simulated conditions, outbreak reports, or quasi-experimental designs. Of the few prospective studies performed under actual patient discharge conditions in the hospital, the sample sizes were generally small, and methods varied from study to study. Indeed, the only prospective controlled study related to clinical efficacy was Passaretti et al. [32]. Of note, another cluster randomized, prospective trial of the ability of UVC to impact patient acquisition of nosocomial pathogens is underway at 9 centers in the USA (clinicaltrials.gov: # NCT01579370).

There is also reason for concern for commercial bias within the literature, as many studies use the device on loan from the company, while other studies are sponsored by the company. Several papers even include authors who are employed by the company under study.

Discussion

While some in vitro studies demonstrated complete killing of experimentally placed bacterial samples, no studies from actual patient rooms after discharge were able to document complete killing of all organisms contaminating the inanimate environment. Much like the challenges faced by standard manual cleaning, the complex surfaces and devices in a hospital room continue to harbor potential reservoirs of pathogens that even touchless methods are unable to eliminate completely.

It is difficult to interpret efficacy studies of touchless devices when the minimal environmental bioburden capable of producing nosocomial transmission remains uncertain. The available evidence on clinical outcomes, albeit for the most part based on low-quality studies, suggests that even incomplete reductions in bacterial loads can reduce patient acquisitions [11, 30–33]. Yet, the experience in outbreak settings illustrate that it does not require a large burden of contamination to threaten the lives of multiple patients, but rather a single protected nidus of infection that is sheltered from decontamination interventions, such as the Velcro cuffs in the experience of Alfandari et al. [42]. The difficulty in locating such reservoirs adds further challenges to cleaning efforts [40]. Hence, even the most enhanced cleaning methods are subject to limitations that may fail to protect patients from environmentally transmitted hospital acquired infections.

The current data on UV and HP disinfection methods suggests that these technologies reduce residual room contamination, can be implemented into busy acute care institutions, and can be used safely within the protocols of specific devices. Convincing evidence of HAI reduction through UV and HP disinfection is lacking. With a steady ongoing refinement of these technologies, and increased experience in the health care setting, the evidence base can be anticipated to strengthen in the future. Thus, touchless cleaning technologies may provide an incremental benefit to standard infection prevention practices by further reducing the bioburden of the inanimate environment and potentially limiting the cross-transmission of pathogens via hospital surfaces.

Compliance with Ethics Guidelines

Conflict of Interest Michelle Doll and Gonzalo Bearman have no conflicts of interest. Deverick Anderson reports royalties from Up To Date, Online, and grants from the CDC and NIH/NIAID. Daniel Morgan reports personal fees from Welch Allyn, grants from VA HSRD, travel expenses paid by IDSA, ASM, SHEA, and personal fees from 3 M.

Human and Animal Rights and Informed Consent This article does not contain any studies with human or animal subjects performed by the author.

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