The uses and limitations of a hand-held germicidal ultraviolet wand for surface disinfection

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ABSTRACT

The morbidity and mortality from healthcare associated infections has raised concern that conventional disinfection methods are inadequate and that other adjunct methods such as room fumigation and ultraviolet irradiation may be needed. There is also concern that these alternative methods may pose a risk to workers and patients.

Objectives. (1) Determine the efficacy of a germicidal UV-C wand for surface disinfection, (2) evaluate changing relative humidity (RH) and different target distances on bacteria kill rates, and (3) assess potential exposure concerns.

Methods. This study investigates whether a hand-held germicidal wand can efficaciously disinfect surfaces treated with either a vegetative or spore forming bacterium and to evaluate the effect of changing environmental conditions such as relative humidity (RH), target position, and target distances on microbial kill rates.

Results. Kill rate was best at 40–65% RH at a temperature range of 21–24°C. Both high and low RH interfered with the ability of UV-C to kill the vegetative microbe. In the case of the spore forming bacterium, increased surface drying time was the most significant factor increasing kill rate.

Conclusions. This research demonstrates that UV-C was efficacious under optimal conditions, a direct beam exposure, and a short target distance (12.7 cm). However, there are limitations when used in non-optimal conditions. Increased distance and indirect beam angles resulted in lower kill rates. It is also important to minimize unnecessary patient and worker exposure during its use.

KEYWORDS

Healthcare-associated infections; surface disinfection; ultraviolet (UV)

Introduction

Healthcare-associated infections (HAIs) are a significant contributor to morbidity, mortality and cost in healthcare facilities.^[1–4] Kleven et al. estimated there were 1.7 million HAIs in 2002 and 98,987 deaths. Scott estimated the cost of HAIs to range from \$28.4–\$33.8 billion after adjusting to 2007 dollars. Research has demonstrated that the cost associated with drug resistant strains is \$27,000–\$127,000 higher than the cost of non-resistant strains.^[5] Cost has been a particular concern for the healthcare industry because in 2008, the Centers for Medicare and Medicaid Services began denying payments for HAIs.^[6] The issue of HAI cost is complex and is influenced by many factors including the type of patient procedure and the type of infectious agent. A 2011 study by

Umscheid et al. found the percentage of HAI that were preventable ranged from 45–69%.^[7] This could result in up to 134,800 fewer infections, 3,100 fewer deaths, and a savings to the nation's healthcare system of \$160–\$630 million annually.

There has been increased interest in using stronger disinfectants or alternative disinfection strategies in the effort to combat HAIs.^[8,9] Some of these newer liquid disinfectants contain hydrogen peroxide, peracetic acid-hydrogen peroxide mixtures, and superoxidized (electrolyzed) water. Two alternative strategies include room fumigation and ultraviolet C (UVC) surface disinfection.^[10,11] Stronger liquid disinfectants, chemical room fumigation, and UVC germicidal irradiation are being deployed in healthcare facilities because of concerns

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about the role of the environment as a cause of HAIs and a perception that current surface cleaning and disinfection methods are ineffective. It is important to remember that germicidal chemical disinfectants have the potential to not only inactivate microbes but to harm patients and workers. A significant concern is that not only the employee using the chemical germicide but patients who may be in the room during or shortly after cleaning have the potential to be exposed. These patients may be more susceptible to harm due to immunocompromising illnesses and may have continuous exposures while they are hospitalized. It is also important to remember that exposure to ultraviolet radiation can damage the skin, eyes, and immune system.^[12] It is also well established that all forms of ultraviolet radiation, including UVC can cause skin cancer.^[13,14] On the positive side, UVC is the least likely of the UV bands to cause skin cancer because of relatively low penetration, permitting the radiation to be absorbed in the outer layer of dead skin cells.^[15]

Methicillin-resistant *Staphylococcus aureus* (MRSA) and other gram-positive bacteria have become an increasingly common problem in healthcare environments.^[16–18] Another major concern has been the upswing in incidence of infections caused by *Clostridium difficile* (*C. difficile*).^[19] This spore former organism is now considered to be the most important cause of diarrheal HAI.^[20] *Acinetobacter baumannii* is yet another microorganism involved in HAIs that has been linked to environmental contamination.^[21–23] While norovirus has been primarily a food borne disease, it is becoming a serious HAI problem in healthcare settings because it survives on surfaces and is highly infectious.^[24] One of the latest microbes of concern are the carbapenem-resistant Enterobacteriaceae (CRE), especially involving *Klebsiella pneumoniae*.^[25,26] CRE is becoming more prevalent in U.S. hospitals because it is difficult to treat, and it also has a case fatality rate that may exceed 40%.^[27] On the positive side, CRE organisms will be less resistant to environmental disinfection than other organisms such as spore formers.

Our understanding of which microbes are causing the most significant morbidity, mortality, and cost continues to evolve. *C. difficile* has been assumed to be one of the most significant pathogens because of its environmental resistance and its high prevalence in hospitals. Stewart and Hollenbeak found that *C. difficile*'s contribution to costs and mortality have been overestimated due to reporting bias.^[28] They found that previous researchers had not controlled for differences in types of hospitals, differences in patient populations, and the presence of comorbidities such as diabetes when estimating the total costs of *C. difficile* to healthcare systems. This is an important consideration because concern over limiting the spread of *C. difficile* infections has been a major factor in the push to find alternative disinfection modalities.

Until recently, the common assumption has been that the number one risk factor for HAI is direct contact spread between a carrier and the patient or autoinfection of the patient due to colonizing organisms.^[29,30] According to the Centers for Disease Control and Prevention (CDC), there have only been a few reports documenting “cause and effect” between environmental contamination and infection.^[31] In the last several years, there have been a number of studies that suggest a more important role of the environment in HAI.^[18,21,30,32–44] There are a number of factors that contribute to the contamination of healthcare environments. Patients infected with MRSA and other communicable diseases will shed these microorganisms and may potentially serve as a source of HAIs.^[33,37,39,45–48] Since *C. difficile* is a spore-former, it would be expected to be viable for months.^[49] More importantly, the patient's environment has long been known as an important reservoir for *C. difficile* infections.^[50] Even gowns and gloves worn to protect the healthcare worker have been found to be contaminated and to serve as potential vehicles of transmission.^[51] A particular concern is that hospital textiles such as linens, surgical drapes, uniforms, patient apparel and many more may play a role in infection transmission.^[52] There is evidence that the type of species or strain of microorganism affects survival in the environment. For example, *A. baumannii* strains survive desiccation better than other *Acinetobacter* sp.^[45,53] In the case of *C. difficile*, there is evidence that the Type 027/NAP1 strain has mutated and now has greater toxin production, pathogenicity, and infectivity.^[19,54] Akerlund et al. refer to this mutated organism as “hypervirulent.”

While there is ample evidence that certain microbes can survive in the environment for long periods of time, the assumption that the environment was the cause of the infection has been based primarily on correlation studies. The actual mechanism of transfer of the infectious agent to the patient is not well understood. A large scale observational study attempted to identify the kinds of contacts between patients, healthcare personnel, and visitors that present a risk of HAI.^[55] The researchers found that in 21.6% of interactions between patient and healthcare provider or a visitor, there was no contact with either the patient or the environment. The most frequent interaction was contact with the patient's environment only (33.5%), followed by contact with intact patient skin (27.1%). The interaction with the highest potential for infection transfer was contact with the patient's blood or body fluids (17.8%). A particular concern was the proper use of gloves while touching blood or body fluids. The study revealed that healthcare providers complied over 94% of the time, whereas only 33% of visitors complied. This is an important consideration because failure to comply with hand

hygiene and gloving policy by visitors may significantly increase the potential for infection transmission.

UV has a long history of use in healthcare settings. For example, UVA has been used for many years to cure plastic resins and as a black light. Black lights have been used to identify the presence of rodent infestations and in hand hygiene demonstrations (Glo Germ). This same approach has been recently applied by environmental services to assess the quality of surface disinfection.^[56] UVC has been used for upper air disinfection in the control of tuberculosis or other respiratory diseases for over 100 years.^[15] The most effective design involves upper-room placement of the germicidal lamps that are shielded to reduce human exposure. Another effective approach is to place the UVC lamps in the exhaust system ductwork, or they may be used in the disinfection of ventilation system cooling coils.^[57–59] To be most effective, the design of the dilution exhaust ventilation should bring the airborne pathogens into close proximity to the UVC germicidal lamps. Chang and Young found that in situations where the UVC radiance is high, the air turbulence is high, and the air velocities are low, germicidal effectiveness is reduced.^[60] They emphasized the importance of conducting tracer turbulence studies before considering the use of germicidal UVC to assure that the airborne microorganisms come into close proximity to the lamps.

While there is a long history of using UVC for upper air disinfection, its use in surface disinfection is a relatively recent development.^[8,61–65] An important potential use of a handheld UVC germicidal wand would be the disinfection of frequently contacted surfaces. Some examples would include keyboard, patient bed rails, bedside tables, and even cell phones. Recently, there has been concern that mobile phones could serve as a reservoir for nosocomial infections.^[66] Researchers found that 100% of healthcare workers' phones were contaminated with microbes due to poor disinfection and poor hand hygiene. A germicidal UVC wand could be an effective alternative to liquid disinfectants to disinfect these fomites. There are a number of challenges using this germicidal modality because, in general, microbes are easier to inactivate in the air than on surfaces. Unfortunately, current research has not considered some of the factors that limit UVC efficacy such as photoreactivation, relative humidity (RH), beam output stability, and beam angle in determining microbial kill rates.^[67–70] Our research explores the effects of RH, beam output, and beam angle on UVC efficacy to determine appropriate uses and limitations of this technology.

Materials and methods

Procedures were conducted in a dedicated laboratory room that had thermostatic controls but no room humidification. Because relative humidity in the room is

Figure 1. UVC wand at the 50 cm target distance while adding humidification.

typically below 30%, a portable humidifier was employed to adjust humidity levels. In addition, a 61 × 61 cm square Plexiglas box was used for all tests, and an adjustable platform was used to vary the source to target distances; see Figure 1. Germicidal UVC was administered using a Cole-Palmer ultraviolet lamp (model HV-09813-00). This unit operates at 254 nm and produces 2400 microwatts/cm² at 12.7 cm using a 40.6 cm long lamp. Intensity measurements were made for several exposure time intervals using a General UV512 C Digital UVC Light Meter designed to measure ultraviolet light in the range of 220–275 nm. A vegetative bacterial strain, *Staphylococcus epidermidis* (*S. epidermidis*) American Type Culture Collection (ATCC) 12228 (Biosafety level 1) and a spore-former, *Bacillus subtilis* (*B. subtilis*) subsp. *spizizenii* ATCC 6633 (Biosafety level 1) were used as surrogates for MRSA and *C. difficile*. Each UV-C irradiation test was repeated in triplicate and involved the following steps.^[8]

A commercially lyophilized pellet (Microbiologic KWIK-STIK) of each microorganism was rehydrated and incubated overnight on a sheep blood agar plate at 37°C. Organisms were plated and incubated overnight twice to allow them to stabilize. Using sterile technique, suspensions of each organism were made in trypticase soy broth (TSB), in the range of 10⁴ or 10⁵ concentrations, using a densitometer designed for solution turbidity measurement of bacterial suspensions. Four vinyl coated laminate surfaces (7.5 cm × 10 cm in size) were streaked with ten microliters of either 10⁴ or 10⁵ concentrations of the microbe, spread in a 7.6 cm circle with a sterile bacterial spreader (Cole-Palmer). Microbiologistics KWIK-STICKS were used to inoculate each plate. Each KWIK-STICK unit contained a lyophilized pellet of a microorganism which was reconstituted, plated, and grown for 24 hr. A dilution was made in trypticase soy broth (TSB) with the growing organism. 10 µL of the dilution were inoculated

Figure 2. UVC wand at a 12.7 cm target distance and the photometer in the center position.

onto the laminate surfaces, and spread in a 3-in circle. Each test surface was left to dry for either 10 or 30 min. The UVC lamp was allowed to warm-up prior to the start of each procedure. The UVC lamp took about three minutes to achieve peak intensity and then steadily lost up to 30% of that intensity over a period of about 30 min. After 30 min, the output was relatively stable and ready for use.

The photometer was placed in positions 1, 2, and 3 from left-to-right; as shown in Figures 2 and 3 positions 1 and 3 were 16.5 cm from the center, as shown in Figure 3, and the UVC wand was positioned at distances of 12.7, 27.9, and 50 cm above position 2. Readings were recorded as $\mu\text{Ws}/\text{cm}^2$ (intensity in $\mu\text{W}/\text{cm}^2$ times the exposure in seconds). In the *S. epidermidis* test runs, the photometer was placed flat against the test surface. Because the sensor was located approximately 1 cm below the surface of the photometer probe, this orientation resulted in an under estimate of scatter radiation intensity. During *B. subtilis* tests, the orientation of the photometer sensor was modified in positions 1 and 3 at a 12.7 cm target distance by placing the probe at a 90-degree angle facing the UVC

Figure 3. Schematic of the geometries of the source to target distances.

lamp. This increased the measurement of scatter radiation by approximately $2\frac{1}{2}$ times. The three contaminated laminated surfaces were placed under the UVC wand for 5 sec, 10 sec, 30 sec or 5 min in positions 1–3, as shown in Figure 3; test surface 4 was used as a control for comparison purposes.

Becton, Dickinson, and Company BBL Prepared Isolator Pack Plates for Environmental Monitoring D/E Neutralizing Agar, Replicate Organism Detection and Counting (RODAC) were used for sampling. RODAC plates are constructed with a raised agar medium so that it can be pressed onto a surface for sampling microbial contamination. After exposure to UVC, each of the RODAC plates were gently pressed onto the contaminated laminate surfaces for 10-sec. RODAC plates were immediately incubated at 37°C for 24–48-hr, and the number of colony forming units (CFUs) was recorded.

After each trial run, test surfaces were disinfected with germicidal wipes. The original procedure called for the use of a quaternary ammonium disinfectant. When it appeared that the residual quaternary ammonium disinfectant was not adequately neutralized and exhibited bacteriostatic properties, we switched to 70% isopropanol. After disinfection, test surfaces were placed in a covered container for reuse. Quality control TSB agar plates were inoculated with each new dilution to check for strain purity. Sterility control TSB agar plates were inoculated with dry swabs rubbed on each laminate surface after they were disinfected and before they were inoculated with organism. Each of these plates were incubated for 24 hr to check for contamination and purity.

Temperature and RH were monitored using an Amprobe THWO-3 digital psychrometer and recorded during all test runs. Averages and standard deviations were reported. Statistical methods such as paired t test and an ANOVA were applied to analyze the significance of these environmental factors.

This study was reviewed and cleared by the Illinois State University Institutional Biosafety Committee (IBC Number 12B-2014), and UV goggles, nitrile gloves, and lab coats were used while working with the microbes and the UVC lamp.

Results

A total of eight trials of 10^5 concentrations of *S. epidermidis* were conducted at a target distance of 12.7 cm, two trials at 29.7 cm, and one trial at 50.0 cm at humidity ranging from 21–84% RH. Table 1 shows the UVC intensities and CFUs at the three target distances and at differing RHs and their effects on *S. epidermidis* microbial kill rates. As shown in Figure 3, at a target distance of 12.7 cm, only position 2 was in the direct beam. At a target distance of

Table 1. The effects of intensity, beam angle, target distance, and RH on *S. epidermidis* on kill rates.^a

Distance	RH (%)	Position 1 (Left)			Position 2 (Center)			Position 3 (Right)		
		μWs/cm ²	CFU	Log Reduction	μWs/cm ²	CFU	Log Reduction	μWs/cm ²	CFU	Log Reduction
12.7 cm	18	10,100	33	3.5	527,600	1	5.0	9,600	35	3.5
	19	10,100	48	3.3	527,600	11	4.0	9,600	45	3.3
	20	10,100	54	3.3	527,600	3	4.5	9,600	25	3.6
	21	8,000	34	3.5	569,566	4	4.4	10,200	34	3.5
	65	11,700	9	4.0	548,400	0	5.0	5,700	10	4.0
	75	11,700	37	3.4	541,200	2	4.7	5,700	34	3.5
	79.5	11,700	24	3.6	536,400	2	4.7	5,700	18	3.7
	84	11,700	44	3.4	537,000	2	4.7	5,700	58	3.2
	43.4	46,700	12	3.9	92,200	15	3.8	54,100	9	4.0
27.9 cm	44	43,200	29	3.5	64,400	26	3.6	44,200	40	3.4
	50.5	28,250	50	3.3	29,484	39	3.4	28,150	49	3.3

^aTest surface drying time was 10 min, exposure time was 5 min, and temperature ranged from 21–23°C.

29.7 cm, only a portion of the test surfaces in positions 1 and 3 received direct beam exposure, and at the 50-cm distance, all test surfaces were in the direct beam.

In Table 1, the highest UVC intensities and kill rates were found in position 2 at an RH range of 44–65%. At a target distance of 12.7 cm in position 2, there was nearly a five log reduction in CFUs during all test runs. In positions 1 and 3, at both high RH ($\geq 75\%$) and low RH ($\leq 21\%$) microbial kill rate was diminished to less than a 4 log reduction. The differences in log reductions comparing direct and indirect beam were all significant at 0.01 p-value, and when comparing positions 1 and 2, under high RH, the reduction in kill rate was significant at a p-value of 0.002. At the higher target distances and at optimal RH (40–50%), a 3.5–4 log reduction was seen in all three positions. UV μ W-sec intensity decreased with increased distance in accordance with the inverse square law.

Table 2 demonstrates that using a 10^4 inoculum, a 12.7 cm target distance, an RH of 45%, and a test surface drying time of 10 min, there was, on average, a less than 3 log reduction (2.7–3.2) in *B. subtilis* CFUs in the center position and approximately a 2-log reduction in positions 1 and 3. Tables 2 and 3 demonstrate that when the drying time was increased to 30 min, significantly higher kill rates were observed. Even at high humidity, nearly a

5-log reduction was observed at all three positions at the 12.7 cm target distance when test surfaces were dried for at least 30 min.

Table 3 demonstrates the effects of beam angle and RH on a 10^5 inoculum of *B. subtilis*. In position 1 and 3 at high humidity there was approximately a 4.3-log reduction and at low humidity approximately a 4.1-log reduction. These differences are not significant. In the center position, there was approximately a 5-log reduction in all tests. However, the differences in log reductions comparing direct beam and indirect beam exposures were significant at a p-value of <0.001 .

Table 4 shows that at target distances of 27.9 and 50 cm, there were similar kill rates with 5 sec and 10 sec exposures. In each case, there was approximately a 3.3–3.4 log reduction in the *B. subtilis* count. A 30-sec exposure only increased the log reduction to 3.5 on average.

In Table 5, the effects of exposure time on *B. subtilis* kill rates was examined. While placement of the UVC lamp at the minimum target distance resulted in the highest intensities, it also treated the smallest surface area. Increasing target distances increased the treatment area but also required longer exposures. Our tests demonstrated that at a target distance of 12.7 cm, 10-sec exposure time resulted in the optimum kill rate (4.9-log reduction) in the center

Table 2. The effects of beam angle, duration of exposure, and RH on a 10^4 inoculum of *B. subtilis*.

RH (%)	Time	Position 1 (Left)			Position 2 (Center)			Position 3 (Right)		
		μWs/cm ²	CFU	Log Reduction	μWs/cm ²	CFU	Log Reduction	μWs/cm ²	CFU	Log Reduction
45	5 min ^a	36,000	91	2.0	537,000	19	2.7	32,100	73	2.1
45	5 min ^a	34,800	116	1.9	486,000	22	2.7	33,900	114	1.9
45	5 min ^a	35,100	119	1.9	546,000	6	3.2	32,400	145	1.8
42	10 min ^b	67,800	1	4.0	1,092,000	0	4	73,200	1	4
42	10 min ^b	64,200	1	4.0	1,095,600	0	4	75,000	0	4
42	10 min ^b	63,000	1	4.0	1,083,600	0	4	72,600	0	4
85	5 min ^b	32,100	0	4.0	535,500	0	4	36,000	1	4
81	5 min ^b	30,900	2	3.7	534,000	0	4	37,500	0	4
83	5 min ^b	30,900	0	4.0	517,800	0	4	37,200	0	4

^aThe initial test run used a 10 min drying time and 5 min exposure at a temperature of 23°C.

^bThese tests used a 30 min drying time and either a 5 or 10 min exposure at temperature of 23–24°C

Table 3. The effects of beam angle and RH on a 10^5 inoculum of *B. subtilis* at a target distance of 12.7 cm, exposure of 5 min, and temperature of 23–24°C.

RH (%)		Position 1 (Left)			Position 2 (Center)			Position 3 (Right)		
		$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction	$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction	$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction
High RH	81	30,900	9	4.0	512,100	0	5	33,000	3	4.5
	80	30,600	4	4.4	487,500	0	5	32,400	2	4.7
	80	29,700	4	4.4	477,000	1	5	33,300	4	4.4
	79	33,000	9	4.0	536,100	1	5	35,100	8	4.1
	79	34,500	5	4.3	537,600	0	5	34,500	14	3.9
Low RH	79	33,000	4	4.4	533,700	0	5	35,400	0	5
	19	29,400	42	3.4	524,400	2	4.7	43,500	20	3.7
	19	27,300	26	3.6	517,200	0	5	41,400	10	4.0
	18	31,800	9	4.0	514,200	1	5	36,600	8	4.1
	19	34,200	7	4.2	519,600	0	5	35,700	8	4.1
Medium RH	19	33,600	2	4.7	516,000	0	5	35,700	6	4.2
	18	31,800	5	4.3	513,600	1	5	35,700	1	5.0
	47	38,100	13	3.9	559,800	0	5	36,900	3	4.5
	51	35,400	7	4.2	545,400	0	5	38,700	5	4.3
	54	34,800	1	5.0	535,500	0	5	37,800	8	4.1

Table 4. The effects of beam angle, distance and exposure time on a 10^5 inoculum of *B. subtilis* at an RH range of 46–50% and temperatures of 22–23°C.

Distance	Time	Position 1 (Left)			Position 2 (Center)			Position 3 (Right)		
		$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction	$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction	$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction
27.9 cm	5 sec	815	56	3.3	1,240	38	3.4	765	45	3.3
	10 sec	1,580	54	3.3	2,400	40	3.4	1,470	45	3.3
	30 sec	4,770	26	3.6	7,260	9	4.0	4,470	27	3.6
50 cm	5 sec	465	42	3.4	485	45	3.3	470	47	3.3
	10 sec	940	43	3.4	970	47	3.3	930	48	3.3

position. The improvement in kill rate by increasing the exposure duration from 5 to 10 sec was significant at a p-value of <0.001. Increasing the exposure to 30 sec did not increase kill rate.

In terms of operator exposures, with the wand 12.7 cm above the test surface, some potentially hazardous scatter radiation was measured. With the photometer 30.5 cm directly above the test surface, we measured $6 \mu\text{W}/\text{cm}^2$. The TLV for ultraviolet radiation with a wavelength of 254 nm is $6 \text{ mJ}/\text{cm}^2$. If a worker used the wand for one hour, the amount of scatter radiation would result in an exposure 3.6 times this limit, and an 8-hr exposure would be 28.8 times the limit.^[71] Scatter radiation at a 90° angle, measured horizontally from the lamp was $18 \mu\text{W}/\text{cm}^2$ at 30.5 cm and $4 \mu\text{W}/\text{cm}^2$ at 50.8 cm (at the opening of the test chamber).

Discussion

The microbial kill rate for *S. epidermidis* was greatest at a relative humidity range of 40–60%. Our results support that high RH interferes with the ability of UV systems to successfully kill pathogens. There has been little research on the effects of low RH (<30%) on the efficacy of UVC irradiation.^[72] We found that low RH also interferes with UVC's ability to kill *S. epidermidis*. The effects of RH on *B. subtilis* kill rates were less pronounced, and the primary factor affecting kill rates was the drying time of the test surfaces. When only a 10-min surface drying time was used, this significantly increased the ability of *B. subtilis* to survive the effects of UV disinfection. The 30-min drying time of test surfaces resulted in a significantly higher kill rate and was determined to present a more realistic measure of actual use conditions.

Table 5. The effects of duration of exposure on a 10^5 inoculum of *B. subtilis* in the center test position at an RH of 44–50% and temperature of 23°C.

Distance	Time	Test 1			Test 2			Test 3		
		$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction	$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction	$\mu\text{Ws}/\text{cm}^2$	CFU	Log Reduction
12.7 cm	5 sec	9,025 ^a	7	4.2	9,025	5	4.3	9,025	9	4.0
	5 sec				8,915	7	4.2	8,915	5	4.3
	10 sec	17,940	1	5	17,940	1	5.0	17,940	2	4.7
	30 sec	53,640	4	4.4	53,640	1	5.0	53,640	4	4.4

^aThis test run was not recorded due to a lab error.

Results follow the inverse square law with the UVC lamp at 12.7 cm, 27.9 cm, and 50.0 cm away from test surface. At lower target distances (Figure 3), positions 1 and 3 only receive indirect beam exposure. At maximum distance of 50 cm, positions 1 and 3 receive direct beam exposure, providing a similar kill rate as position 2. The effects of distance on beam intensity and beam geometry are important considerations when using UVC as a surface germicidal agent. Placement of the UVC lamp at the minimum source to target distance will result in the highest intensity, but it will also treat the minimum surface area. Placement of the lamp at a longer target distance will increase the treatment area, but it may be necessary to increase the exposure time to maximize the kill rate. Our tests demonstrated that at a target distance of 12.7 cm, 10-sec exposure time resulted in the optimum kill rate (4.9-log reduction).

Limitations observed include: (1) mercury vapor UVC lamps steadily lose intensity for about 30 min before stabilizing; (2) photoreactivation was not tested. This is a phenomenon where inactivated microbes repair cellular damage and fully recover once exposed to longer wavelength light.^[68,69] We cannot rule out that some of our results may have been affected by this phenomenon; and (3) exposure to UVC may result in ocular or dermal effects. Therefore, it is essential that all individuals, especially patients, avoid unnecessary exposures. When using a handheld disinfecting wand, personal protective equipment for the eyes and skin must be worn.

Conclusions

One limitation of using a handheld UVC lamp is that output is not stable. The 30-min warm-up time and 30% loss of intensity makes dose calculations challenging. Source to target distance and beam geometry were critical factors regarding radiation intensity and kill rates. Also, there is a tradeoff when considering the optimal source to target distance. A short target distance provides higher intensities and kill rates but treats a smaller surface area. Humidity had an effect on kill rates for *S. epidermidis* but not *B. subtilis*. For *B. subtilis*, surface dryness was a critical factor. Irradiating a damp surface treated with *B. subtilis* resulted in a significant reduction in kill rate. A limitation of this research was that we did not test photoreactivation. We cannot rule out that some of our results may have been affected by this phenomenon. A final concern is that exposure to UVC may result in ocular or dermal effects. Our results suggest that there is a potential for significant amounts of scatter radiation to the worker using the handheld UVC lamp. Therefore, it is essential that all individuals operating the device, take special care to avoid exposing themselves or exposing patients. When

using a handheld disinfecting wand, personal protective equipment for the eyes and skin must be worn.

Germicidal UVC is being actively promoted for use in hospitals without consideration of its efficacy or potential risks. By understanding the risks and benefits of using UVC for surface disinfection, health and safety professionals can better advise healthcare administrators about the appropriate uses of this technology.

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