

ORIGINAL ARTICLE

Terminal Decontamination of Patient Rooms Using an Automated Mobile UV Light Unit

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(See the commentary by Rutala and Weber, on pages 743–747.)

OBJECTIVE. To determine the ability of a mobile UV light unit to reduce bacterial contamination of environmental surfaces in patient rooms.

METHODS. An automated mobile UV light unit that emits UV-C light was placed in 25 patient rooms after patient discharge and operated using a 1- or 2-stage procedure. Aerobic colony counts were calculated for each of 5 standardized high-touch surfaces in the rooms before and after UV light decontamination (UVLD). *Clostridium difficile* spore log reductions achieved were determined using a modification of the ASTM (American Society for Testing and Materials) International E2197 quantitative disk carrier test method. In-room ozone concentrations during UVLD were measured.

RESULTS. For the 1-stage procedure, mean aerobic colony counts for the 5 high-touch surfaces ranged from 10.6 to 98.2 colony-forming units (CFUs) per Dey/Engley (D/E) plate before UVLD and from 0.3 to 24.0 CFUs per D/E plate after UVLD, with significant reductions for all 5 surfaces (all $P < .02$). Surfaces in direct line of sight were significantly more likely to yield negative culture results after UVLD than before UVLD (all $P < .001$). Mean *C. difficile* spore log reductions ranged from 1.8 to 2.9. UVLD cycle times ranged from 34.2 to 100.1 minutes. For the 2-stage procedure, mean aerobic colony counts ranged from 10.0 to 89.2 CFUs per D/E plate before UVLD and were 0 CFUs per D/E plate after UVLD, with significant reductions for all 5 high-touch surfaces. UVLD cycle times ranged from 72.1 to 146.3 minutes. In-room ozone concentrations during UVLD ranged from undetectable to 0.012 ppm.

CONCLUSIONS. The mobile UV-C light unit significantly reduced aerobic colony counts and *C. difficile* spores on contaminated surfaces in patient rooms.

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For several decades, environmental surfaces in hospitals were considered to play little or no role in the transmission of healthcare-associated infections. However, a growing body of evidence suggests that contaminated environmental surfaces can contribute to the transmission of healthcare-associated pathogens—such as vancomycin-resistant enterococci (VRE), methicillin-resistant *Staphylococcus aureus* (MRSA), *Clostridium difficile*, *Acinetobacter* species, and norovirus—by serving as sources from which healthcare workers may contaminate their hands or perhaps by direct transmission to susceptible patients.¹ Accordingly, cleaning and disinfecting environmental surfaces in patient care areas are now recognized as important elements of infection control programs.^{2–4} Despite this, multiple studies have documented that housekeepers often do not clean surfaces as recommended.^{5–9} As a result, there is increasing interest in new technologies that can reliably decontaminate environmental surfaces in healthcare fa-

ilities. UV light has been used in air-handling systems and upper-room air-purifying systems to destroy microorganisms and can inactivate microorganisms on surfaces,² but few studies have evaluated the potential use of UV light systems for decontaminating patient rooms in hospitals.^{10,11}

We conducted a prospective observational study to determine the ability of a mobile UV light unit to reduce bacterial contamination of environmental surfaces in patient rooms in a 500-bed university-affiliated community teaching hospital.

METHODS

One-Stage Procedure

An automated mobile UV light unit (Tru-D; Lumalier) that emits UV-C (254 nm range) was placed in a convenience sample of 20 patient rooms after patient discharge and after terminal cleaning had been performed by hospital house-

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keepers. The machine allows the operator to set the dose of UV light that will be administered to the room. For the purpose of this study, the UV light dose was set at 22,000 $\mu\text{Ws}/\text{cm}^2$ to eradicate bacterial spores. Eight sensors embedded around the periphery of the device detect how much UV light bounces back from surrounding surfaces. The device terminates the cycle when all sensors on the device have determined that the desired dose of UV light has been delivered to surfaces in the room. The automated UV light unit was placed in the center of the patient's room with the door to the patient's bathroom open. The device was turned on and operated until the cycle was complete, and the device turned itself off.

Aerobic colony counts. Aerobic colony counts from 5 high-touch surfaces in each room were sampled using Dey/Engley (D/E) neutralizing agar contact plates (BD Diagnostics or Remel). The high-touch surfaces included bedside rail, overbed table, television remote, bathroom grab bar, and toilet seat in the patient's bathroom. The bedside rail, overbed table, and television remote had direct line-of-sight exposure to UV light, whereas the bathroom grab bar and toilet seat did not (ie, they were "shadowed areas"). Each of the 5 high-touch surfaces was sampled before and after UV light decontamination (UVLD) of the room. Plates were incubated at 37°C for 48 hours, and aerobic colony counts were determined for each surface. The efficacy of the process against vegetative bacteria was expressed by comparing the following measures before and after a treatment cycle: mean aerobic colony count, proportion of surfaces yielding a positive culture result (more than 1 colony-forming unit [CFU]), and number of surfaces yielding less than 2.5 CFUs/cm² for the aerobic colony count.⁸ The latter value has been used by some experts to define surfaces in healthcare facilities as "clean."⁸

Log reductions in *C. difficile* spores. To evaluate the efficacy of the automated UV light system for decontaminating spores, we used a modification of the ASTM (American Society for Testing and Materials) International E2197 quantitative disk carrier test method to determine the log reductions achieved for *C. difficile* spores.¹² A modification of the ASTM E2197 method was used because there is currently no standardized method for evaluating the antimicrobial efficacy of area decontamination systems such as mobile UV-C light devices or hydrogen peroxide vapor technologies.

To inoculate stainless steel carrier disks (Muzeen and Blythe, Winnipeg, Canada) with *C. difficile* spores, we used either of 2 spore suspensions. One was a ready-made spore suspension containing approximately 10⁵ or 10⁶ CFUs of non-toxicogenic *C. difficile* ATCC 43598 spores that was obtained from the Centre for Research on Environmental Microbiology, Ottawa, Canada. For other experiments, a spore suspension of the same strain of *C. difficile* was prepared using methods described elsewhere.¹³ Briefly, colonies of *C. difficile* were inoculated onto 10 anaerobic blood agar plates (BD Diagnostics) and incubated anaerobically for 48 hours. The plates were then held aerobically at room temperature for 7

days. All colonies were harvested and placed into 5 mL of sterile distilled water and 5 mL of ethanol. After a half hour, 300 μL of the suspension was centrifuged, the supernatant was decanted, and the spores were resuspended in 300 μL of sterile distilled water and vortexed repeatedly until no visible clumps were present in the suspension.

The stainless steel disks (1 cm diameter) were inoculated with 10 μL of *C. difficile* spore suspension (approximately 10⁵ spores). Disks were air-dried overnight and placed in sterile petri dishes, which were placed in patient rooms on the overbed table and chair (in direct line of sight) and on the floor under the bed, the toilet seat, and shower floor (shadowed areas) in the patient's bathroom. Inoculated stainless steel disks not exposed to UVLD served as controls.

Three inoculated control disks (not exposed to UV light) and 5 disks placed on surfaces in each decontaminated room were placed in 10 mL of phosphate-buffered saline with 0.1% Tween 80 and vortexed for 60 seconds to elute the spores. Serial 10-fold dilutions were created by transferring 1 mL into 9 mL of phosphate-buffered saline and continuing this for 5 dilutions. The entire content of each of the dilutions was filtered through a 22- μm filter (Microfil S; Millipore). The filters were placed on BHIYT (brain-heart infusion/yeast extract/Na taurocholate) agar and incubated anaerobically, and colonies were counted. Log reductions were calculated by subtracting the log number of spores present on disks exposed to UV light from the log number recovered from unexposed control disks.

Because UV-C light in wavelengths of less than 200 nm (especially 185 nm) can generate ozone from oxygen in the air, we wondered whether any of the antimicrobial effect attributed to the mobile UV light unit was due to generation of ozone, which also has antimicrobial activity. As a result, in-room ozone concentrations were recorded before and at the end of UVLD cycles using a portable detection device (Aeroqual Series 200 monitor) that had a lower limit of detection of 5 ppb of ozone. On several occasions, a handheld UV light sensor ($\times 9$ radiometer; Lumalier) was used to determine the amount of UV-C irradiance at 254 nm that was detected immediately outside rooms in which the UVLD procedure was in progress. The sensor was placed in front of windows of the patient's room, under the door frame, and along the vertical portion of the closed door.

Two-Stage Procedure

Since some areas in the patient's bathroom were not in direct line of sight of the UV light unit (shadowed areas), we were interested in evaluating whether a 2-stage administration of UV light, one that included administration in the patient's bathroom, would improve the response. In an independent exploratory sample of 5 rooms, the device was placed in the patient's bathroom with the door closed, turned on, and operated until the cycle was complete. Then the device was placed near the center of the patient's room with the bath-

room door closed, turned on, and operated until the cycle was complete. Cycle times were recorded at the end of each room treatment. Aerobic colony counts before and after the 2-stage procedure and *C. difficile* spore log reductions were determined using the same methods as for the 1-stage procedure.

Statistical Analysis

Analyses for the 1-stage procedure were conducted to evaluate the continuous aerobic colony count and the proportion of high-touch surfaces for specific criteria (more than 0 and less than 2.5 CFUs/cm²). For the continuous measure, a balanced 5 (sample site) × 2 (time [before and after]) repeated-measures multiple analysis of variance (MANOVA) with Greenhouse-Geisser adjustment was used. For the dichotomous criteria, generalized estimating equation (GEE) modeling was used for the presence or absence of any colonies or for those that met the less than 2.5 CFUs/cm² criterion. GEE, an application of the generalized linear model, is the model of choice for analyzing repeated-measures binomial data. The model specified an independent correlation matrix structure and a logit link function, consistent with the dichotomous outcome. Follow-up comparisons for both approaches used Bonferroni adjustment to protect for α inflation.

We conducted a within-subjects MANOVA on *C. difficile* spore log reductions to evaluate site differences with available data from 18 of the 20 rooms in which the 1-stage procedure was performed. Because of the small sample size and exploratory nature of the 2-stage procedure, analyses were limited to descriptive statistics before and after UV light administration and log reductions for the *C. difficile* spore reduction.

RESULTS

One-Stage Procedure

The first 20 rooms included in the study varied from 46.3 to 86.1 m³. The median UV light treatment cycle time for the 20 rooms was 67.8 minutes, with a range of 34.2–100.1 minutes.

Aerobic colony counts. Descriptive statistics for aerobic colony counts recovered from each of the 5 high-touch surfaces before and after the UVLD procedure are shown in Table 1. Analysis of the continuous measure of colony counts revealed a significant difference by type of surface ($F(2.2, 42.6) = 7.90, P = .001$) and by time (significantly lower after UVLD; $F(1, 19) = 27.53, P < .001$), as well as a significant interaction ($F(2.2, 42.3) = 4.60, P = .01$). Despite the significant interaction, all pairwise comparisons of colony counts from before and after UV light treatment were significant (all $P < .02$ using the Bonferroni adjustment for multiple comparisons). Figure 1 shows mean colony counts by surface before and after UV light treatment.

The GEE analysis evaluating the presence or absence of any colonies indicated that fewer surfaces yielded a positive

TABLE 1. Aerobic Colony Counts Before and After UV Light Decontamination (UVLD) for 5 High-Touch Surfaces in Rooms 1–20 (1-Stage Procedure) and Rooms 21–25 (2-Stage Procedure)

	Bedrail	Table	TV remote	Grab bar	Toilet
Rooms 1–20					
Before UVLD					
Mean	24.1	10.6	30.1	98.2	63.0
Median	15.5	8.5	9.5	84	12.5
Range	0–95	0–47	0–104	0–300	0–350
After UVLD					
Mean	1.9	0.3	1.3	24.0	6.6
Median	0	0	0	13	2
Range	0–14	0–4	0–12	0–160	0–40
Rooms 21–25					
Before UVLD					
Mean	89.2	10.0	41.4	79.2	37.8
Median	42	5	12	58	42
Range	13–300	3–33	3–170	10–150	6–65
After UVLD					
Mean	0	0	0	0.2	0.4
Median	0	0	0	0	0
Range	0	0	0	0–1	0–1

NOTE. Data are colony-forming units per D/E plate.

culture result after UV light treatment than before treatment (Wald $\chi^2(1) = 44.73, P < .001$), and there was no significant main effect across surface (Wald $\chi^2(3) = 4.03, P = .40$). Overall, 90% (90/100) of surfaces yielded a positive culture result before UV light treatment, compared with 47% (42/90) after UV light treatment. However, there was a significant interaction between high-touch surface and time (Wald $\chi^2(4) = 11.95, P = .02$). Bonferroni-adjusted follow-up tests indicated that bedside rails, overbed tables, and television remotes (all $P < .001$) were significantly more likely to be culture negative after UV light treatment than before treatment, although grab bars ($P = .06$) and toilet seats ($P = .30$) were not.

The analysis evaluating the criterion of less than 2.5 CFUs/cm² showed a similar pattern of results for before and after UV light treatment (Wald $\chi^2(1) = 38.53, P < .001$). Overall, 23% of surfaces yielded a culture result of 2.5 CFUs/cm² or more before UV light treatment, compared with 2% after UV light treatment. Similarly, there was a significant interaction between high-touch surface and time (Wald $\chi^2(4) = 16.16, P = .003$), such that bedside rails ($P < .001$), overbed tables ($P < .001$), television remotes ($P < .001$), and toilet seats ($P = .01$) were significantly more likely to yield less than 2.5 CFUs/cm² after UV light treatment than before treatment, although grab bars ($P = .06$) were not.

Log reductions in *C. difficile* spores. Mean log reductions in *C. difficile* spores for the 5 sites after UV light treatment ranged from 1.7 for the toilet to 2.9 for the floor under the bed (Table 2). A within-subjects MANOVA showed that there was a significant difference by site ($F(4, 68) = 4.07, P < .001$). Bonferroni-adjusted follow-up tests indicated that the

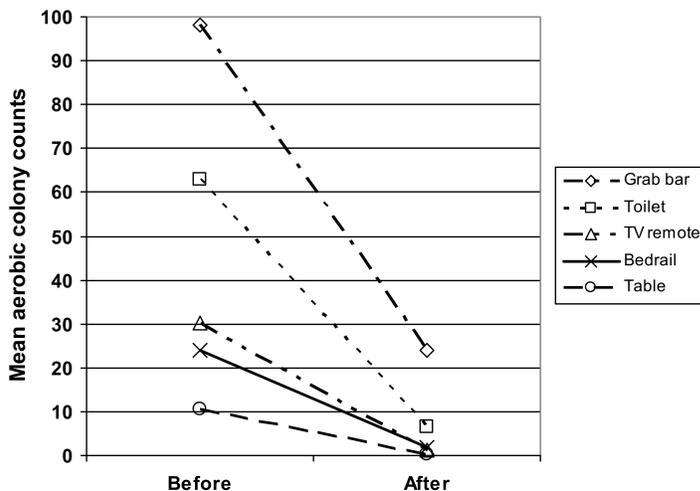


FIGURE 1. Mean aerobic colony counts (in colony-forming units per D/E plate) before and after UV light treatment for 5 high-touch surfaces in rooms 1–20.

floor had greater mean log reductions (2.86) than both the shower (1.79) and toilet (1.66) sites but did not differ from the table (2.34) or chair (2.14). No other pair comparisons were significant.

In-room ozone concentrations after UV light treatment cycles ranged from not detectable to 0.012 ppm. None reached levels that would have yielded antimicrobial activity. UV light level readings obtained in front of windows of patient rooms undergoing UV light treatment were consistent with background levels in patient care wards. UV light level readings taken under the doors or from doorjamb of rooms undergoing UV light treatment revealed that all were below acceptable levels for surface UV-C irradiation (data not shown).

Two-Stage Procedure

The exploratory sample of 5 rooms varied in size from 57.0 to 79.7 m³. The median duration to complete the 2-stage UV light treatment was 83.7 minutes, with a range of 72.1–146.3 minutes. Median aerobic colony counts on the 5 high-touch surfaces before UVLD ranged from 5 CFUs per D/E plate for overbed tables to 58 CFUs per D/E plate for bathroom grab bars (Table 1). Median colony counts after UVLD were 0 for all 5 high-touch surfaces, and only a single aerobic colony was recovered from 1 bathroom grab bar and 2 toilet seats.

Mean *C. difficile* spore log reductions for the 2-stage procedure were not compared directly because of the small sample size, but all showed mean log reductions ranging from 1.4 to 3.2 (Table 2).

DISCUSSION

We have demonstrated that an automated, portable UV light device significantly reduced aerobic colony counts on high-touch surfaces in patient rooms. Colony counts were reduced

to the greatest degree on surfaces that were exposed directly to UV light coming from the automated device. Colony counts were also reduced on surfaces such as grab bars and toilet seats in the patients' bathrooms, which were not in direct line of sight from the device (shadowed areas), but to a lesser degree. In the 20 rooms in which the 1-stage procedure was conducted, the greatest log reductions in *C. difficile* spores were obtained for disks placed under patient beds, despite the fact that these were considered to be in shadowed areas. This finding may have been related to the close proximity of these disks to the UV light unit and to the fact that in some instances they may have been in direct line of sight of the lowermost portion of the UV lamps. With the 1-stage procedure, 90 (90%) of the 100 surfaces yielded a positive culture result before UV light treatment, compared with 44 (44%) of 100 surfaces after UV light treatment. In contrast, in the rooms where the 2-stage procedure was conducted, 25 (100%) of 25 surfaces yielded a positive culture result before UV light treatment, compared with 3 (12%) of 25 surfaces after UV light treatment. Although the 2-stage procedure took an average of 16 minutes longer to perform than the 1-stage procedure, the additional time spent to achieve improved disinfection of objects in the patients' bathrooms may be justified for the following reasons. The skin of patients with *C. difficile* or VRE is frequently colonized, and these organisms can contaminate and survive on surfaces for days to weeks.^{14–16} Patients who are subsequently admitted to rooms occupied by such patients will likely have direct contact with contaminated surfaces in the bathroom. Furthermore, the increased risk of pathogen acquisition associated with prior room occupancy by patients with such organisms suggests that thorough decontamination of bathroom surfaces may be beneficial.^{17–20} However, further studies are clearly needed to establish the relative importance of surfaces in patient bath-

TABLE 2. Log Reductions in *Clostridium difficile* Spores on Stainless Steel Carrier Disks

	Floor under bed	Table	Chair	Shower floor	Toilet	Overall
Rooms 1–20 (<i>n</i> = 18)						
Mean	2.9	2.3	2.1	1.8	1.7	2.2
Range	1.4–4.3	0.6–4.9	0.9–3.5	0.8–4.4	0.01–4.3	0.01–4.9
Rooms 21–25						
Mean	2.0	2.3	1.4	3.2	2.5	2.3
Range	1.1–4.0	1.8–3.0	0.7–2.0	2.6–3.9	1.0–4.3	0.7–4.3

rooms and high-touch surfaces such as bedside rails in transmission of pathogens.

Our study included several unique features. In contrast to earlier published studies,^{10,11} we used a modification of the ASTM E2197 quantitative disk carrier test method to assess the effect that room decontamination by means of UV light has on *C. difficile* spores. By inoculating *C. difficile* onto stainless steel disks that were placed in direct line of sight of the device as well as in shadowed areas, we found that UV light treatment yielded a median of a 2-log reduction in *C. difficile* spores. Another unique aspect of our study was the inclusion of monitoring of in-room ozone levels during UVLD cycles. These measurements revealed that none of the antimicrobial activity associated with the automated UV light device could be attributed to the generation of ozone. In addition, unlike previous studies we performed limited sampling of UV light levels immediately outside patient rooms during decontamination cycles and found that there was virtually no risk of UV light-related skin or conjunctival irritation to personnel outside the room.

Two previous studies evaluated the ability of the same automated UV light device to decontaminate surfaces in laboratory settings and hospital rooms.^{10,11} After inoculating surfaces with MRSA, VRE, or *C. difficile* spores, Nerandzic et al¹⁰ found that a similar dose of UV light reduced the frequency of MRSA and VRE contamination by 93% and of *C. difficile* spores by 80%. They found that the device reduced *C. difficile* spores and MRSA by more than 2–3 log CFUs/cm² and VRE by more than 3–4 log CFUs/cm². Similarly, Rutala et al¹¹ reported that the device we studied reduced MRSA and VRE colony counts on inoculated surfaces by 3–4 logs and *C. difficile* spores by 2.8 logs. That we observed somewhat lower log reductions in *C. difficile* spores than Nerandzic et al¹⁰ and Rutala et al¹¹ was most likely the result of differences in study designs. Nerandzic et al¹⁰ inoculated *C. difficile* spores onto 1-cm² surface areas of bench tops before UVLD and then used pre-moistened sterile swabs to sample treated surfaces, followed by plating of swab samples on cycloserine-cefoxitin-brucella agar containing 0.1% taurocholic acid and lysozyme at 5 mg/mL. Rutala et al¹¹ inoculated *C. difficile* spores onto a 4-cm² area of Formica, exposed spores to UVLD, and then used contact plates to recover spores from the treated surface. We used 2 different methods of preparing *C. difficile* spore suspensions but noted similar log reductions with both methods. Further-

more, we placed *C. difficile* spores onto the concave surface area of 1-cm stainless steel disks, exposed the disks to UVLD, and then eluted spores from disks using ASTM E2197 methods. In our study, it is likely that placing a large inoculum of spores onto an area less than 1 cm² may have presented a more severe challenge to any decontamination protocol. Furthermore, by eluting spores from treated carrier disks rather than using moistened swabs to recover spores from inoculated surfaces, we may have recovered a greater proportion of remaining viable spores, which may have yielded somewhat lower log reductions. It should also be noted that placing an inoculum of 10⁵ *C. difficile* spores onto such a small area does not reflect the levels of contamination that naturally occur on environmental surfaces in rooms of patients with *C. difficile*-associated disease. Previous studies that sampled various surface areas have reported that cultures often yielded less than 10 CFUs per surface sampled, with some surfaces yielding greater than 200 CFUs.^{10,21–23} By using a specialized sponge to sample multiple surfaces in the room of a patient with *C. difficile*-associated diarrhea, Boyce et al²⁴ found a maximum of 1.3 × 10³ CFUs per sponge culture. These studies suggest that levels of environmental contamination are far lower than the 10⁵ CFUs inoculated onto stainless steel disks in this study.

The automated UV light device was easy to use and required only a few minutes to set up. It does not require constant monitoring by the operator because the device turns itself off when a cycle has been completed and does not require sealing of air conditioning or heating vents or doors. However, it is important to emphasize that precleaning of rooms by housekeepers is necessary to reduce gross contamination of surfaces because UV light does not penetrate most substances. We noted an odor in treated rooms immediately after completing the UVLD cycle. The odor dissipated rapidly, and we documented that it was not attributable to ozone generation.

In conclusion, we confirmed the results of 2 previous studies that demonstrated that an automated UVLD device significantly reduced environmental contamination on high-touch surfaces in patient rooms. Although the methods we used to assess the efficacy of the device differed from those used in previous studies, the levels of reduction in vegetative bacteria and *C. difficile* spores observed in our study were similar to those reported previously. Further studies of UVLD

devices are warranted to determine the effect that they have on the transmission of healthcare-associated pathogens.

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Potential conflicts of interest. J.M.B. reports that he has served as a consultant to 3M, Advanced Sterilization Products, Bioquell, Cardinal Health, and the Clorox Company. All other authors report no conflicts of interest relevant to this article.

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