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Ultraviolet-C effectiveness for bacterial decontamination in the hospital setting: A systematic review

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ABSTRACT

Introduction: Bacteria are the most common agent reported to cause hospital-acquired infection (HAI) and nurses play a key role in achieving optimal decontamination. Ultraviolet-C (UV-C) is a promising candidate to reduce the bacteria infection burden. Therefore, this review aims to explore the UV-C application and its effectiveness in reducing bacteria contamination on various objects that can act as sources of HAI transmission.

Methods: Searches were conducted on the PubMed, ScienceDirect, Scopus, and Cumulative Index to Nursing and Allied Health Literature databases. The inclusion criteria were randomized clinical trials, and non-randomized clinical intervention studies, written in English and published between January 2018 and March 2023. The search strategy used a population (P), intervention (I), comparator (C), and outcome (O) approach.

Results: A total of 21 eligible studies were included in this review with four being related to decontaminating medical devices, two to personal equipment, nine to communication devices, and the remaining six to the environment. The exposure to UV-C radiation varies ranging from 24 s to 24 h (continuously) and it reduced the level of bacteria even up to 100%. Meanwhile, previously the objects were detected to be contaminated with pathogenic and resistant bacteria.

Conclusion: UV-C exposure can be effectively used to decontaminate various objects in hospitals. However, special consideration should be given to semi-critical devices due to contact with mucosal tissue. Further studies are needed regarding the application of doses and duration of UV-C exposure to eliminate bacteria completely.

Keywords: Ultraviolet-C; decontamination; bacteria; hospital-acquired infection; HAI

INTRODUCTION

Hospital-acquired infections (HAI) also known as health-care-associated and nosocomial infections continue to be a problem worldwide. The global HAI rate is 0.14% with an increase of 0.06% per year and the highest rate is in the African region (1). According to the Centers for Disease Control and Prevention (CDC), about one in 31 patients has at least one treatment-related infection acquired while in the hospital (2). The most frequent of HAI include pneumonia, surgical wound infections, gastrointestinal infections, urinary tract infections (3). Moreover, the World Health Organization (WHO) (4) emphasizes that HAI leads to prolonged hospitalization, long-term disability, increased resistance of micro-organisms to antimicrobials, enormous additional costs, and unnecessary deaths.

Bacteria are the most common causative agent in many reported cases of HAI. Gram-positive organisms include *Streptococcus* spp., *Enterococcus* spp., coagulase-negative *Staphylococci*, *Staphylococcus aureus*, and *Clostridioides difficile*. Meanwhile, gram-negative organisms include *Escherichia coli*, *Klebsiella pneumoniae*, *Klebsiella oxytoca*, *Proteus mirabilis*, *Pseudomonas aeruginosa*, *Acinetobacter baumanii*, *Burkholderia cepacian*, *and Enterobacter* spp. Some bacteria that are resistant to various antibiotics. Examples of such bacteria are *methicillin-resistant Staphylococcus aureus* (MRSA), *vancomycin-resistant Enterococcus* (VRE) (3,5). These bacteria can be acquired from other patients, hospital staff, as well as contaminated facilities (3,6). Hospitalized patients with immunosuppression, older age, and some underlying co-morbidities (e.g diabetes mellitus) might also increase the risk of HAI (5).

Decontamination practices including cleaning, disinfecting, and sterilizing all potential sources of bacteria are a critical part of HAI prevention (7). Medical devices based on level of contact are divided into three categories consisting of critical such as surgical instruments, semi-critical including endoscopes and respiratory therapy, as well as non-critical namely reflex hammers which require appropriate decontamination (8). Additionally, communication tools such as mobile phones and tablets used by both health

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workers and patients, objects used by health workers, as well as the environment where patients and staff come into contact can become vectors and require optimal decontamination (9-11).

Nurses play a vital role in assisting with infection control and prevention in the hospital setting. They have responsibility for the safety of the patient's environment, including environmental cleanliness and medical device decontamination (12,13). Nurses facilitate patient recovery while minimizing infection-related complications by leveraging skills and knowledge of the nursing practice (13). Moreover, caring is dynamic and can change over time due to many factors, one of which is based on the latest technological developments to improve service quality (12). This also applies to the use of technology for decontamination which should be pursued to increase the effectiveness and efficiency in reducing bacteria (14).

Ultraviolet-C (UV-C) technology is a candidate to optimize decontamination practice. It should be noted that UV-C has a wavelength range of 200–280 nm, which is considered the most germicidal wavelength range. At this wavelength, DNA absorbs photons and induces the formation of bipyrimidine dimmers, mainly photospore products (15,16). UV-C is widely used to decontaminate bacteria in various fields such as water decontamination (17). UV-C with 222 nm is known to have an effective effect on inactivating bacteria, yeast, viruses, and endospores. Whereas UVC 225 nm had a better fungicidal effect on fungal spores and hyphae (18). In vitro studies also show that exposure to UV-C for 10-20 seconds can effectively inactivate several HAI-related microorganisms such as *P. aeruginosa, E. faecalis, A. baumannii, S. enterica, E. coli and S. aureus.* (19).

Therefore, this review aims to explore UV-C application and its effectiveness for decontamination of bacteria present in various objects in contact with patients and healthcare workers, as well as the environment. It is expected to provide important information on UV-C application in hospitals and facilitate further robust investigations to assess the extent of utilization in the future.

METHODS

This study was carried out based on the updated Preferred Reporting Items for Systematic Review and Meta-Analyses (PRISMA) guidelines (20). It was registered in PROSPERO with the registration number CRD42023400108. The compilation strategy used a population, intervention, comparator, and outcome (PICO) approach (21). The population is patients and health workers who come in contact with medical and communication devices, personal equipment, as well as the environment. The intervention given was disinfection with UV-C, without a comparator or with other decontamination methods, and routine decontamination as a comparator. The outcome is the level of bacteria colonies or the level of reduction in contamination.

Search strategy

The literature review was conducted in four databases, namely PubMed, ScienceDirect, Scopus, as well as Cumulative Index of Nursing and Allied Health (CINAHL). This strategy compiled variations in terms through synonyms and Medical Subject Headings (MESH) to create the search keywords to be applied using the logic of Boolean and Wildcard, according to the requirements of each database. Subsequently, the searching process was initiated using the following keywords: (ultraviolet-C OR ultraviolet OR UV-C lamp OR UV-C OR UV light) AND (decontamination OR disinfection OR disinfectant OR decontaminant OR sterilization) AND (medical devices OR medical equipment OR equipment OR environment OR telephone OR communication devices) AND (bacterial OR bacterial growth) AND (hospital OR inpatient). The articles included in this review were those published between January 2018 and March 2023. The Inclusions criteria were randomized-clinical trials, and non-randomized clinical intervention studies with pre-post design, non-equivalent control group, stepped-wedge design. Meanwhile, the exclusion criteria were various types of reviews, case reports, editorial materials, books, and comments, articles that discuss trends in the use of UV disinfection but do not provide trial data, as well as those with ineffective disinfection results against bacteria reduction.

The study selection process was based on the inclusion criteria mentioned in the search process. The initial screening was conducted to exclude irrelevant titles, abstracts, and full-text articles, followed by an independent review regarding the eligibility of the retrieved articles. The reviewers screened, selected, validated, extracted data, and assessed the methodological quality of all text articles. Disagreements in these processes were resolved by discussion, while data extraction items were added, deleted, or adjust as agreed by all members of the review team. The PRISMA flow chart in Figure 1 illustrates these findings and explanations for articles excluded at the full-text stage.

Included studies were qualitatively analyzed by presenting information on the UV-C intervention in detail, including brands, wavelengths or doses, duration, and presence of pre-cleaning, as well as disinfected objects, bacteria involved, and the result. The results can be in the form of changes in the calculation of bacteria colonies before and after disinfection with UV ($p < 0.05$) and/or the percentage of the effectiveness of interventions on bacteria loads. When there is a comparative group, the results of the UV disinfection effectiveness are compared with the comparison group as shown in Table 1.

The risk of bias in the included studies was assessed by the two reviewers independently using the revised Cochrane risk-of-bias tool for randomized trials (RoB 2), cluster-randomized trials (RoB 2 CRT), and randomized crossover trials (22) to assess randomized and clinical trials. Meanwhile, non-random studies were assessed using the Risk of Bias tool for Non-randomized Intervention Studies (ROBINS-I tool) (22).

RESULTS

The PRISMA flow diagram for study inclusion is shown in Figure 1 which involved an electronic search on four databases and produced a total of 3906 articles. After removing duplicates, comments, reviews, letters, and titles that were not appropriate, the articles were reduced to 110 for full-text assessment of eligibility. Among these, 89 articles

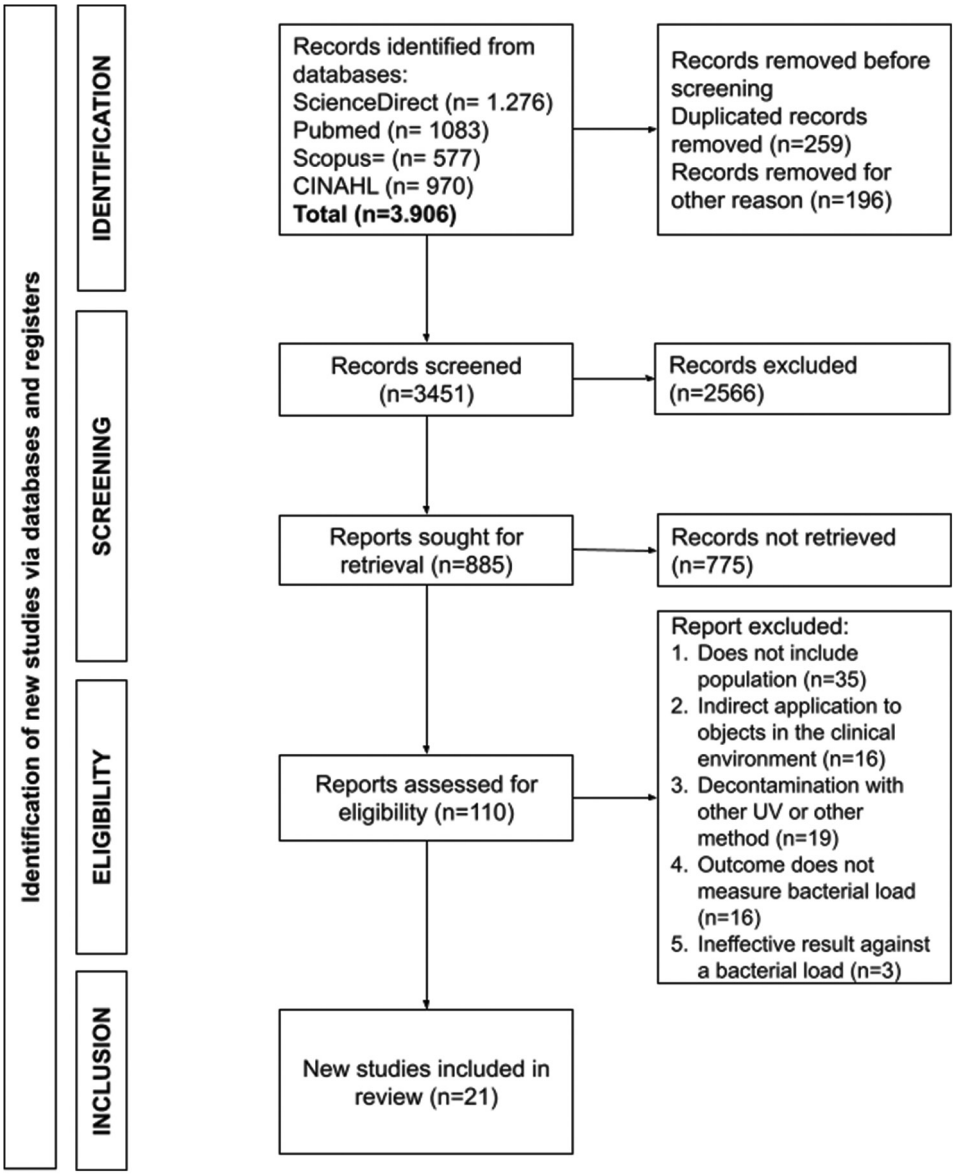

FIGURE 1. PRISMA protocol flowchart from search strategy and selection of relevant studies to finding studies that are included in the review.

were excluded because they did not meet the inclusion criteria, leaving a total of 21 for narrative synthesis as shown in Table 1. Out of the 21 included studies, there were 5 with RCT designs, 1 RCT cluster, 1 crossover, and 14 non-randomized clinical interventions. All samples were taken after the patient and/or health worker contact while in the hospital, or after the identification of bacterial contamination in the sample, then inoculation was carried out on the object for the decontamination test.

The objects disinfected using UV-C are categorized as medical and personal equipment, communication tools, as well as the hospital environment (Table 1). Medical devices in studies that were decontaminated using UV-C include stethoscopes, reflex hammers, vein tourniquets, Frenzel nystagmus glass, tuning forks, bandage scissors, bottle and content for nasal irrigation, as well as endoscopes (rhinoscopy/laryngoscopy). UV disinfection can also be applied to communication devices that are often used in hospitals, such as personal mobile devices, smartwatches, Vocera badges, Vocera collaboration suite or iPod touch, shared pens and stylus, and iPad with a protective case. In addition, N95 masks and contaminated shoe soles can be decontaminated using this technique. The application of UV-C disinfection to the environment has become very common since the beginning of the 2019 Corona Disease Pandemic (COVID-19) (23). It can be used to decontaminate bacteria from the air and surface of the room in the hospital.

Various brands of UV-C disinfection devices with different sizes and doses are used in these studies to reduce, or even eliminate all bacteria in objects. Tools have a variety of shapes, ranging from pen-like, or storage boxes to open-shaped which can emit radiation for large rooms. Meanwhile, the same UV-C wavelength can have different radiation strengths depending on one of the spaces receiving the lighting, while the dose is expressed in joules/square millimeter (J/m^2) or milli joules/square centimeter (mJ/cm^2) as described in some studies.

Some objects require pre-cleaning to remove the visible dirty parts before UV-C is applied, such as using water-based tissue. Objects with uneven surfaces such as endoscopy, generally require pre-cleaning before irradiation. Furthermore, UV-C disinfection is confirmed through bacteria colony

TABLE 1. Summary of studies demonstrating the utilization and effectiveness of UV-C for bacterial decontamination of various objects in a hospital setting

Author	Study Design	Object for decontamination	UV disinfection brand/ Prototype; Wavelength and Doses	Duration; precleaning	Comparison/other decontamination methods	Bacteria	Author's result
Medical equipment							
Rudhart et al. (2022) (40)	Pre-post design	Stethoscope, Reflex hammer, Vein tourniquet, Frenzel nystagmus glass, Tuning fork, Bandage scissor	D25 UV light system; 253.7 nm and 6872 μW/cm^2	25 s; water-based wipe	None	*Staphylococcus* spp., *E faecium, Bacillus* spp., *P. aeruginosa, Corynebacterium* spp., *Paenibacillus 2, M. luteus, Pantoea spp., R. mucosa*	After UV disinfection, 118 out of 120 samples were proven sterile, and only a small amount of contamination in two samples by normal skin flora bacteria with 0.02±0.1 CFU. Residual contamination of 1 CFU Bacillus sp was still detected on the tourniquet surface.
Husain et al. (2020) (41)	Non-equivalent control group	Bottle and bottle content	SteriPen Ultra Katadyn Product, Inc; Not explained	24 and 48 s (for bottle and content); none	Stage 2 (Bottle content): Water Distiller, carbon filtration, reverse osmosis, boiling method Stage 3 (Bottle and content): Two different bottles without agitation	*S. aureus, B. subtilis, P. aeruginosa,* and *L. pneumophila*	Stage 2: Decontamination of tap water and bottled distilled water by UV results in>99% reduction of bacteria. Stage 3: UV exposure to uncontaminated tap water without agitation gave a reduction of 97.96% in 24 s and a reduction of 100% in 48 s. There was no growth of *L. pneumophila* and *B subtilis* bacteria.
Rudhart et al. (2020) (42)	Pre-post design	Endoscopes (rhinoscopy/ laryngoscopy)	D25 UV system (UV Smart B.V., Delft, The Netherlands); 253.7 nm and 6872 μW/cm^2	25 s; water-based tissue (Tristel Rinse Wipes, Berlin, Germany)	None	*Coagulase-negative Staphylococcus, M. luteus, Neisseria* spp., *Viridans streptococci, S. aureus, Bacillus* spp., *Corynebacterium* spp., *P. aeruginosa, E. coli, Proteus spp., Enterobacter cloacae, Enterococcus* spp., *H. streptococci*	After decontamination, only 10% (n=5) of endoscopes were slightly contaminated with an average value of 0.12 CFU (±0.39) by normal skin flora bacteria. The remaining 90% of the sample (n=45) showed no more bacterial contamination (0 CFU).
Sebastian Marcos et al. (2020) (43)	Crossover study	Stethoscopes	A biosafety cabinet (LabGard Energy Saver with Philips UV 30W tube); 253.7 nm	1 min	Isopropyl alcohol (70%) swabs (Universal Alcotip preinjection swabs, Shermond, UK) Anistel (Tristel Solutions, UK)	No bacteria identification	Bacterial contamination after UV disinfection was reduced to 67.9% (95% CI, 36.48–99.33). All stethoscopes returned positive cultures after 24 h and were then re-disinfected.
Personal equipment							
Jiang et al. (2021) (44)	Randomized controlled trial (RCT)	N95 respirators (3M™ 1860, 3M™ 8210)	3B Medical Lumin UV Sanitizer and Disinfectant for CPAP Mask; 330 mJ/cm^2	5 min on each side; None	72 h at room temperature ("time"), heat at 70°C with a dry oven for 30 min ("heat")	*E. coli*	The value of the decrease in bacterial colonies after UV treatment was not specifically explained. However, all treatments were associated with a reduction in bacterial counts of 8.6 colonies (95% CI−11.6 to−5.5, with p<0.01).

(*Contd...*)

TABLE 1. (*Continued*)

Author	Study Design	Object for decontamination	UV disinfection brand/ Prototype; Wavelength and Doses	Duration; precleaning	Comparison/other decontamination methods	Bacteria	Author's result
Rashid et al. (2018) (37)	A single-blind Randomized controlled trial (RCT)	Rubber-soled shoe soles	Not explained	1 min; None	No intervention control group	*S. aureus, E. faecalis, E. coli, C. difficile*	UVC exposure to the shoe sole significantly reduced contamination (Mean 2.79±1.25; p<0.0001). The highest reduction for *E. coli* (Mean 2.6±0.79), followed by *E. faecalis* (Mean 2.19±0.68), *S. aureus* (Mean 1.74±0.88), and *C. difficile* (Mean 0, 42±0.54) (p<0.0001, for all bacterial reduction). The bacterial count from furniture, bedding, and patient dummy samples was decreased from 96 to 100% to 5-8% after UV-C disinfection.
Communication devices							
Sumarli et al. (2022) (45)	Randomized controlled trial (RCT)	Mobile devices	UV-C sanitation device, Industrial-grade (Cubby+) (Vioguard, Bothell, WA); Not explained	90-s; None	No intervention control group	No bacteria identification	A significant reduction in bacterial growth was observed between baseline (17.33±2.66) and 3 h (6.08±1.27) with p<0.001.
Malhotra et al. (2020) (46)	Pre-post design	Personal mobile communication devices	UV-C device (PhoneSoap Med+Version 1, UT); Not explained	30 s; None	None	*S. aureus, E. faecalis, Pseudomonas* spp., *Acinetobacter* spp., *Coagulase-negative, Staphylococcus* spp., *B. cereus*	The average morning CFU pathogenic bacteria decreased from 274,341±497,241 to 5,171±20,832 after UV intervention with a decrease of 98.2% with p=0.038. Bacterial CFU at night also decreased from 718.8±1.320 to 9.38±35, 99.9% with p=0.049. The burden of pathogenic bacteria in 24 h with 2 cycles of UV disinfection decreased by 99.99% with=0.037.
Christie et al. (2021) (47)	Non-equivalent control group	Cell phones	UV-C device hands-free handle (PhoneSoap MedPro Version 1, UT); 254 nm	30 s; None	Germicidal wipes, Combine (UV+germicidal wipes)	No bacteria identification	Disinfection with UV-C achieved a 99.99% cumulative percent reduction with a mean of 0.91±0.37, whereas germicidal wipes achieved a 99.92% cumulative percent reduction with a mean of 0.86±0.31 with p=0.50.
Huffman et al. (2020) (48)	Pre-post design	Smartphone, Smartwatch, Vocera Badge, Vocera Collaboration Suite/ iPod Touch	CleanSlate UV; Not explained	30 s; None	None	*Acinetobacter* spp., *Arthrobacter* spp., *B. cereus, Coagulase-negative Staphylococcus, Coliform, Enterococcus spp., Ewingella* spp., *Gram-negative bacilli, Klebsiella* spp., *Pantoea* spp., *Pseudomonas, Serratia, Sphingobacterium, S. aureus*	Before UV-C exposure, B. Cereus and Gram-negative bacilli are only detected on 1 communication device. Only 4.65% (4/86) of the devices grew pathogenic bacteria after UV-C disinfection, and it was statistically significant to decrease bacterial growth (p=0.002)

(*Contd...*)

TABLE 1. (*Continued*)

Author	Study Design	Object for decontamination	UV disinfection brand/ Prototype; Wavelength and Doses	Duration; precleaning	Comparison/other decontamination methods	Bacteria	Author's result
Resendiz et al. (2019) (49)	Randomized controlled trial	Vocera Badges (Vocera; San Jose, CA)	UV-C cabinet (ReadyDock, CT); Not explained	30 s; None	Chemical decontamination	MRSA, VRE, or *C. difficile*	A 97% reduction of aerobic bacteria was achieved after UV-C irradiation and a 100% reduction in anaerobic bacterial growth. UV-C was more significant than chemical disinfection in reducing the growth of anaerobic bacteria with $p<0.01$.
Kaiki et al. (2021) (50)	Pre-post design	Mobile phone	Care222; 222 nm and 9-15 mJ/cm^2	1.5 and 2.5 min; None	None	MRSA and other bacterial	10% of mobile phones are found to be contaminated with MRSA. Exposure to UV-C radiation (222 nm) for 1.5 and 2.5 min (doses, 9 and 15 mJ/cm^2) achieved mean log10 MRSA CFU reductions of 2.91 and 3.95.
Emig et al. (2020) (51)	Non-equivalent control group	Shared pens and styluses	The Steri-Write system (North Canton, OH); 265-nm	30- and 90-s; None	Untreated with UV-C	*C. auris*, VRE, MRSA	The UV-C for 90 s was significantly more effective than the UV-C for 30 s in reducing *C. auris*, VRE, MRSA, and bacteriophage Phi X174. In comparison to untreated control pens, the UV-C for 90-s reduced the frequency of recovery of MRSA from 20% (14/69 participants) to 3% (2/69 participants) with $p=0.056$, and the mean number of MRSA colonies was reduced from 11 (range, 1-58 CFU) to 1.5 (range, 1-2 CFU) with $p=0.001$.
Muzslay et al. (2018) (29)	Trial I: Non-random Stepped wedge design Trial II: Non-equivalent control group	iPad Air 1 and Apple iPad mini 2 (screen and protective case)	D6000™ UV-C (Codonics, Inc., Ohio, USA); 254 nm	60 s; None	Not disinfected (Washout period)	Aerobic bacterial	Trial I: Contamination was higher in protective cases than in screens, the median was 42 CFU/25 cm^2. UV-C effectively decontaminated tablets below the detection limit (median was 0 CFU/25 cm^2) but were re-contaminated within 48 h. Trial II: Screen contamination is further reduced with daily device disinfection compared with 48 h of disinfection; the median is 2.5 CFU/25 cm^2.
Allen et al. (2020) (52)	A blinded randomized control trial (RCT)	iPad Air (Apple, CA, USA) with protective case (Otterbox, CO, USA)	UV device (PhoneSoap, Lindon, UT, USA); 3275 mW/cm^2	30 s; None	Isopropyl alcohol and quaternary ammonium germicidal wipes, no routine cleaning	Normal skin flora and *S. aureus*	UV decontamination reduced bacterial contamination significantly (risk ratio ¼ 0.29, 95% CI, ¼ 0.09±0.95) compared to no routine cleaning ($p<0.05$). Germicidal wipes also reduced the amount of bacterial contamination (risk ratio ¼ 0.17, 0.04±0.67).

(*Contd...*)

TABLE 1. (*Continued*)

Author	Study Design	Object for decontamination	UV disinfection brand/ Prototype; Wavelength and Doses	Duration; precleaning	Comparison/other decontamination methods	Bacteria	Author's result
Hospital environment							
Yang et al. (2019) (32)	Non-equivalent control group	Patient's room surface (7×3 meters), UV is placed in 3 positions	Hyper Light Disinfection Robot (Hyper Light P3); None	5 min at each site (total 15 min); None	Room without UV-C irradiation (control)	Multidrug-resistant *A. baumannii* (MDRAB), multidrug-resistant *P. aeruginosa*, VRE, MRSA, *A. fumigatus, M. abscessus*,	The reduction rate of bacteria from different patient rooms after UV-C was 100%, except for bed rails, bedside tables, and telephones (range 0-98%). A significant reduction in mean CFU after UV-C was shown after 24 h (35 CFU vs. 0 CFU, $p<0.0005$) and 48 h incubation (165 CFU vs. 0 CFU, $p<0.0001$).
Kelly et al. (2022) (33)	Non-equivalent control group	Rooms within the Trauma ICU, (1) on a portable table; (2) on a sink; (3) under the bed; (4) on the bed; and (5) behind a portable side table	Germicidal ultraviolet-C devices; 254 nm, 900 mW/cm^2 at 1 meter and 450 mW/cm^2 at 2 meters	20 min (5-min warm-up period, 15-min disinfect period); None	Aerosolized hydrogen peroxide (aHP) disinfection	Extended-spectrum beta-lactamase *K. pneumoniae*, carbapenem-resistant *K. pneumoniae*, MRSA, VRE, MDRAB and *C. auris*.	Bacterial reduction rates from 94.91% after UV-C devices disinfection, whereas aHP achieved an average reduction rate of 50.71%.
McGinn et al. (2022) (53)	Non-equivalent control group	Room for CT scan imaging (approx. 34 m2). 12 surfaces were taken around the room for samples	UVGI robot platform (Akara, Ireland) TUV 36W SLV, Philips, Netherlands); 254 nm and 13.01±4.36 mJ/cm^2	20 min to more than 45 min; daily routine cleaning	Manual disinfection using biocides	No bacteria identification	A significant decrease in CFU level after the UV-C procedure with $p\leq0.001$. The average rate of CFU decreased from pre-disinfection (Median=8) to post-disinfection (Median=2). A significant reduction in microbial load was measured after UVGI conditions ($p=0.001$) and manual cleaning ($p=0.05$).
Jennings et al. (2022) (31)	A blinded randomized control trial (RCT)	Air in the Operative field	UV-C LED; 278 nm	Depend on the surgical duration (Mean 57 min); None	A sham UV-LED	No bacteria identification	There was a statistically significant difference in total CFU level between the UV-C used during operation versus sham device (38 vs. 322, $p=0.0030$).
Ethington et al. (2018) (54)	Pre-post design	Air in the rooms at the special care unit (SCU)	UV-C room-level air cleaning (VidaShield; South Bend, IN); 253.7 nm	UV-C runs continuously; Hospital cleaning protocols	None	No bacteria identification	Airborne bacteria after UV-C installation in patient rooms were reduced by an average of 42% (175 vs. 102 CFU/m^3, $p=0.035$). There was also a decrease in the average airborne bacterial particles by 33% in the biohazard chamber and 46% in aisles with $p>0.05$
Astrid et al (2021)(55)	Non-equivalent control group	Waiting room in outpatient polyclinic with an area of 137 m2	UV-C robot (Ultra Violet Disinfection Robot® (UVD-R) by Clean Room Solutions); 254 nm; 25 mJ/cm^2 to 100 mJ/cm^2 (direct exposure within 1 m)	UV-C runs within 20-25 minutes	Unexposed from UV-C	*S. saprophyticus, S. lugdunensis, A. baumanii, A. viridans, S. pneumonia, S. aureus and E. casseliflavus*	UV-C significantly reduces microbial growth on surfaces after manual cleaning and disinfection. UV-C inhibits the growth of C. auris but is not killed effectively by standard UV-C disinfection cycles. Technical operator intervention is also required for the operation of the UV-C robot during the disinfection process.

CFU: Colony forming unit, *S. aureus: Staphylococcus aureus, P. aeruginosa: Pseudomonas aeruginosa, C. auris: Candida auris, A. baumannii: Acinetobacter baumannii, E. faecalis: Enterococcus faecalis*

counting using a colony forming unit before and after the intervention, changes in reduction value of the mean, standard deviation, and *p*-value, as well as the percentage of effectiveness. In studies with comparative intervention or control groups without intervention, the significance of the difference is also compared.

Some included studies present object contamination at the baseline point and pre-intervention specifically in the RCT design, while some show pre-intervention results without a baseline. Identification of bacteria that contaminate objects before disinfection was also carried out in 14 studies, one study found limited aerobic and anaerobic bacteria, while 13 others specifically identified the bacteria contaminating the object. Based on the included studies, the bacteria identified to contaminate medical devices include, *Staphylococcus* spp., *Enterococcus* spp., *Bacillus* spp., *Corynebacterium* spp., *Paenibacillus* spp., *Pantoea* spp., *Neisseria* spp., *Proteus* spp., *P. aeruginosa*, *E. faecium*, *R. mucosa and L. pneumophila*, *coagulase-negative Staphylococcus*, *Viridans streptococci*, *E. coli*, *Enterobacter cloacae*, and *H. streptococci.*

Meanwhile, bacteria that contaminate communication devices used by patients and health workers include *S. aureus*, *E. faecalis*, *B. cereus*, *Candida auris*, coagulase-negative *Staphylococcus*, *Pseudomonas* spp., *Acinetobacter* spp., *Staphylococcus* spp., *Acinetobacter* spp., *Arthrobacter* spp., *Gram-negative bacilli* spp., *Klebsiella* spp., *Pantoea* spp., *Serratia*, *Sphingobacterium*, MRSA, VRE, or *C. difficile,* and normal skin flora. The hospital environment can also be contaminated with *C. auris*, *M abscessus*, *A fumigatus*, MRSA, VRE, Multidrug-resistant *P. aeruginosa* (MDRPA), multidrug-resistant *A. baumannii*, extended-spectrum-beta-lactamase-producing *K. pneumoniae*, and carbapenem-resistant *K. pneumoniae*. The exposure of decontaminated objects to UV-C radiation varies, from 24 s to 24 h.

Tables 2 and 3 show the results of the risk of bias assessment, where clinical trial studies by randomization were assessed using risk assessment tools RoB 2, RoB CRT, and crossover with the results of four articles belonging to the "low" category and three classified as "some concerns" (Table 2). Most of the articles did not include details about how the randomization process was performed, as well as participant or intervention provider awareness of the assignment process. Providing sham interventions can reduce bias as reported by Jennings et al. (2022) using a sham UV-C lamp with a blinded process. Allen et al., (2020) and Rashid et al., (2018) also greatly reduced the risk of intervention-related bias in their studies.

In the study conducted by Sumarli et al. (2022), respondents who owned mobile devices were not blinded, they not only knew that their mobile devices were being sampled for bacteria examination but also knew whether their devices were selected for UV-C intervention. This condition might have raised their awareness and influenced hygiene practices. Furthermore, the outcome measures in Jiang et al. (2021) were classified as "some concerns," due to the varying respirator use times, which could increase the possibility of bias.

The risk of bias assessment for non-randomized clinical intervention studies using ROBINS-I is shown in Table 3. The results included one article in the "critical," 2 in the

TABLE 2. Risk of bias assessment of the included randomized studies using revised Cochrane risk-of-bias tool for randomized trials (RoB 2), cluster-randomized trials (RoB 2 CRT), and randomized crossover trials

Author	Risk of bias tool	Randomization process	Recruitment participant in a cluster RCT	Period and carryover effects	Effect assignment to intervention	Effect of adhering to an intervention	Missing outcome data	Measurement of the outcome	Selection of the reported result	The overall risk of biased judgment
Jiang et al. (2021) (44)	RoB 2	L			H	L	L	Sc	Sc	Sc
Rashid et al. (2018) (37)	RoB 2	L			L	L	L	L	L	L
Resendiz et al. (2019) (49)	RoB 2	Sc			Sc	Sc	L	L	L	L
Allen et al. (2020) (52)	RoB 2	L			L	L	L	L	L	L
Jennings et al. (2022) (31)	RoB 2	L			L	L	L	L	L	L
Sumarli et al. (2022) (45)	RoB 2 CRT	L	Sc		H	H	L	L	L	Sc
Sebastian Marcos et al. (2020) (43)	Crossover trials	L		Sc	L	H	L	L	L	Sc
Astrid et al (2021)(55)	RoB 2	L			L	L	L	L	L	L

L: Low, Sc: Some concerns, H: High

TABLE 3. Risk of bias assessment of the included non-randomized intervention studies using a risk of bias tool to assess non-randomized studies of interventions (ROBINS-I tool)

Author	Bias due to confounding	Bias in the selection of participants for the study	Bias in classifying interventions	Bias due to deviations from intended interventions	Bias due to missing data	Bias to measuring outcomes	Bias in selecting reported results	Overall risk of bias judgment
Rudhart et al. (2022) (40)	H	M	H	H	L	H	M	C
Husain et al. (2020) (41)	L	M	L	M	L	L	L	L
Rudhart et al. (2020) (42)	M	L	M	L	L	H	L	M
Malhotra et al. (2020) (46)	M	L	L	M	M	L	L	M
Christie et al. (2021) (47)	M	L	M	L	L	L	L	L
Huffman et al. (2020) (48)	L	M	M	L	L	L	L	L
Kaiki et al. (2021) (50)	M	M	M	H	L	L	L	H
Emig et al. (2020) (51)	L	L	L	L	L	M	M	L
Muzslay et al. (2018) (29)	L	H	M	L	L	L	L	L
Yang et al. (2019) (32)	M	L	L	L	L	M	L	L
Kelly et al. (2022) (33)	L	M	M	L	L	L	L	L
McGinn et al. (2022) (53)	M	L	L	L	L	H	L	M
Ethington et al. (2018) (54)	L	H	M	M	L	L	L	H

L: Low, M: Moderate, H: High, C: Critical

"high," three in the "moderate," and seven in the "low" category. The "critical" classification for the risk of bias assessment in the study of Rudhart et al. (2022) was due to the sample that was too varied with an unequal number per type of sample, even though all of them were classified as semi-critical medical devices. In addition, there was no single standard for each contamination and control group to compare interventions.

DISCUSSION

This systematic review explores the use of UV-C radiation on various hospital objects and assesses its effectiveness in reducing bacterial contamination. Several previous review articles may have discussed the use of UV-C to reduce the burden of pathogens that cause infection in hospitals. One of them provides a review of the effectiveness of UV-C in helping to disinfect environmental surfaces that have the potential to be exposed to SARS-CoV-2 as the cause of coronavirus disease 2019 (24). Another review article also describes UV-C as a tool that can be used for environmental decontamination from various agents, which focuses on the efficacy and safety of its use (25). This review is specifically focused on discussing the role of UV-C for decontamination of bacteria as the most common pathogens that cause HAI.

Medical device decontamination differs depending on the critical classification of the tool based on the WHO as previously explained (8). Based on the studies included in this review, medical devices are in the semi-critical and non-critical categories, where semi-critical devices require high-level disinfection based on CDC recommendations (26). Husain et al (2020) and Rudhart et al (2020) found a reduction in the bacteria contamination of endoscopes by up to 90%, as well as bottles and nasal water ranging from 97.96% to 100% after exposure to UV-C. Even though the level of reduction in bacterial contamination after the UV-C intervention is close to the optimal value, there is still a risk of bacteria remaining on the endoscopes as the part of semi-critical devices.

Rutala & Weber (2019) (27) explained that there are at least 3 reasons why the risk of outbreaks remains high in semicritical devices such as endoscopes. First, studies have shown that endoscopes may contain 107-10 (7-10-log10) enteric microorganisms. Therefore, any deviation from proper reprocessing may result in failure to remove contamination. Second, endoscopes have not only heavy microbial contamination (107-1010 bacteria) but a complex associated components that are difficult to clean and disinfect. Third, the presence of biofilms can influence the failure of endoscope reprocessing. Cadnum et al (2020) (28) also explained that UV-C technology is still considered not to meet decontamination criteria, and high-level disinfection cabinet remains more promising. Further investigation is needed for the application of UV-C radiation to semi-critical medical devices.

In contrast to the semi-critical types, most non-critical medical devices such as a stethoscope do not need to be transported to a central processing area for decontamination, rather, they can be decontaminated at the point of use. The disinfection process simply uses low-level disinfectants (26). Rudhart et al., (2022) and Sebastian Marcos et al., (2020) results showed that the reduction of bacteria in non-critical devices ranges from 67.9% to sterile (100% bacteria-free) after UV-C exposure. Pre-cleaning using water wipes can be applied to apparently dirty or non-critical objects with surfaces that tend to be uneven, thereby allowing a lot of dirt to be tucked in. However, the duration of UV-C exposure to non-critical objects should be carefully considered.

Communication devices such as mobile phones are a potential source of cross-contamination. Apart from personal use, most hospital employees often share cell phones at work and when the devices are not cleaned properly, they can carry bacteria that spread the infection to patients and hospital staff. Other communication devices such as tablets/iPad which are held by many officers to communicate patient health records can also be a medium for the growth of pathogenic bacteria (10,29,30). Given that they come in

contact with the skin, communication tools can be classified as non-critical (30). Based on the review results, UV-C exposure seems promising for the decontamination of communication devices. Short exposure for 30 min can suppress pathogenic bacteria and longer exposure can reduce resistant bacteria such as MRSA.

UV disinfection appears to be effective for decontaminating shoe soles as well as N95 masks that will be reused by healthcare workers. Regarding the use of UV-C for environmental disinfection, it depends on the classification of the environment as critical or non-critical (26). Noncritical environmental surfaces such as bed rails, bedside tables, and floors can become critical when they come in contact with the patient's mucosa or body fluids. According to the included studies, UV-C radiation is effective in reducing the bacteria load on air and surfaces in the hospital environment. A study used even UV-C exposure in the operative field and the results were effective compared to sham exposure (31). The application for 5 to 15 minutes on the surface of the room showed a reduction in infection by resistant bacteria such as MRSA and MDRPA (32,33).

Special attention is needed to review further studies evaluating the effectiveness of UV-C against Bacillus, Clostrium or Clostridioides bacteria. These bacteria are capable of forming spores and are persistent. Bacillus subtilis is an aerobic organism, while *Clostridioides difficile* (formerly *Clostridium difficile*) is an obligate anaerobic (34,35). Bacterial endospores or spores are among the most resilient cells. Due to their extreme resistance to several physical and chemical conditions, spores can spread and survive in the environment for long periods of time (35). Endospores can return to being vegetative cells that actively carry out metabolism when environmental conditions support the growth and reproduction of bacteria (36). Deliberately inoculating spore bacteria by leaving them in a supportive environment until the spores grow is carried out as in the study of Rashid et al (2019) (37) and then disinfected with UV-C. Another included studies involving spore bacteria did not explain about endospores, it can be concluded that only the vegetative forms are considered related to the effect of UV-C disinfection.

UV-C light irradiation for decontamination can be used for many purposes in hospitals. Fukui et al., (2020) concluded from their experiments that UV-C light with a wavelength of 222 nm at a dose of 50-500 mJ/cm^2 is harmless to humans but still germicidal (38). However, caution is required due to radiation exposure. Raggi et al. (2018) (39) explained that UV-C shows effective results in reducing bacteria contamination and is cost-effective. In addition, germicidal UV-C can be used to disinfect non-critical medical devices, reusable masks, communication devices, and the hospital environment because they are relatively safe with fairly good effectiveness.

Limitations

We could not perform a quantitative synthesis because UV-C decontamination is applied on various objects with different levels of contamination and different decontamination standards. In addition, the dose of UV-C given is also different and highly dependent on the type of UV-C device used in the inclusion studies.

CONCLUSION

UV-C can be applied to disinfect various objects in hospitals but consideration is needed regarding the importance of pre-cleaning before disinfection, the duration of exposure, and the dose given to optimize bacteria reduction. Given their critical level of contact with the body, semi-critical medical devices should use disinfection techniques based on CDC standards. However, UV-C exposure for bacteria decontamination is not advocated due to a lack of valid evidence. Based on the related low costs, coupled with its easy no-touch operation, as well as its effectiveness, UV-C can be widely used as a decontamination aid in hospitals.

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AUTHOR CONTRIBUTIONS

This systematic review project was conceptualized by RTA. Data were extracted, analyzed, and tabulated by RTA, IYW, EPL, and RL (including all figures and tables). Manuscripts were written by RTA, and EPL, and edited and checked for scientific content by RL. All authors have contributed significantly to the research design.

DECLARATION OF INTERESTS

Authors declare no conflict of interest.

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