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REVIEW ARTICLE

UVC Decontamination in Healthcare Environments

Valerie Edwards-Jones*

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Abstract

Ultra Violet light-C (UVC) irradiation is used as a disinfection method in healthcare, agriculture and the food and water industries. In healthcare, it is seen as an alternative to hydrogen peroxide following terminal cleaning with conventional disinfectants. There are a number of different UVC systems on the market with varying properties that impact on their performance. The performance of each system is tested using standard testing methods and compliance with these standards is essential in many healthcare facilities before purchase. UVC is absorbed by proteins, DNA and/or RNA of the microorganism following exposure. The absorption of a photons causes adjacent thymine bases in DNA to bind together forming thymine dimers, instead of linking with a complementary base on the other strand. This causes disruption of DNA, rendering the microorganism incapable of replication. The main parameters of UVC decontamination include the wavelength emitted (usually 254 nm), dose (a high dose is recommended, above 100 mJ/cm^3), relative humidity (30-60%) and room temperature (20 +/- 1ºC). No personnel should be within the area of decontamination when UVC is being emitted for health and safety risks. This is a brief overview of factors affecting performance and its impact in the healthcare environment.

Key Words: *UVC; Infection control; Surface decontamination; Air decontamination; HAI*

Introduction

The ability of Ultra Violet light-C (UVC) to inactivate microorganisms was discovered in the early 1800's but the discovery of the dosage, appropriate wavelengths and mode of action was not discovered until later that century, Reed (2010) has detailed the history of UVC use associated with air decontamination and its renewed interest since 2000 due to problematic Healthcare Associated Infections (HAIs) [1]. For example, multi-drug-resistant pathogens such as *Mycobacterium tuberculosis*, recent pandemics and bioterrorism threats [1]. UVC is now used across a range of industries and healthcare settings for surface, air, water, food and equipment decontamination and in healthcare, ultrasound probes and endoscopes [2]. In the food industry, UVC is used to decontaminate filling equipment, conveyor belts, containers, working surfaces, fresh fruit as well as liquid food processing [3-5]. Water decontamination using UVC can be used as a substitute for chlorine addition, however it does not provide residual water disinfection which may be a requirement in some industries [6,7]. UVC is also used in wastewater disinfection and

Emeritus Professor of Medical Microbiology, Manchester Metropolitan University, Manchester, United Kingdom

Corresponding author: Valerie Edwards-Jones, Emeritus Professor of Medical Microbiology, Manchester Metropolitan University, Manchester, United Kingdom, E-mail: v.edwards-jones@sky.com

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is seen as a safe and efficient physical technology that does not require the use of chemical agents and can be used alone or in combination with other processes [8]. In addition, biofilm control on artificial surfaces in water systems can be mediated by UV based oxidation processes [9]. UVC is used to reduce transmission of respiratory infections spread by aerosols from infected persons in various environments and since the COVID-19 pandemic, air quality has become an important issue once again, leading to development of air purifiers combining UVC and HEPA filters which decontaminate circulatory air [1,10-12]. In many hospitals, UVC is used to decontaminate endoscopes and as an adjunct to terminal cleaning to decontaminate the environment, from individual patient rooms to operating theatres and personal protective equipment [13-16]. Various parameters can influence the success of decontamination including performance of UVC emitter and shadowing effects caused by items within the rooms [17].

Safety is of paramount importance when operating UVC devices both for the operative and personnel/patients within the vicinity [18]. The UVC emitters have to meet strict manufacturing criteria to ensure compliance with electrical wiring and safety as well as ozone emission and optical safety of the UVC lamps (for example in the UK detailed under NETB 2023/01B) as well as a range of international standards covering accepted human exposure criteria as detailed in for example BS EN ISO 15858 standard [19,20]. This provides explanations and brief guidance on UV-C penetration through transparent materials, reflection of UV-C, Personal Protective Equipment (PPE) recommendations for cases where the exposure levels exceed the maximum and safety training of personnel [20,21]. Prior to 2022, most UVC devices were tested for antimicrobial efficacy by using a modified airborne surface disinfection standard EN 17272:2020 [22]. Here, the system was placed within an enclosed test chamber at a specified distance/location (usually 1 meter) and the active ingredient (e.g., ozone, hydrogen peroxide etc.) injected in the appropriate form (e.g. gas, vapor, aerosol) and the reduction in microbial counts on the exposed surfaces expressed in logarithm scale ($\log_{10}$) to assess compliance to the standard. In 2022, a new standard, BS8628:2022 was implemented to ensure that the UVC device complied to challenges with certain environmental factors to improve testing [23]. This test is now carried out in a blacked-out test chamber (to minimize the effects of reflection) with the UVC emitting device placed 2 meters from test coupons holding the microorganism. The coupons are placed flat on the surface at 1 meter above the floor. In addition, the blacked-out test chamber is kept at a temperature of 20 ± 1ºC and relative humidity of 30-60% before starting the cycle.

The efficacy of the different UVC systems vary depending upon dose, emission time, wavelength used and organism tested [24].

Types of UV light

The electromagnetic spectrum is divided into seven regions ordered by decreasing wavelength and increasing energy and frequency (Figure1).

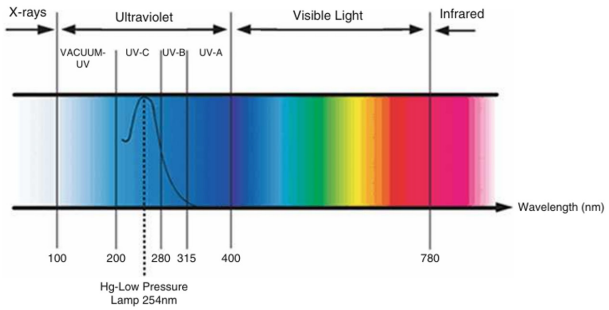

Figure 1) *Electromagnetic spectrum and position of UV light.*

These are radio waves, microwaves, Infrared (IR) visible light, Ultra Violet (UV), x-rays

and gamma rays [25]. Ultraviolet falls in the range between visible light and X-rays and can be subdivided into three sub bands namely; UVA (315-400 nm), UVB (280-315 nm) and UVC (200-280 nm). UVC has the shortest wavelength and the highest energy and as such can act as a surface and air disinfectant [24,26]. Most natural UV energy comes from the sun with 10% of sunlight being attributed to UV with 95% UVA and 5% UVB. There is no measurable UVC energies from solar radiation on the earth's surface because ozone, oxygen and water absorb it [27]. As a disinfection system, UVC is produced artificially by lamps (usually vaporized mercury or other gas) and are commonly used at 254 nm, but there is no consensus on the exact optimal wavelength [24]. Bacterial DNA and RNA have peak absorbances of light at 260-265 nm [24].

Generation of UV light

There are four types of light sources are used to emit UVC light: mercury-vapor, pulsed xenon, LEDs and excimer lamps [24]. Mercury-vapor lamps can be divided into three classes: Low-Pressure (LP), Medium-Pressure (MP) and High-Pressure (HP) lamps, of which the LP lamps have the highest UVC efficiency and are thus most used [24]. All the light is emitted at 185 nm or 254 nm, with a peak emission of 254 nm [28,29]. They do require a warm up period prior to use. MP and HP lamps emit a discontinuous spectrum and are therefore used less frequently [29]. Safety concerns over handling, ozone and possible accidental lamp breakage and release of mercury vapor which is toxic to man, has led to a reduction in their use [29,30].

Pulsed-xenon lamps generate substantial UV radiation with a spectrum, ranging between 200 nm and 1000 nm. These have proven efficacy and emit UVC through pulses of high intensity filtered light [29]. There are similar safety concerns to all UVC lamps and eyes and the skin should be protected when operated.

The newer generation LED lamps do not contain mercury which makes them more environmentally friendly require no warm up and are less affected by temperature [24,30]. For LEDs, the light emission peak can be modified by the manufacturer to a value between 255 nm and 275 nm and using LEDs at different wavelengths in one system, a wavelength spectrum can be emitted [2,29]. LEDS are less efficient than low pressure mercury vapor lamps but have the advantage of safety, no warm up time and wavelength choices [29]. Lastly, there are different types of excimer lamps depending upon the gas used, all with their characteristic spectrum. For UVC disinfection, krypton chloride (KrCl) lamps are most popular and emits light at 222 nm known as far UVC [29,26]. The advantage of KrCl is that inactivation of bacteria and viruses appear to be similar to that of 270-280 nm [29]. This is a relatively new disinfection method with limited data about its effectiveness but evidence is mounting to show that the safety risks may be less problematic due to a lower penetration depth into the skin and eyes [31]. There is less demonstrable damage to biological systems but the effect in the long term needs to be determined [31,32]. Furthermore, ozone is produced due to the emittance of wavelengths <240 nm and as such production of ozone and its safety using far UVC must be considered when used [33].

How UVC works

The photons produced by UVC is absorbed by proteins, DNA and/or RNA of the microorganism following exposure. Adjacent thymine bases in DNA bind together forming thymine dimers instead of linking with a complementary base on the other strand [24,34] (Figure 2).

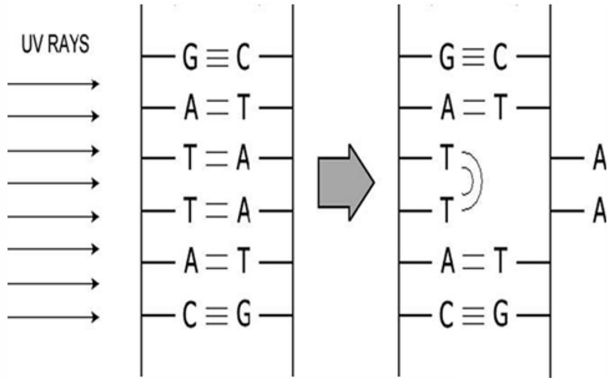

Figure 2) *Formation of thymine dimers in DNA strands compared to normal DNA structure.*

This causes disruption of DNA and ultimate inactivation of the microorganism [24,34]. In DNA viruses, thymine dimers occur and also bonding between thymine bases and the proteins in the viral capsid [24,35]. In RNA viruses, a similar process occurs with the pyrimidine bases, uracil, forming uracil dimers [24]. Where there is partial inactivation (for example, due to insufficient dosage) DNA/RNA repair mechanisms can be activated within the cell following exposure, reducing the antimicrobial effect [2,36].

DNA repair mechanisms used by microorganisms following UVC exposure

Microbial cells have developed a number of repair mechanisms to counteract the DNA damage caused by UVC. The two most common are termed photoreactivation, which requires the enzyme photolyase and light energy and dark repair [36]. Photoreactivation, mediated by the enzyme photolyase, is one of the frequently occurring repair mechanisms in a variety of microorganisms [37]. Briefly, the photolyase enzyme specifically binds to the pyrimidine dimers and reverses the damage using light energy by splicing out the corrupted segment of single stranded DNA allowing reformation of double stranded DNA, a second mechanism, dark repair requires the enzyme N-glycosylase to cleave the pyrimidine cross-links in DNA [37]. It does use light energy to mediate this reaction but utilizes nutrients from the surrounding environment [24,36,38,39].

Repair by photoreactivation can be partially counteracted by using the UVC source for longer, emitting a higher dose, or by using a spectrum of wavelengths. The dose influences the amount of photoreactivation and the percentage of photoreactivation can be reduced by emitting a higher dose which in turn will achieve a higher inactivation. Using UVC at a lower temperature also helps reduce the effect of photoreactivation presumably by reducing the enzymatic reaction [2,37,38]. Therefore, it is important that emitted dosage as well as temperature is controlled within the environment to maximize antimicrobial effects of the emitted UVC [39,40]. These parameters are tested in the new standard BS8628:2022 and any microorganism of concern can be tested and $\log_{10}$ reduction determined in a set time period [23]. This could be an important feature within a healthcare setting if there is a multi-drug-resistant strain or a spore forming bacterium colonizing the air/surfaces of the environment. Studies have shown that bacteria are most susceptible to UVC light, followed by viruses, fungi then spore over a set time period [41].

Some microorganisms are better than others at utilizing these repair mechanisms and the efficiency of repair may account for differences in susceptibility [40]. Also, the levels of GC/AT ratios in the DNA/RNA vary between species, theoretically creating different levels of dimerism and inactivation. As early as the 1970's Singers and Ames proposed a correlation between the amount of UVC and the GC content of a microorganism and the effect of the formation of thymine dimers on DNA GC content [42]. Their theory proposed the high GC content indicated less thymine dimers would be formed, resulting in less UVC damage, ultimately being more resistant to

UVC. Bacterial GC content ranges from 13% to 75% (conversely 25 to 87% AT ratios) so it could be assumed as true [41]. However, two further studies disproved this theory, one proposed by Bak et al. [43] that unicellular organisms that do not follow any correlation and proposed that the distribution of GC content is shown in a random state [44]. This was corroborated by using more sophisticated analytical technology by Yang [44] who examined thymine and double thymine in 30 bacterial DNA sequences and showed this GC to be in a random state and limited congruence to UVC exposure.

It may be that susceptibility to UVC in microorganisms may be a combination of penetration of photons, DNA sequence and repair mechanisms. As such, studies on individual organisms should be undertaken if it is going to be used to tackle decontamination with multi-drug-resistant pathogens or spore forming bacteria known to persist in the environment. A number of studies have now been undertaken and a comprehensive table of pathogens *vs* dosage from 244 references has been compiled and described by Masjoudi et al. [45]. The lamp type is documented and the data tabulated by Fluence (UV Dose) (mJ/cm^2) for a given $\log_{10}$ reduction without photoreactivation [45].

UVC dose and intensity for optimum deactivation of microorganisms

Work undertaken in studies have shown that that bacteria are more susceptible to UVC with variable doses required on the strain under test [2]. Some of the key pathogens causing HAI have been studied and shown that Methicillin Resistant *Staphylococcus aureus* (MRSA) require approximately the same dosage as the sensitive strain (2.8-18 mJ/cm^2) to achieve 4 $\log_{10}$ reduction using low pressure mercury vapor lamps [45].

In table 1, examples of the common HAI's are listed for reference, taken from Masjoudi et al. (Table 1).

TABLE 1
Some common pathogens and the dose required to produce up to a 4 $\log_{10}$ reduction on a surface.

	Fluence (UV Dose) (mJ/cm^{-2}) for a given log reduction without photoreactivation				
Pathogen	**Lamp type**	**1 log**	**2 log**	**3 log**	**4 log**
Staphylococcus aureus (methicillin resistant) MRSA	LP	1.2	2.4	3.7	4.8
Acinetobacter baumanii NCTC 12156	LP	0.6	1.8	3.3	4.8
Klebsiella pneumoniae	LP	5	7	10	12
Pseudomonas aeruginosa NCTC 13437-Antibiotic resistant	LP	0.7	1.5	2.3	6
Rotovirus SA-11 Monkey kidney cell line MA 104	LP	8	15	27	38
Candida auris AR Bank 0382	LP	21	32	55	90
Clostridum sporogenes	LP	5.2	11	63	95

Key: LP = Low pressure mercury vapor lamp.

Dosage (fluence- mJ/cm^2) is the amount of energy received by microorganisms over time. It is calculated by the dose calculation equation (1)

UV dose (mJ/cm^2) = UV Intensity (mW/cm^2) x exposure time (seconds)……Equation (1)

The intensity of the UVC from the lamps can be measured using radiometers and intensity is inversely proportional to the squared distance between the light source and the surface and is governed by the Inverse Square Law [2].

Measuring the dosage can be difficult in a healthcare setting unless the system has internal controls or external devices are used. Therefore, a dose of 100 mJ/cm^2 based on several different studies comparing dosage to $\log_{10}$ reduction in organism numbers is usually used as an indication of appropriate emission [24,45,46]. Two simple devices used within the environment to monitor appropriate emissions are 1) Radiometers which give a numerical readout when placed in the vicinity of the UVC emitter of irradiance at the appropriate wavelength and 2) Dosimeters, color changing papers, produced by (Intellego Technologies) [47-50].

Material degradation caused by UVC

Exposure times of 10-45 min for room disinfection and 25 secs to 5 min for medical equipment are reported in the literature [51]. It is important not to overcompensate the dosage when operating the UV-C system as too high a dose can cause material degradation within the room and may affect medical equipment [24]. Therefore, dosage optimization is extremely important. Some studies have shown that prolonged use of UVC can affect surface integrity, thus causing problems with polyethylene coatings and silicon rubber insulators in some medical equipment [52,53].

Healthcare studies

Contamination of environmental surfaces in healthcare is important in the transmission of infection and of growing concern is the impact this may play in Healthcare Associated Infections (HAIs), especially with multi-drug-resistant strains of Methicillin Resistant *Staphylococcus aureus* (MRSA) and spores of *Clostridioides difficile* which can survive in the dust and on surfaces for prolonged time periods [54]. It is then possible to contaminate the patient, or healthcare worker through touch or with contaminated objects of greatest concern is the possibility of contracting infection from the previous occupant through contaminated surfaces [54-56]. Terminal cleaning of the room is undertaken following discharge of the patient but it is not always successful at eradicating any potential pathogens therefore anything that can reduce pathogens on surfaces and other source of infection should be welcomed [57].

Comparison of room disinfection systems and operational challenges

Whole room disinfection systems are becoming more accepted within healthcare settings, hydrogen peroxide (H_2O_2) decontamination devices and UVC being most utilized. Each have their advantages and disadvantages however, although UVC systems have a shorter delivery time, there are concerns over shadowing and the UVC not reaching its target [58]. Hydrogen peroxide systems have the ability to perfuse through the atmosphere and decontaminate all surfaces in adjacent rooms, such as bathrooms, but are the costliest to use in terms of time needed by the operator and time the room is out of action [58].

In 2022, a full review of reported studies using four methods of automated Whole Room Disinfection (WRD) was reported. This is

used as an adjunct to manual terminal cleaning currently and until this review there was limited data on the efficacy *in situ* [59]. Four devices were identified in the hospital setting 1) Aerosolized Hydrogen Peroxide (aHP), 2) gaseous hydrogen peroxide and 3) UVC and Pulsed-Xenon UV (PX-UV). The review considered *in vitro* evaluation of the system and *in situ* studies. The systems showed excellent efficacy with *in vitro* evaluation with H_2O_2 vapor systems having the highest *in vitro* efficacy, followed by UVC. In contrast, however, *in situ* evaluations demonstrated less optimal environments and because with the contamination parameters were a total unknown, outcomes were difficult to fully assess [60-63]. The benefits and limitations are summarized in Table 2.

TABLE 2
Comparison of whole room disinfection methods.

	Method of disinfection	Operational practicalities	Advantages	Limitations	References
Aerosolized H_2O_2 (AHP)	5-6% hydrogen peroxide fogged into a room. Dry mist formed and disinfects contact surfaces. Naturally broken down to water and oxygen after exposure.	User friendly. One unit therefore easy to transport. Preparation includes cleaning, sealing of vents and doors with tape.	Capable of disinfecting difficult-to-reach areas, such as the inside of a drawer or the back of a closet.	Particles are affected by gravity. Unidirectional nozzle can mean the distribution particles is sometimes not homogeneous. H_2O_2 is toxic room has to be vacated during disinfection. Re-entry when concentration of H_2O_2 declines to 1 ppm. (aeration phase). Lengthy cycle time (2-3hrs).	[59-61]
H_2O_2 vapour	Evaporation of a 30-35% H_2O_2 solution into a room. H_2O_2 is broken down to water and oxygen after exposure. Facilitated by an aeration unit which reduces the disinfection cycle time.	H_2O_2 vapour systems consist of multiple units. More complicated than AHP systems to operate. Preparation includes cleaning, sealing of vents and doors with tape.	Ability to disinfect difficult-to-reach areas. Heat heat-generated evaporation of H_2O_2. Multiple nozzles on the devices, the H_2O_2 vapour is homogenously distributed.	H_2O_2 is toxic room has to be vacated during disinfection. Re-entry when concentration of H_2O_2 declines to 1ppm. (aeration phase). Due to the active aeration unit, the cycle time (the disinfection cycle excluding preparations) is reduced compared to aHP (1.5 to 2hrs). HPV systems can cause micro-condensation on surfaces potentially enhancing the biocide efficacy but also damaging coatings.	[59-63]

UVC	UVC emit a radiation with a wavelength of 254 nm. Constantly emitted during the disinfection cycle.	A range of UV-C systems are currently available. Stationary systems have to be moved within the patient rooms by an operator in between disinfection cycle to disinfect all areas. Robot systems move autonomously through a room. Room has to be cleaned and vacated before disinfection.	UVC has a short disinfection time. The room is immediately accessible after disinfection. No aeration is needed. Disinfection with a stationary device is estimated at 50 min. Robotic system takes 10-20 min. No chemicals are used therefor no residue.	**Shadowing:** Pathogens are protected when shadowed by objects (e.g. equipment, chairs, beds), as the UV radiation cannot reach such pathogens. **Pathogen coating:** Pathogens within respiratory droplets and aerosol particles are shielded from the full effects of UV radiation partially. **Logistical issues:** Logistical issues that include the operation, scheduling, and moving of UV fixtures limit the adoption of systems as they cannot be used when humans are nearby. **Distance of object from UVC emitter:** Objects in a patient room containing polymers (i.e. medical devices and consumables) are susceptible to UV radiation and might be damaged.	[58,59]
PX-UV	PX-UV emits radiation of a broad spectrum of wavelengths (200-320 nm). This spectrum includes both UV-C, UV-B and UV-A radiation. Moreover, the radiation is not emitted continuously, but with short pulses.	Single operational unit. Stationary unit. Room has to be cleaned and vacated before disinfection.	Disinfection of a single room including the manual repositioning of the stationary device, only takes approximately 12-20 min.	Environmentally friendly as no chemicals are used in the disinfection process. No residue is left. Similar to UV-C, the main limitation of PX-UV is the limitation of its efficacy due to shading. Other factors limiting the efficacy of UV are an increased distance between the device and the surface and a shortened disinfection time.	[59]

Use of UVC to decontaminate rooms

Different UVC equipment can be used for room decontamination depending upon the conditions. Usually, UVC robots, UVC lamp units and reactors are placed within the room and operated for a set time period, either determined by internal controls or by external process conditions [60,64]. Many systems require manual repositioning in between cycles to ensure complete UVC coverage of the surfaces during emission and this operational time has to be factored into costings when purchasing decisions are made. They are a number of

different UVC systems and they differ based on the number and type of UVC lamps used, number of columns, the use of robotics and use of internal monitoring controls [59]. The operation of these systems has to be sufficiently flexible so they can be used within any shaped room. The operational time and placement of lamps/columns is usually recommended by the manufacturer and some systems do automatic internal mapping and decide on the necessary operational time [59]. Flexibility of the systems is paramount and there are some with a single tower and eight to ten lamps and built with integral radiometer control, robotic systems allowing movement within surfaces and multi tower systems which can allow flexibility of emission to reach areas of shadowing [65-68]. It is therefore important that when choosing the system for your facility it meets the requirements of the standards (BS8628;2022) as well as the requirement of the users.

It has been shown that terminal cleaning plus UVC emission can reduce the numbers of microorganisms on surfaces and in the air in healthcare settings and there have been a number of different systems assessed in a range of environments including dentistry [69-71]. In a recent study undertaken in a burn's unit in Denmark in 2020, Lindbald and colleagues [46], demonstrated the levels of UVC on the surfaces depended on the locations in the room; i.e. the distance from the UVC emitter and whether any surfaces were in the shadows from the UV light. It was shown that the UVC levels in different areas varied between 15.9 mJ/cm^2 and 1068 mJ/cm^2 (median 266 mJ/cm^2) within the room. Surfaces, at shorter distances and in the direct line of emission of the UVC device showed statistically significant higher UVC levels than surfaces in the shadow of equipment and that the dosimeter color change corresponded with the radiometer readings [46].

The outcomes of any *in situ* application of UVC are as only as good as the trained operatives and when a dedicated team is used, HAI infection rates can reduce, especially in high through put areas. In one study, using a dedicated UV disinfection team, HAI rates decreased by 16.2% following program implementation [72]. In another study, UVC was fixed to the ceiling of rooms (each unit contained a fully shielded chamber with a UVC bulb housed atop a standard 2 × 4 ceiling light fixture) and activated following cleaning with the normal disinfectants [73]. Following a 12 pre-installation and 12 months post study, the use demonstrated an average reduction of 8.8-3.5 infections per month and a reduction in infection rate of 20.3%-8.3 % in a one-year period [73].

UVC systems have also been used during orthopaedic surgery and reduction in infection rates noted [74]. Over the long term, further cross-over studies need to be undertaken to determine whether there is a genuine overall reduction in infection rates in patients. If this is demonstrated conclusively then all hospitals should use terminal cleaning adjuncts and create the cleanest possible environment for the patients housed in the rooms and wards. In the wake of HAIs, especially those that are drug resistant, then this would seem a sensible approach to preventing infection going forward.

Conclusion

UVC is a great adjunct following terminal cleaning to reduce bioburden in the environment that could potentially be the source of healthcare associated infection. The costs of purchasing these systems are substantial so the benefits of using them in healthcare environments are very important. Logistical challenges of their implementation such as ease of use, who will operate them and maintenance are all important factors. In addition, compliance with the

microbiological efficiency demonstrated by the new standard (BS8628;2022) is of paramount importance. Negative attributes, such as shadowing and material degradation could be overcome by having more controls (either internal or external) that determine dosage more accurately. Some manufacturers have already started to address these by incorporation of radiometers within the systems, using robots to allow movement of the towers and also adding additional towers that can emit UVC from different positions (horizontally and vertically), to give more flexibility and overcome shadowing. The use of UVC decontamination systems going forward should reduce infection rate of pathogens known to be acquired from a contaminated environment and make hospitals a safer place for the patient.

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