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Major article

Postdischarge decontamination of MRSA, VRE, and *Clostridium difficile* isolation rooms using 2 commercially available automated ultraviolet-C–emitting devices

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Background: Two ultraviolet-C (UVC)–emitting devices were evaluated for effectiveness in reducing methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant enterococci (VRE), and *Clostridium difficile* (CD).

Methods: Six surfaces in rooms previously occupied by patients with MRSA, VRE, or CD were cultured before and after cleaning and after UVC disinfection. In a parallel laboratory study, MRSA and VRE suspended in trypticase soy broth were inoculated onto stainless steel carriers in triplicate, placed in challenging room areas, subjected to UVC, and subcultured to detect growth.

Results: Sixty-one rooms and 360 surfaces were assessed. Before cleaning, MRSA was found in 34.4%, VRE was found in 29.5%, and CD was found in 31.8% of rooms. Cleaning reduced MRSA-, VRE-, and CD-contaminated rooms to 27.9%, 29.5%, and 22.7%, respectively (not statistically significant). UVC disinfection further reduced MRSA-, VRE-, and CD-contaminated rooms to 3.3% ($P = .0003$), 4.9% ($P = .0003$), and 0% ($P = .0736$), respectively. Surface colony counts (excluding floors) decreased from 88.0 to 19.6 colony forming units (CFU) ($P < .0001$) after manual cleaning; UVC disinfection further reduced it to 1.3 CFU ($P = .0013$). In a multivariable model of the carrier study, the odds of detecting growth in broth suspensions after UVC disinfection were 7 times higher with 1 machine (odds ratio, 6.96; 95% confidence interval, 3.79-13.4) for a given organism, surface, and concentration.

Conclusions: UVC devices are effective adjuncts to manual cleaning but vary in their ability to disinfect high concentrations of organisms in the presence of protein.

INTRODUCTION

Environmental contamination of patient rooms plays a role in the transmission of antibiotic-resistant organisms (AROs), such as methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant enterococci (VRE), and *Clostridium difficile* (CD).[1,2] This role is highlighted by evidence that patients are at higher risk of ARO acquisition in rooms where the previous occupant was either infected or colonized with an ARO.[3-7] Potential contributing environmental factors include suboptimal discharge cleaning and disinfection, a problem that is further compounded by evidence that AROs can survive on hospital surfaces for weeks to months.[8]

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The evolving evidence regarding the inadequacy of standard terminal decontamination has highlighted the potential of automated environmental cleaning systems, such as ultraviolet-C (UVC)–emitting devices, as adjunctive measures. Numerous in vitro studies of these devices typically demonstrate a 3-4 log reduction in bacterial bioburden.[8] Their effectiveness in reducing ARO bioburden in clinical settings has also been documented.[9-13] With the exception of 26 MRSA isolation rooms in the Nerandzic et al study, these studies did not assess the impact of discharge cleaning prior to UVC decontamination and they did not specifically assess the effectiveness in the presence of a known protein load.[9]

We describe a prospective observational study at a tertiary care hospital that used 2 commercial UVC devices to evaluate the incremental benefit of UVC decontamination in MRSA, VRE, and CD isolation rooms. In vitro studies to evaluate the effectiveness of both devices in the presence of a protein challenge were also assessed.

METHODS

In-use evaluation

Vancouver General Hospital is a 728-bed, tertiary care academic teaching hospital in British Columbia, Canada. Between February and November 2013, isolation rooms of recently discharged patients known to have either MRSA, VRE, or CD were identified through the cleaning call center, at which point the research technologist was also notified in order to obtain samples pre- and postcleaning and disinfection and after UVC decontamination. Housekeeping staff performed discharge isolation cleaning per hospital protocol using accelerated hydrogen peroxide for surfaces and a neutral detergent for floors after removing all mobile equipment, personal items, linens, and curtains. The device operator then opened all cupboard doors and drawers prior to UVC decontamination of the room according to manufacturer instructions. The research technologist timed the UVC decontamination and then sampled the room surfaces for the third time. The common touch surfaces tested included the overbed table, bed adjustment control, sink, toilet rim, washroom handrail, and floor.

UVC-emitting devices

Two low pressure mercury UVC light devices were used sequentially. The Tru-D SmartUVC (Lumalier Corp, Memphis, TN) uses a sensor to detect direct and reflected UVC light and has 2 emitter settings: vegetative (12,000 uWs/cm^2) for MRSA and VRE and sporicidal (22,000 uWs/cm^2) for CD spores. The machine calculates the appropriate dose for the room size and is left in the room for the duration of the cycle; the device is controlled via a wireless handheld device.

The R-D Rapid Disinfector system (Steriliz, Rochester, NY) uses 4 detached sensors to detect direct UVC light and has one setting that is both vegetative and sporicidal (46,000 uWs/cm^2). The machine is designed to permit repositioning of the device after 2 of the 4 sensors have reached a predefined dose. The R-D machine is controlled via a wireless handheld device, and the data are automatically uploaded to a cloud daily via Wi-Fi and stored on a central server.

Microbiologic methods

One research technologist conducted all the environmental assessments. Replicate organism detection and counting (RODAC) plates (BD, Sparks, MA) were touched to the predetermined surfaces for a contact time of 30 seconds. Plates were incubated and colony counts performed at 24 and 48 hours. At 48 hours, suspicious colonies were selected and subcultured to Chromagar (Oxoid, Nepean, ON, Canada) to identify VRE and MRSA. A 33-cm^2 mylar sheet template to replicate the size of the RODAC plates was used to swab the adjacent surface sites for CD. Specimens were immediately plated to Cycloserine Cefoxitin Fructose Agar (Anaerobe Systems, Morgan Hill, CA) and Cycloserine Cefoxitin Mannitol Broth with Taurocholate (Anaerobe Systems). Cycloserine Cefoxitin Fructose Agar plates were read at 24 and 48 hours, and colony counts were recorded; broth cultures were subcultured anaerobically on day 5 and examined for the presence of CD. Traditional biochemical tests and MALDI-TOF (Bruker Daltonics, Billerica, MA) technology were used to confirm genus and species of all organisms of interest.

Laboratory carrier studies

MRSA and VRE were serially diluted in either saline or broth to create suspensions of 10^9, 10^8, 10^7, and 10^6 colony forming units (CFU)/mL. Stainless steel washers were inoculated with 10 uL of the suspensions in triplicate and placed in sterile petri dishes. These were placed on the bed, inside an opened closet, and on top of the washroom sink in a cleaned, unoccupied hospital room. The UVC emitting machines were operated according to manufacturer instructions, and both machines were used equally in this phase of the evaluation. The stainless steel washers were then cultured for growth of MRSA or VRE.[14]

Statistical analysis

Standard descriptive statistics were performed. The McNemar test was used to determine the difference in the proportion of paired plates positive with any ARO before and after manual cleaning and before and after UVC disinfection. The McNemar test was also used to determine the difference in the proportion of rooms positive with any ARO before and after manual cleaning and before and after UVC disinfection. A *t* test with Welch correction was used to determine the difference between mean aerobic colony counts before and after manual cleaning and UVC disinfection. Regression analysis was used to compare the 2 UVC machines in the laboratory carrier study, with the final model based on minimized Akaike information criterion and model fit. (Akaike information criterion selects the best quality model by assessing goodness of fit while including a penalty to discourage overfitting by increasing the number of parameters.) A post hoc power analysis indicated that the overall sample size was large enough to yield a power of 99% at $\alpha = 0.05$. Statistical analyses were performed with R Studio (Version 0.98.953; RStudio, Boston, MA).

Ethics

The study protocol was reviewed by both hospital and university ethics review boards and was deemed a quality improvement project.

RESULTS

Effectiveness of manual cleaning

Prior to cleaning, 34.4% of rooms cultured positive on any one surface for MRSA, 29.5% tested positive for VRE, and 31.8% tested positive for CD; manual cleaning did not significantly change these results (Table 1). UVC disinfection, however, reduced the percentage of MRSA, VRE, and CD to 3.3%, 4.9%, and 0% respectively. Table 2 examines the effect of cleaning and UVC disinfection on actual colony counts. The bioburden on high-touch surfaces was reduced after manual cleaning to a mean of 20 CFU, which UVC subsequently reduced further to 1.3 CFU. Interestingly, the bioburden on the floor actually increased from 241.4 CFU to 591 CFU ($P = .0013$), but UVC

Table 1
Percentages of rooms contaminated with MRSA, VRE, or CD before and after manual cleaning and UVC disinfection

Organism	Before manual cleaning	After manual cleaning	*P* value*	OR (95% CI)	After UVC disinfection	*P* value*	OR (95% CI)
MRSA	21/61 (34.4)	17/61 (27.9)	.502	0.67 (0.236-1.774)	2/61 (3.3)	.0003	0.00 (0.000-0.279)
VRE	18/61 (29.5)	18/61 (29.5)	.773	1.00 (0.267-3.741)	3/61 (4.9)	.0003	0.00 (0.000-0.279)
CD	7/22 (31.8)	5/22 (22.7)	.617	0.33 (0.006-4.151)	0/22 (0)	.0736	0.00 (0.000-1.091)
MRSA, VRE, or CD	39/61 (63.9)	32/61 (52.5)	.211	0.53 (0.196-1.34)	5/61 (8.2)	.0001	0.00 (0.000-0.146)

NOTE. Values are n/N (%) or as otherwise indicated.
Abbreviations: *CD*, *Clostridium difficile*; *CI*, confidence interval; *MRSA*, methicillin-resistant *Staphylococcus aureus*; *OR*, odds ratio; *UVC*, ultraviolet-C; *VRE*, vancomycin-resistant enterococci.
*McNemar test for paired samples, 2-tailed *P* value.

Table 2
Aerobic colony forming units per RODAC plate before and after manual cleaning and UVC disinfection

Site	Paired samples	Before manual cleaning	After manual cleaning	*P* value*	After UVC disinfection	*P* value*
Five high-touch surfaces	300	88.0 ± 274.3	19.6 ± 779.1	<.00001	1.3 ± 20.4	.0013
Floors	61	241.4 ± 184.6	590.9 ± 97.7	.0013	8.8 ± 9.5	<.00001
Total	361	114.0 ± 210.1	116.2 ± 390.8	.924	2.6 ± 12.3	<.00001

NOTE. Values are mean ± SD or as otherwise indicated.
Abbreviation: *UVC*, ultraviolet-C.
*The *t* test with Welch correction for continuous variables with unequal variance, 2-tailed *P* value.

Table 3
Percentages of surfaces contaminated with MRSA, VRE, or CD before and after manual cleaning and UVC disinfection

Organism	Before manual cleaning	After manual cleaning	*P* value*	OR (95% CI)	After UVC disinfection	*P* value*	OR (95% CI)
MRSA	50/360 (13.9)	21/360 (5.8)	<.00001	0.28 (0.127-0.546)	2/360 (0.55)	<.00001	0.00 (0.000-0.214)
VRE	41/360 (11.4)	25/360 (6.9)	.012	0.39 (0.166-0.824)	3/360 (0.83)	<.00001	0.00 (0.000-0.183)
CD	9/125 (7.2)	5/125 (4)	.343	0.43 (0.072-1.877)	0/125 (0)	.0736	0.00 (0.000-1.091)

NOTE. Values are n/N (%) or as otherwise indicated.
Abbreviations: *CD*, *Clostridium difficile*; *CI*, confidence interval; *MRSA*, methicillin-resistant *Staphylococcus aureus*; *OR*, odds ratio; *UVC*, ultraviolet-C; *VRE*, vancomycin-resistant enterococci.
*McNemar test for paired samples, 2-tailed *P* value.

disinfection was able to reduce this to a mean of 8.8 CFU ($P < .0001$). Prior to cleaning, MRSA, VRE, and CD contaminated 13.8%, 11.4%, and 7.2% of surfaces, respectively. Although manual cleaning reduced the bioburden, UVC disinfection further reduced bioburden by 8- to 10-fold (Table 3).

Laboratory carrier studies

Both UVC machines killed MRSA and VRE consistently up to concentrations of 10^6 CFU/mL when suspended in a saline solution. The same laboratory carrier studies performed in a protein suspension (n = 324 disks) found that UVC disinfection was challenged at high organism concentrations (Table 4).

When results from the high concentration protein challenge were examined using a multivariable model adjusted for organism, surface, and concentration (Table 5), machine type was the variable with the greatest independent effect on the presence of bacterial growth. Samples treated with machine 2 were 7 times more likely to culture bacteria from stainless steel disks than machine 1 for any given organism, surface, and concentration (odds ratio [OR], 6.96; 95% confidence interval [CI], 3.79-13.4). In a sensitivity analysis to determine the impact of modeling bacterial concentration as a continuous variable, the magnitude or direction of odds of growth for machine type or organism remained the same. The odds for bacterial growth were significantly higher for carriers placed in open closets (OR, 2.04; 95% CI, 1.06-4.00) and on top of sinks (OR, 20.5; 95% CI, 9.19-49.6). Concentration was also a significant variable. For a 1-unit change in concentration from 3-6 (approximately 10 CFU), the odds of growth are roughly tripled (OR, 3.52; 95% CI, 2.49-5.14). Organism was not significant to the model, indicating that VRE and MRSA are eliminated at comparable rates.

Table 4
Distribution of bacterial growth by explanatory variables

Variable	Growth (n = 188)	No growth (n = 136)	Total (N = 324)
Machine			
1	70 (43.2)	92 (56.8)	162 (50.0)
2	118 (72.8)	44 (27.2)	162 (50.0)
Organism			
MRSA	90 (55.6)	72 (44.4)	162 (50.0)
VRE	98 (60.5)	64 (39.5)	162 (50.0)
Surface			
Bed	42 (38.9)	66 (61.1)	108 (33.3)
Closet	55 (51.0)	53 (49.0)	108 (33.3)
Sink	91 (84.3)	17 (15.7)	108 (33.3)
Concentration (CFU/mL)			
10^3	8 (22.2)	28 (77.8)	36 (11.1)
10^4	54 (50.0)	54 (50.0)	108 (33.3)
10^5	64 (59.3)	44 (40.7)	108 (33.3)
10^6	62 (86.1)	10 (13.9)	72 (22.2)

NOTE. Values are n (%).
Abbreviations: *CFU*, colony forming units; *MRSA*, methicillin-resistant *Staphylococcus aureus*; *VRE*, vancomycin-resistant enterococci.

DISCUSSION

Many existing studies evaluating the real-world effectiveness of UVC emitters have focused on comparing the emitters directly with manual cleaning.[9,11,13,15,16] A strength of this study is the real-world evaluation of 2 UVC machines and the parallel laboratory study using carrier disks and organisms suspended in a protein suspension. It also supports the conclusions of Nerandzic, Sitzlar, and colleagues[9,17] that UVC emitters should be used as adjuncts to traditional cleaning.

MRSA, VRE, and CDI were still present in rooms after manual cleaning, emphasizing the potential for reservoirs even after an

Table 5
Adjusted odds of bacterial growth obtained from multivariable model of growth of MRSA or VRE in protein broth after UVC disinfection on stainless steel carriers

Variables	OR	95% Confidence interval
Machine		
1	Reference	—
2	6.96	3.79-13.35
Organism		
MRSA	Reference	
VRE	1.40	0.79-2.50
Surface		
Bed	Reference	—
Closet	2.04	1.06-4.00
Sink	20.50	9.19-49.54
Concentration	3.52	2.49-5.13

Abbreviations: *MRSA*, methicillin-resistant *Staphylococcus aureus*; *OR*, odds ratio; *UVC*, ultraviolet-C; *VRE*, vancomycin-resistant enterococci.

enhanced discharge isolation clean, similar to observations made by Sitzlar et al.[17] These results are particularly worrisome because housekeeping staff were aware that they were being audited and were trying their best to be meticulous. Of additional concern was the observation of organism introduction after manual cleaning. Of 360 surfaces assessed, MRSA was found on 50 (13.8%) surfaces before and 21 (5.8%) surfaces after manual cleaning. Although this represents a statistically significant reduction (OR, 0.28; 95% CI, 0.127-0.546), manual cleaning removed MRSA from 40 of 50 MRSA-contaminated surfaces, but 10 of 50 surfaces remained MRSA contaminated. Unfortunately, MRSA was introduced on 11 previously negative surfaces. Forty-one surfaces initially cultured VRE; 26 of these were culture negative after manual cleaning, 15 remained VRE positive, and 10 surfaces had VRE introduced after manual cleaning. These results demonstrate that UVC disinfection can mitigate potentially harmful situations where manual cleaning is either insufficient or actually introduces pathogens to the patient environment.

Traditionally, floors are not assessed in environmental audits because the belief is that they are always contaminated, and the risk of pathogen transmission is low. We actually observed an increase in mean aerobic CFU for the floors after manual cleaning. For floor cleaning, a neutral detergent was used, and the solution and mop head was changed after every third room. Neutral detergent solutions or mops can act as reservoirs for bacteria, and these results emphasize the need for use of a disinfectant or alternatively to change neutral detergent solutions and mops heads after every room use.[18] In our experience, UVC disinfection mitigated against flaws in the execution of manual cleaning.

Both machines performed very well using stainless steel carriers inoculated with organisms in saline solutions. However, the technology was challenged when organisms were placed in a protein suspension. The level of contamination of hospital room surfaces has been reported to be from <10 to >1,000 colonies/cm^2 in various studies.[2] Our experiment was designed to represent a worst case scenario, where manual cleaning misses an area contaminated with patient fluids, a real concern given the observations of the cleaning challenges in our study.

The Akaike information criterion score was used as a means of comparing alternative models to determine the best model (Table 5). This multivariable model indicated that at high protein concentrations, one machine outperformed the other, and both machines were increasingly challenged with rising concentrations of organisms in protein suspension and also when organisms were placed out of line of site (closet and sink). The Hosmer-Lemeshow χ^2 goodness of fit test gave a large P value ($\chi^2_6 = 4.16$, $P = .38$), which indicates that there is no evidence of misspecification or poor fit. These results emphasize the adjunctive nature of UVC technology and the importance of manual cleaning in reducing organic material. The observations are supported by the work of Zhang et al[19] who noted that eradication of CD spores with ultraviolet radiation was compromised in the presence of organic material when ATP readings were >1,000. Unlike Nerandzic et al,[20] who found no difference between 2 ultraviolet disinfection systems when comparing carriers placed on a laboratory bench, our study using carrier disks was performed in a hospital room where the distances between the carriers and the ultraviolet source varied, as did the presence of shadows. This greater challenge likely accounted for the differences noted between machines in the presence of protein in our study compared with their study.

With respect to the performance of the 2 UVC-emitting machines, both were equally excellent in enhancing the overall patient room cleanliness as an adjunct to manual cleaning in a real-world setting. However, there were important operational and usability differences between the machines. Machine 1 has a faster average use time of 14 minutes compared with machine 2's time of 35 minutes for a regular setting and 57 minutes for the sporicidal cycle. However, machine 1 did have a longer setup time to place the 4 detectors in the room corners, increased hands-on time to move the machine to the different room positions as per manufacturer recommendations, and increased time to clean the 4 detectors after each use. Machine 2, while having much longer cycle times, can be left in the patient room with little to no user interference. We performed a human factors evaluation, including a needs assessment, heuristic evaluation, and task analysis to compare the design of a device with validated design rules to identify usability problems.[21-23]

How an institution decides on the machine that is right for them will depend largely on hospital room capacity, peak turnover times, usability and workflow assessments, and patient and staff safety. In an institution where occupancy rates near 100% and room turnover time must be as short as possible, it would make sense to choose the faster emitter. Conversely, an institution where occupancy is lower, with less room turnover time pressures, could take advantage of the walk-away nature of another machine so that the housekeeper can focus on other tasks. Other important factors to consider are the ability to select only 1 cycle time (less possibility of user error in cycle selection), ergonomic issues, including the footprint of the machine and its ability to pass through small entrances, the sight-line of the machine when it has a cover (making it more difficult for petite operators to maneuver equipment), and the user-friendliness of the software. We recommend that each institution perform both a needs assessment and human factors engineering analysis when considering UVC technology because it is important to understand the physical and cognitive demands placed on the operator of the device.

Understanding the effects of UVC decontamination on the patient environment is a necessary step in evaluating the impact of its use on patient care. This study is a single-center study, and the results may not reflect other hospital experiences where cleaning and decontamination processes may be different. Furthermore, the study is limited in that it does not assess the impact of UVC on reducing health-acquired infections.

Although UVC disinfection is an excellent adjunct to the cleaning process, the decreased effectiveness in the presence of protein is a cautionary note. This study underlines the continued importance of manual cleaning and the potential for UVC disinfection to enhance health care facility cleanliness.

CONCLUSIONS

Manual cleaning of patient rooms is suboptimal. UVC-emitting machines effectively reduce patient room contamination with MRSA, VRE, and CD over and above manual cleaning when used

sequentially. More study is required to determine its effect on the prevention of hospital-acquired infections.

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