Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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COVID-19 outbreak: Should dental and medical practices consider uv-c technology to enhance disinfection on surfaces? – A systematic review

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ABSTRACT

Aims: During the COVID-19 pandemic the search for complementary methods to enhance manual disinfection in dental and medical practices raised relevance. We sought evidence for the addition of ultraviolet-C (UV-C) disinfection to manual cleaning protocols –and whether it improves the logarithmic (log) reduction of surface pathogen colonies.
Methods: This review was registered at the International Prospective Register of Systematic Reviews (PROSPERO) under the number CRD420200193961. Six electronic sources were consulted looking for clinical trials performed in healthcare environments in which pathogens were quantified by colony-forming unit (CFU)-enumeration before and after interventions, all databases were last consulted on May 2021. We assessed the risk of bias using an adapted Revised Cochrane Risk of Bias Tool (RoB 2). The certainty of the evidence was qualified according to the Classification of Recommendations, Evaluation, Development, and Evaluation (GRADE) approach.
Results: We identified 1012 records and 12 studies fulfilled the inclusion criteria. All included studies reported enhanced disinfection in the UV-C arm; most of them reported 1-log to 2-log reduction in approximately 10 to 25 min. Only three studies reached a 5-log and 6-log reduction. When manual cleaning was performed alone, only two studies reported a 1-log reduction using a chlorine-based disinfectant. We detected a high risk of bias in 1 study. Certainty of evidence was classified as moderate and low.
Conclusions: The evidence points out the effectiveness of UV-C technology in reducing manual cleaning failures, enhancing the logarithmic reduction of surface pathogen colonies. However, the safety and success of these devices will depend on several physical and biological factors. A judicious project must precede their use in clinical and medical offices under the supervision of a physicist or other trained professional.

1. Introduction

The severe acute respiratory syndrome (SARS-CoV-2), a respiratory illness triggered by a novel strain of coronavirus that led to a global pandemic, had its first reports in December 2019 in the city of Wuhan, province of Hubei – China [1]. This highly contagious virus is transmitted mainly via respiratory droplets from coughs and sneezes [2], but also might spread through aerosols [3,4] and by indirect contact via contaminated surfaces [5]. The coronavirus disease 2019 (COVID-19) pandemic forced public health around the world to implement measures to slow the spread, presenting unprecedented challenges in infection control [6].

Disease transmissions in healthcare facilities can occur in several ways including indirect contact with contaminated high-touch surfaces that have been improperly sterilized [7]. The high-speed drill instruments used in dental practices can generate large amounts of aerosols and droplets potentially contaminated that can settle on surfaces presenting a significant danger to spread viruses. Aerosols are smaller particles that can remain suspended in the air for hours and over long distances contaminating the surrounding environment and surfaces

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when they fall [8]. As well as other common nosocomial pathogens, human coronaviruses can persist viable for up to 72 h on surfaces but they can be efficiently inactivated by manual cleaning using validated [9,10]. However, manual disinfection is often suboptimal due to various personnel issues and failure to follow the manufacturer's recommendations [11], and maintaining high standards of infection preventive measures is of high importance for dental and medical practices.

During the ongoing COVID-19 pandemic, improvements were implemented in 99.7% of dentists surveyed in the US [12]. A nationwide survey carried out in Brazil reported the impact on dental clinical routine was high or very high by 84% of respondents [13]. Several ways are proposed to reduce the risk of transmission, such as ceasing or rescheduling dentistry, screening patients before dental treatment, and inactive/removing the virus-containing aerosol by engineering controls together with the use of enhanced personnel protective equipment (PPE) [8]. Also, in experimental conditions, altering the physical response of water to the high-speed drill or ultrasonic forces showed marked suppression of aerosol generation and the distance any aerosol may spread [14]. Despite that, enhancing conventional methods requires the modification of human behavior, which is difficult to achieve and sustain. For this reason, non-touch decontamination devices such as the UV-C technology, have been suggested as coadjutant to reduce cross-contamination in healthcare facilities.

The UV-C irradiance is a particular spectrum of UV radiation in a range between 200 and 280 nm that has been used for several decades as germicidal for disinfection of nosocomial pathogens on air and water [15]. Over the UV-C range, a more detrimental effect on microbial cells occurs because the intercellular components of microbes (e.g., RNA, DNA, and proteins) can absorb UV-C photons, destroying their ability to multiply and cause disease [16]. Environmental disinfection in hospitals is often enhanced by applying a UV-C dose (irradiance × exposure time) that depends on the device used, either portable or fixed that can be controlled at a distance to prevent human exposure [17].

In addition to eliminating pathogenic agents, UV-C irradiation can be detrimental when the operator is directly exposed to light. The most common wavelength emitted is 254 nm, which overlaps the absorption of DNA/RNA. However, it can trigger dangerous effects on human skin, such as "sunburn" in the short term or skin cancer in the long term and in the eye, from photokeratitis to ultimately retinal damage [16], making it essential that personnel are absent during disinfection procedures. By contrast, UV-C radiation at 222 nm is reported as harmless for humans [18,19]. The devices approved adequately by local legislation must be displayed safety warnings and all operators adequately trained to avoid inappropriate usage.

Although the use of UV-C disinfection has been extensively reported, its success in improving the reduction of microbial colonization in real-life scenarios is still controversial in part because irradiation is limited by micro shadows [15]. Thus, our systematic review aimed to analyze the evidence from trials performed in healthcare facilities that assessed UV-C disinfection's ability to reduce manual cleaning failures enhancing the logarithmic reduction of nosocomial pathogens colonized on surfaces.

2. Methods

2.1. Protocol and registration

We conducted this review according to the recommendations of the Cochrane Collaboration for Systematic Reviews and reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 checklists for paper and abstract in **Table S1** and **Table S2,** respectively [20], and registered at PROSPERO (http://www.crd.york.ac.uk) under the registration number CRD420200193961.

2.2. Eligibility criteria

2.2.1. Inclusion and exclusion criteria

We included controlled and uncontrolled before-after trials, experimental or quasi-experimental performed in healthcare environments, in which CFU was counted before and after disinfection of exposed surfaces to calculate the log reduction of nosocomial pathogens provided by UV-C intervention compared to manual cleaning alone or another non-touch method. Extended abstracts, case reports, and those studies in which disinfection was performed in veterinary hospitals or laboratories were excluded, as well as opinion articles, descriptive studies, review articles, guidelines, and technical articles.

2.2.2. Search strategy and study selection

We based the search strategy on the PICO question: Can the addition of UV-C technology enhance the disinfection of contaminated surfaces in healthcare facilities? It was executed on five electronic databases (PubMed, Embase, Scopus, Web of Science, and the Cochrane Library) and one gray literature source (Grey Matters). Sources were last consulted on March 2021. The MeSH terms used were: "Health facilities", "Dental Clinic*", "Hospital*", "Ultraviolet Radiation C", "Ultraviolet rays" and "Disinfection". Both MeSH and the other input terms were adapted correctly according to each source's syntax rules, and the Boolean operators (OR, AND) were used to combine the terms as shown in **Table S3**. We inserted all citations found into a reference management software (EndNote®, version X7, Clarivate Analytics), and duplicates were manually and automatically deleted.

After duplicates removal, we assessed all citations by titles and abstracts for eligibility. Retrieved studies were then assessed by full-text reading without language restrictions or publication date. The selection was performed independently by two review authors (MA, SV), with a third reviewer to be consulted for final decisions (GM).

2.2.3. Extraction data

We extracted the following data from the included studies: authors, country, study design, health facility, description of the surfaces, sample characteristics (number of samples and pathogens identified in samples), UV-C technology intervention (device, wavelength (nm) applied, UV-C dose (J/m^2) or irradiance (W/m^2), exposure time), manual cleaning disinfectants, results (CFU counts, reduction (%), log reduction), statistical analysis and outcome. When missing, we calculated log reduction in those studies in which CFU counts were specified before and after interventions. In cases where the data were incomplete, doubts about the methodology, or cases in which the articles were unavailable for reading in full-text, the authors were contacted by email weekly for five consecutive weeks.

Extraction data was performed by two reviewers independently (MA, SV) and verified by a third reviewer (AB) to resolve discrepancies.

2.3. Risk of bias assessment

We assessed the risk of bias using an adapted [21] Revised Cochrane Risk of Bias Tool (RoB 2) [22,23]. Each study was analyzed for selection bias, performance bias, detection bias, attrition bias, and reporting bias through the following domains: description of sample calculation or large sample size; standardization of sample procedures (reproducible and comparable between groups); standardization of the manual disinfection method and blinding of operators; standardization of the UV-C performance and blinding of operators; blinding of outcome assessment; incomplete outcome data before intervention (description of pathogens identified in samples and colonization counts before the intervention); incomplete outcome data after the intervention (description of pathogens identified in samples, colonization counts after the intervention, and calculation of colonization reduction% and log reduction—or data available to calculate); and selective outcome reporting.

The possible risk-of-bias judgments were: low risk of bias, some concerns, and high risk of bias. We assessed the overall risk-of-bias judgment based on the following criteria: low risk of bias – the study was judged to be at low risk of bias for all domains for this result; some concerns – the study was judged to raise some concerns in at least one domain for this result, but not to be at high risk of bias for any domain; high risk of bias – the study was judged to be at high risk of bias in at least one domain for this result or the study is judged to have some concerns for multiple domains in a way that substantially lowers confidence in the result [23].

2.4. Level of evidence (GRADE tool)

The body of evidence was summarized guided by a narrative GRADE. According to this approach, the certainty in the evidence might be rated as high, moderate, low, or very low, depending on whether the risk of bias, inconsistency, indirectness, imprecision, and other considerations are serious or not serious.

The qualitative analyses were assessed by two reviewers independently (MA, SV) and verified by a third reviewer (BT) to resolve discrepancies.

3. Results

3.1. Study selection

We identified 1722 records in database searching. After duplicates removal, automatically and manually, we screened 1012 records by title and abstract and reviewed 65 full-text documents for potential eligibility; 54 articles did not meet inclusion criteria. The reasons for exclusions are detailed in **Table S4**.

Finally, 12 studies fulfilled the eligibility and we included them for qualitative analyses [24–35], no extra articles were found in references or other sources. Each phase of the selection study is summarized in **Fig. 1**.

3.2. Characteristics of the included studies

Among the 12 articles that fulfilled inclusion criteria, 11 are experimental studies (2 prospective) and 1 quasi-experimental [27]. All of them performed disinfection on high-touch surfaces in healthcare environments exposed to relevant nosocomial pathogens. Five of these studies were controlled before-after trials [24–28], assessing CFU counts

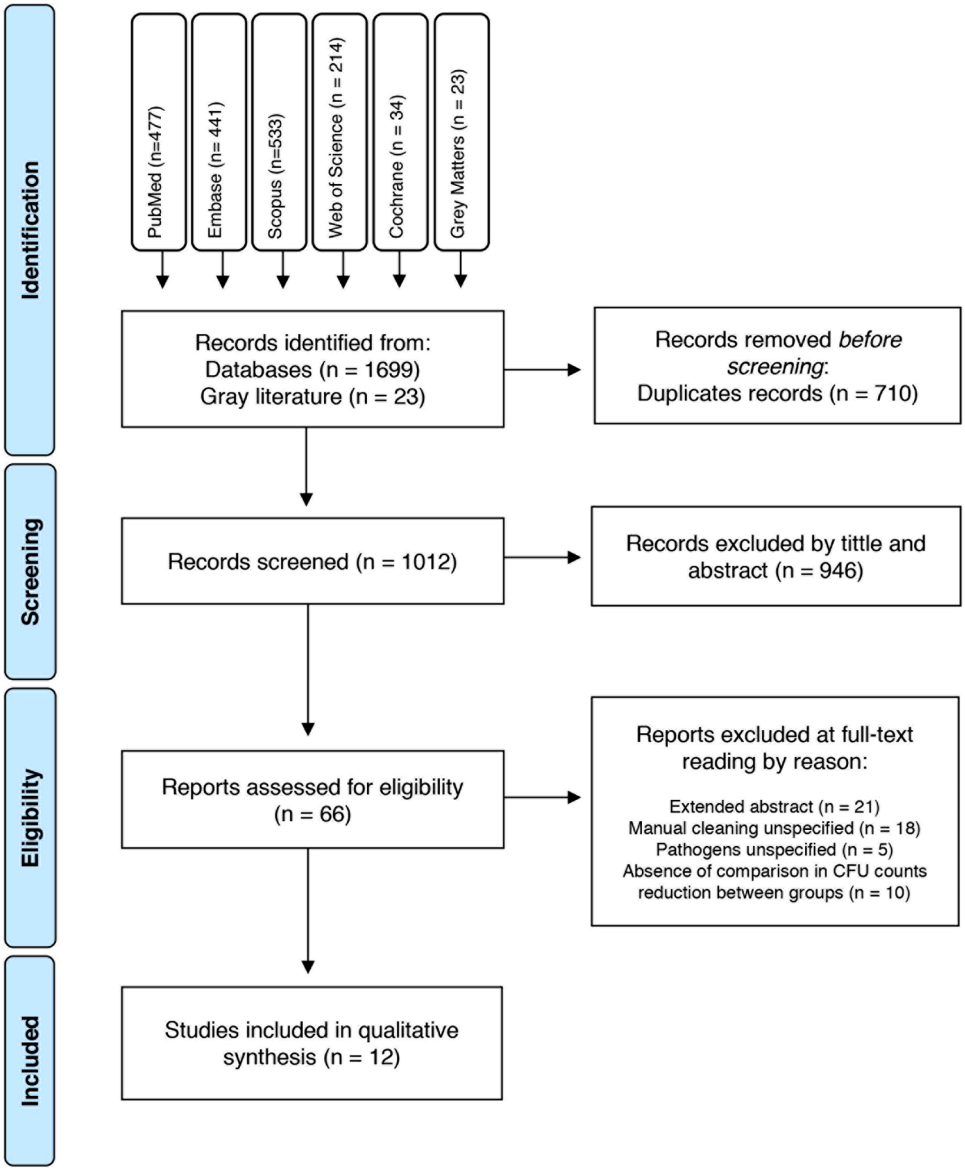

Fig. 1. PRISMA 2020 flow diagram summarizing each phase of this systematic review.

and log reduction provided by the addition of UV-C disinfection (308 samples) compared to manual cleaning alone or another no-touch method (299 samples). Seven studies were uncontrolled before-after [29–35], assessing the additional CFU count reduction provided by UV-C intervention (5112 samples) versus manual cleaning alone (5152 samples). Data extracted from each study are detailed in **Table 1**.

All the experiments performed a standard manual cleaning protocol with different validated disinfectants and cleaners: sodium hypochlorite (SH) in different concentrations, quaternary ammonium compound (QAC), hydrogen peroxide (HP), and detergent (DT). Although all of them performed manual cleaning after patients were discharged, each protocol presents at least one variation depending on the standard manufacturer protocols. One study compared UV-C and Hydrogen Peroxide Vapor (HPV) system (Bioquell) both in addition to manual cleaning with QAC [28].

The UV-C interventions were performed with different devices; 9 studies used the Pulsed Xenon Ultraviolet Light (PX-UV) (Xenex Disinfection Systems, San Antonio, TX, USA) varying from two to five 5-min cycles (depending on if the room had a bathroom) [24–27,29–31,33,34]. The PX-UV device emits both UV-B (315–280 nm) and the full UV-C spectrum (280–100 nm) at a pulsed frequency of >60 Hz.

Two studies used the Tru-D Smart UV-C (Lumalier Corp, Memphis, TN) [28,35]; Wong et al., used the R-D Rapid Disinfector system (Sterilize, Rochester, NY) as well [35]. Both devices emit low-pressure mercury UV-C light in the 254-nm range, but UV-C exposure times in the experiments were unspecified in the studies.

3.3. Results of individual studies

The statistical analysis in the studies assessed the difference of means or medians between the experimental arms. All the uncontrolled before-after trials demonstrated an additional reduction in CFU counts after UV-C intervention (using PX-UV, Tru-D Smart Lumalier, and R-D Rapid Disinfector devices). Better results were observed when the previous manual cleaning was performed using QAC and SH 10% or another chlorine-based disinfectant. All the controlled before-after studies reported a superior reduction in CFU counts in the UV-C group compared to the manual cleaning alone, but, in 2 studies, this difference was not significant. One of them performed manual cleaning with HP in the UV-C group and with SH 10% wipes in the control group [26]; the other study performed manual cleaning with QAC in the UV-C group and with SH 10% in the control group [24] (both used PX-UV device). In one study, the reduction in CFU counts after UV-C intervention (using Tru-D Smart Lumalier device) was superior compared to manual cleaning alone but inferior compared to the HPV system; both were performed in addition to manual cleaning with SH 10% or QAC [28].

The difference in CFU counts at baseline versus post-intervention indicates the intervention tested's log reduction capability; determined by neutralizing the treated and untreated samples at the same time and then counting the bacterial colonies [32]. The log reduction calculated for relevant nosocomial pathogens positive in samples is detailed in **Table 2.**

Both touch and non-touch disinfecting methods demonstrated a significant reduction in CFU counts of overall pathogens. When MRDOs were positive in samples, 3 studies reported $a \geq$ 2-log reduction: 5-log (99.999%) [34] and 6-log (99.9999%) [30,31] reduction after UV-C intervention in addition to manual cleaning with chlorine-based disinfectants and QAC. Only in 2 studies, manual cleaning without non-touch intervention reported a 1-log (90%) reduction using SH 10% and HP with peracetic acid [27,30]. In studies in which C. *Difficile* was found positive in samples, no methods reported more than 0-log (< 90%) reduction.

3.4. Qualitative assessment of studies and risk of bias

The majority of the studies exhibited a risk of bias, mainly related to sample calculations and operators' blinding. However, we judged them to be a low risk of bias because their samples were representative, and they mentioned a standardization of the processes. However, we judged 3 studies to be some concerns due to small sample sizes [31], incomplete data after the intervention [34], and missing information about the time of exposure in UV-C intervention [35]. Only 1 study was judged to be an overall high risk of bias due to a high risk in the attrition bias domain. The authors claimed a 6-log reduction but reported only the CFU counts after the intervention (not before), making it impossible to verify the log reduction [32]. An overview of the included studies' judgments is presented in **Fig. 2**, and the judgment of each study can be found in **Table 3**.

3.5. Level of evidence

In the narrative of the certainty of evidence using the GRADE tool for controlled before-after studies, we used the CFU counts differences between the intervention and control group. In uncontrolled before-after studies, we used the difference in CFU reduction between before and after interventions.

The certainty of the evidence for controlled before-after studies was judged to be moderate. The level was downgraded by serious inconsistency due to high heterogeneity across the studies, mainly because of the variety of manual cleaning protocols performed and different pathogens tested.

The level of evidence of uncontrolled trials was downgraded to low due to serious inconsistency and serious imprecision of estimates. The absence of a separated control group in these studies because of the nature of the studies' design, hindering the evidence's accuracy as shown in **Table 4**.

4. Discussion

Our systematic review aimed to summarize and analyze the evidence from clinical trials assessing UV-C disinfection's ability to enhance the log reduction of infectious agents remaining on surfaces after manual cleaning protocols. We included experimental and quasi-experimental trials after eligibility criteria. Out of the 12 included studies, only 1 study was judged to be a high risk of bias and all of them reported an enhanced log reduction of pathogen colonization after the UV-C intervention. However, the significance of this improvement varied according to the UV-C device and the manual cleaning protocol of choice. No merging of data was possible due to heterogeneity across the included studies. Thus, our review is focused on a qualitative analysis of the literature.

Some studies revealed that coronaviruses can persist viable on surfaces, such as stainless steel or plastic, for up to 72 h [9,10]. Although they can be efficiently inactivated by manual disinfection procedures with ethanol, hydrogen peroxide, or chlorine-based disinfectants [10], manual cleaning in real-life scenarios is often suboptimal due to various personnel issues and failure to follow the manufacturer's recommendations for disinfectant use [11]. These issues were also observed in our included studies, in which only 2 trials (conducted in the US and Canada), reported a 1-log kill rate (90%) reduction on MDROs colonization when manual cleaning was performed alone with a chlorine-based disinfectant or hydrogen peroxide with peracetic acid [27,30], the remaining 10 reported 0-log reduction.

According to The United States Environmental Protection guidelines (EPA), a disinfectant should achieve $a \geq$ 5-log ($\geq$ 99.999%) reduction in $\leq$ 10 min $\pm$ 5 s for qualifying bacteria to support residual disinfectant claims. Moreover, an acceptable non-residual virucidal efficacy (3-log reduction) should be demonstrated at $\leq$10-minutes to support residual virucidal claims [36]. To better understand the log reduction, if there are one million pathogens present on a surface, a 1-log reduction would reduce pathogens to 100,000 (90%); a 2-log would reduce to 10,000 (99%), and so on. Therefore if the disinfectant reached a 6-log reduction, it would leave only one in one million [37]. Thus, there is a significant

Table 1
Characteristics of the included studies.

Author Country Year Study design	Health facility	Surfaces	Characteristic of the sample Pathogens identified	No. of samples cultured	UV-C intervention arm Device and disinfectant used	Wave-length (nm)	Irradiance ($\mu W/cm^2$)	Time of Exposure	Control description	Statistical Analysis	Outcomes
Kitagawa Japan 2020 CBA Experi-mental	Hospital: CDI isolation rooms.	High-touch surfaces: bedrail, over-bed table, bedside table, toilet seat, toilet assist bar, sink counter, intravenous infusion pump control panel, treatment cart, ventilator control panel	*Clostridium difficile*	286 At baseline = 72 After manual clean = 72 At baseline = 71 After manual clean + UV-C = 71	PX-UV in addition to QAC wipes	315–100 nm	10.8μW/cm^2	2 or 3 times— a 5-minute cycle per room	Manual clean alone with chlorine-based disinfectant: SH 0.1%-0.5%	McNemar test, Wilcoxon rank-sum test, ANCOVA	UV-C in addition to manual cleaning with QAC significantly reduced overall C. *difficile*-positive in samples and CFU counts when compared to manual clean alone with chlorine-based disinfectant, without a significant difference between groups after adjustments.
Kitagawa Japan 2019 BA Experi-mental	Hospital: ICU, EICU, & HCU.	High-touch surfaces: bed rails, bed control panels, overbed tables, vital sign monitor control panels, infusion pump control panels, bedside tables, door handles, and sink counters	MRSA & AB	306 At baseline = 102 After manual clean = 102 After manual clean + UV-C = 102	PX-UV in addition to QAC wipes	315–100 nm	10.8μW/cm^2	2 or 3 times— a 5-minute cycle per room	———	McNemar test, Wilcoxon rank-sum test	UV-C in addition to manual cleaning with QAC resulted in a significant improvement in total CFU counts reduction per plate for both AB and MRSA compared to manual cleaning alone ($P < .001$ and $P < .001$, respectively) and in the number of AB- and MRSA-positive samples (58.8%−28.4%, $P = .001$ and 19.6%−3.9%, $P < 0.001$, respectively)
Zeber United States 2019 BA Experi-mental	Hospital: patient's rooms	High-touch surfaces: bedrail, call button, toilet seat, bathroom handrail, and tray table	MRSA & AB	$N = 1800$ At baseline for 4 groups = 600 After manual clean for 4 groups = 600	PX-UV in addition to 4 different disinfectants & cleaner: chlorine-based disinfectant (SH 10%), HPA, QAC & DT	315–100 nm	10.8μW/cm^2	2 or 3 times— a 5-minute cycle per room	———	Bayesian negative binomial multilevel regression model.	UV-C in addition to manual cleaning with 4 different disinfectants presented lower CFU model-estimated mean (95% uncertainty interval) 56% (48%–63%) and 93% (62%–99%) for both AB & MRSA, respectively, compared to manual clean alone.

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Table 1 (*continued*)

Author Country Year Study design	Health facility	Surfaces	Characteristic of the sample Pathogens identified	No. of samples cultured	UV-C intervention arm Device and disinfectant used	Wave-length (nm)	Irradiance ($\mu W/cm^2$)	Time of Exposure	Control description	Statistical Analysis	Outcomes
				After manual clean + UV-C for 4 groups = 600							Better results were observed when UV-C was used in addition to manual cleaning with QAC and chlorine-based disinfectant (99.9999% reduction)
Casini Italy 2019 Ps BA Experi-mental	Hospital: patients' rooms, ICU & OT	High-touch surfaces: surgical table, tray table, anesthetic machine, monitor, infusion pump, scialitic lamp, electrosurgery; hydrotherapy tank, tray table, monitor, patient bed, infusion pump; patient bed, tray table, medication cart, call button, push-button.	Staphylococcusspp., Enterobacter cloacae, vibrio alginoliticus, Cryseobacterium menigosepticum, Edwarsiella hoshinae, Methylobacterium mesofilicum, KPC-K. pneumoniae, Extended Spectrum β Lactamase-producing Klebsiella pneumoniae (ESBL-K. pneumoniae), and bacillus identified as C. *difficile*	$N = 345$ At baseline = 135 After manual clean = 125 After manual clean + UV-C = 85	PX-UV in addition to chlorine-based disinfectants	315–100 nm	$10.8\mu W/cm^2$	2 or 3 times— a 5-minute cycle and 2 times— a 10-min cycle on the operating room	———	Wilcoxon matched-pairs signed-rank test.	UV-C in addition to manual cleaning with chlorine-based disinfectants, significantly reduced microorganisms (99.9999%) improving manual cleaning failures. After UV-C intervention, approximately all the average of CFUs were 0 CFU/24 cm2, i.e. 6-log reduction.
Rutala United States 2018 Ps BA Experi-mental	Three community hospitals	High-touch surfaces: bed rail, over-bed table, supply or medicine cart, chair, sink, toilet seat, shower floor, side counter, linen hamper lid, and bathroom floor	MDR Acinetobacter, *Clostridium difficile*, MRSA & VRE	$N = 7360$	Tru-D smart UVC in addition to chlorine-based disinfectant and QAC	254-nm	———	———	———	Wilcoxon rank-sum tests	UV-C in addition to manual cleaning with QAC was significantly superior to QAC alone in reducing several important pathogens ($P < .001$) Manual bleach clean alone and plus UV-C led to a decrease but this reduction did not reach statistical significance compared to QAC alone.
Zeber United States 2018 Ps CBA Experi-mental	Hospitals	High-touch surfaces: toilet seat, toilet handrail, bed rail, tray table, call button, or telephone.	MRSA & AB	$N = 140$ At baseline = 28 After manual clean = 28 At baseline	PX-UV in addition to chlorine-based disinfectant and QAC	315–100 nm	$10.8\mu W/cm^2$	2 or 3 times— a 5-minute cycle per room	Manual clean alone with chlorine-based disinfectant and QAC	Multivariable models, negative binomial (Poisson) regression.	UV-C in addition to manual cleaning with chlorine-based disinfectant and QAC reduced overall MRSA and AB CFU counts by 75.3% and 84.1%, respectively, versus only 25%−30% at control sites.

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Table 1 (*continued*)

Author Country Year Study design	Health facility	Surfaces	Characteristic of the sample Pathogens identified	No. of samples cultured	UV-C intervention arm Device and disinfectant used	Wave-length (nm)	Irradiance ($\mu W/cm^2$)	Time of Exposure	Control description	Statistical Analysis	Outcomes
				= 42 After manual clean + UV-C = 42							
Beal United Kingdom 2016 BA Experi-mental	Teaching hospital: clinical hematology unit:	Top of the patient table, floor in corner of the room, bed controls, floor in front of the toilet, top of service rail, nurse call buzzer, door handle – bathroom, bed safety rail, tap on the sink, toilet flush handle, top of the fridge, toilet bin lid, chair arm, telephone on top of the lock	VRE & AB	*N* = 300 At baseline = 100 After manual clean = 100 After manual clean + UV-C = 100	PX-UV in addition to manual clean with a general-purpose detergent in warm water	315–100 nm	10.8μW/cm^2	3 times— a 5-minute cycle per room	———	Box −whisker plots and a chi-squared test	Manual cleaning reached an 83% reduction for AB CFU counts, with an additional 14% reduction following UV-C disinfection, resulting in an overall reduction of 97%. There was a 38% reduction in the number of sites where VRE was detected, from 26 of 80 sites following manual cleaning to 16 of 80 sites with additional UV disinfection.
Hosein United Kingdom 2016 Ps BA Experi-mental	Hospital clinical isolates of MRSA, VRE, multidrug-resistant Acinetobacter, and CPE	High-touch surfaces: bedrail, tray table bathroom handrail toilet seat, bathroom faucet.	MDROs	*N* = 552 At baseline = 184 After manual clean = 184 After manual clean + UV-C = 184	PX-UV in addition to a chlorine-based disinfectant prepared with 1 L of water to produce a hypochlorous acid disinfectant solution with detergent (troclosene sodium)	315–100 nm	10.8μW/cm^2	3 times— a 5-minute cycle per room	———	Wilcoxon signed-rank tests & McNemar test	After UV-C in addition to manual cleaning with chlorine-based disinfectants, CFU counts decreased by 78.4%, a 91% reduction from initial bioburden levels before manual clean. UV-C intervention resulted in a 5-log CFU reduction for MDROs on spiked plates.
Wong Canada 2015 BA Experi-mental	General Hospital: isolation rooms of MRSA, VRE, or C. *Difficile*	High-touch surfaces: overbed table, bed adjustment control, sink, toilet rim, washroom handrail, and floor	AB, MRSA, VRE, C. *Difficile*	*N* = 1083 At baseline = 361 After manual clean = 361	Tru-D smart UVC and R-D Rapid Disinfector system; both in addition to manual cleaning with HP	254-nm	Vegetative 12,000μWs/cm^2, Sporicidal 22,000μWs/cm^2 Vegetative and sporicidal	———	———	McNemar test, *t* test with Welch correction.	After manual cleaning with HP CFU counts (excluding floors) decreased from 88.0 to 19.6 ($P<.0001$); UV-C intervention further reduced it to 1.3 CFU ($P=.0013$) Samples treated with

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Table 1 (*continued*)

Author Country Year Study design	Health facility	Surfaces	Characteristic of the sample Pathogens identified	No. of samples cultured	UV-C intervention arm Device and disinfectant used	Wave-length (nm)	Irradiance ($\mu W/cm^2$)	Time of Exposure	Control description	Statistical Analysis	Outcomes
				After manual clean + UV-C = 361			46,000 uWs/ cm^2				machine 2 were 7 times more likely to culture bacteria from stainless steel disks than machine 1 for any given organism, surface, and concentration (OR, 6.96; 95% CI, 3.79–13.4)
Ghantoji United States 2015 CBA Experi-mental	Hospital: isolation rooms of C. *Difficile*	High-touch surfaces: the bathroom handrail, horizontal/ vertical surface facing into the room; bed control panel; bedrail; top of the bedside table, pump control panel or other equipment control panel, when available.	*Clostridium difficile*	*N* = 288 At baseline = 74 After manual clean = 74 At baseline = 70 After manual clean + UV-C = 70	PX-UV in addition to manual cleaning with HP	315–100 nm	10.8μW/cm^2	3 times— a 5-minute cycle per room	Manual clean alone with HP and chlorine-based disinfectant (SH 10%)	Wilcoxon rank-sum test	The mean level of contamination for manual cleaning with chlorine-based disinfectant was 0.71 CFU (*P*=.1380), and 1.19 CFU (*P*=.0017) for UV-C in addition to HP. The difference in final contamination levels between the two cleaning protocols was not significantly different (*P*=.9838).
Jinadatha United States 2014 CBA Quase-Experi-mental	Hospital: acute care	High-touch surface: bedrail, toilet seat, bathroom handrail, call button, tray tab.	MRSA	*N* = 150 At baseline = 50 After manual clean = 50 At baseline After manual clean + UV-C = 50	PX-UV in addition to manual cleaning with a chlorine-based disinfectant (SH 10%)	315–100 nm	10.8μW/cm^2	3 times— a 5-minute cycle per room	Manual clean alone with a chlorine-based disinfectant (SH 10%)	Wilcoxon Rank Sum test	UV-C in addition to manual cleaning with a chlorine-based disinfectant resulted more efficiently in reducing the overall MRSA load 99.4% compared with manual clean alone 91.1%. PPX-UV was superior to manual cleaning for MRSA (IRR = 7; 95% CI <1–41)
Havill United Kingdom	Hospital	High-touch surfaces: bedrail, overbed	AB & Clostridium. *Difficile*	*N* = 300 At	Tru-D Smart UVC in addition to QAC or a chlorine-	254-nm	22,000μWsec/ cm^2	——	HPV system in addition to QAC or	Chi-squared test, Wilcoxon	Both HPV and UV-C in addition to manual cleaning with QAC or

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Table 1 (*continued*)

Author Country Year Study design	Health facility	Surfaces	Characteristic of the sample Pathogens identified	No. of samples cultured	UV-C intervention arm Device and disinfectant used	Wave-length (nm)	Irradiance ($\mu W/cm^2$)	Time of Exposure	Control description	Statistical Analysis	Outcomes
2012 CBA Experi-mental		table, TV remote, grab bar, toilet seat.		baseline = 75 After manual clean + HPV = 75 At baseline = 75 After manual clean + UV-C = 75	based disinfectant (SH 10%)				chlorine-based disinfectant (SH 10%)	signed-rank test.	chlorine-based disinfectant, reduced bacterial contamination, including spores, but HPV was significantly more effective ($P<$ .0001) UV-C was significantly less effective for sites that are out of the direct line of sight.

CBA, Controlled Before-After Study; BA, Before-After Study; Ps, Prospective Study; UV-C, Ultraviolet-C; CFU, Colony-Forming Unit; ICU, Intensive Care Unit; EICU, Emergency Intensive Care Unit; HCU, High Care Unite; CDI, *Clostridium difficile* Infection; CI, Confidence Intervals; OR, Odds Ratio; PX-UV, Pulsed Xenon Ultraviolet Light (Xenex); SH, Sodium Hypochlorite; MRSA, methicillin-resistant Staphylococcus aureus; AB, Aerobic Bacteria; MDROs, Multidrug-resistant Organisms; ANCOVA, Analysis of Covariance; HP, hydrogen peroxide; HPA, Hydrogen Peroxide with Peracetic Acid; QAC, Quaternary Ammonium Compounds; HPV, Hydrogen Peroxide Vapor; HPC, Bacterial Heterotrophic Plate Count; IRR, Incident Rate Ratio.

Table 2
Log reduction with the presence of relevant nosocomial pathogens positive in samples.

Study	Intervention	MDROs CFU	Reduction (log)	AB CFU counts	Reduction (log)	C. *Difficile* CFU	Reduction (log)	EPIs[a] CFU	Reduction (log)
Controlled before-after studies (assessing UVC in addition to manual cleaning compared to manual cleaning alone or another no-touch method)									
Kitagawa 2020						**Mean (SD)**			
	At baseline	——	——	——	——	2.54 (8.45)		——	——
	After manual cleaning with a chlorine-based disinfectant (SH 0.1%−0.5%)	——	——	——	——	0.90 (3.82)	**64.57% (0-log)**	——	——
	At baseline	——	——	——	——	1.76 (5.16)		——	——
	After UV-C in addition to manual cleaning with QAC	——	——	——	——	0.34 (1.18)	**80.68% (0-log)**	——	——
Zeber 2018		**Mean (SD)**		**Mean (SD)**					
	At baseline	31.8 (86.3)		151.3 (206.7)		——	——	——	——
	After manual cleaning with QAC or chlorine-based disinfectant	17.4 (62.6)	**45.29% (0-log)**	111.2 (155.4)	**26.5% (0-log)**	——	——	——	——
	At baseline	16.9 (29.1)		396.8 (313.9)		——	——	——	——
	After UV-C in addition to manual cleaning with QAC or chlorine-based disinfectant	2.7 (7.2)	**84.02% (0-log)**	97.9 (136.5)	**75.32% (0-log)**	——	——	——	——
Ghantoji 2015						**Mean**			
	At baseline	——	——	——	——	2.39		——	——
	After manual cleaning with HP and a chlorine-based disinfectant (SH 10%)	——	——	——	——	0.71	**70.3% (0-log)**	——	——
	At baseline	——	——	——	——	4.61		——	——
	After UV-C in addition to manual cleaning with HP	——	——	——	——	0.80	**83.0% (0-log)**	——	——
Jinadatha 2014		**Mean; median (IQ)**							
	At baseline	127.3; 28.5 (8–1)		——	——	——	——	——	——
	After manual cleaning with a chlorine-based disinfectant (SH 10%)	11.3; 1.0 (0–4)	**91.1% (1-log)** *	——	——	——	——	——	——
	At baseline	108.2; 123.0 (14–1)		——	——	——	——	——	——
	After UV-C in addition to manual cleaning with a chlorine-based disinfectant (SH 10%)	0.7; 0.0 (0–1)	**99.4% (2-log)** *	——	——	——	——	——	——
Havill 2012				**Mean; median (range)**					
	At baseline	——	——	33.1; 18.02 (0->200)		——	——	——	——
	After HPV in addition to manual cleaning with QAC or a chlorine-based disinfectant (SH 10%)	——	——	0.1; 0.0 (0–4)	**99.7% (2-log)** *	——	——	——	——
	Pre-cleaning	——	——	40.6; 25.02 (0->200)		——	——	——	——
	After UVC in addition to manual cleaning with QAC or a chlorine-based disinfectant (SH 10%)	——	——	6.9; 1.6 (0–160)	**83% (0-log)**	——	——	——	——
Uncontrolled before-after studies (assessing UVC in addition to different manual cleaning methods)									
Kitagawa 2019		**Mean (SD)**		**Mean (SD)**					
	At baseline	5.7 (2.1)		29.8 (58.6)		——	——	——	——
	After manual cleaning with QAC	1.1 (3.9)	**80.7% (0-log)**	14.4 (38.7)	**51.7% (0-log)**	——	——	——	——
	After UV-C in addition to manual cleaning with QAC	0.3 (2.0)	**94.7% (1-log)** *	1.7 (6.1)	**94.3% (1-log)** *	——	——	——	——
Casini 2019								**Median**	
	At baseline	——	——	——	——	——	——	74	
	After manual cleaning with a chlorine-based disinfectant	——	——	——	——	——	——	4	94.59% **(0-log)**
		——	——	——	——	——	——	0	

(*continued on next page*)

Table 2 (*continued*)

Study	Intervention	MDROs CFU	Reduction (log)	AB CFU counts	Reduction (log)	C. *Difficile* CFU	Reduction (log)	EPIs[a] CFU	Reduction (log)
	After UV-C in addition to manual cleaning with a chlorine-based disinfectant								**99.9999% (6-log)** *
Zeber 2019		**Sum**		**Sum**					
	At baseline	316		11,412		——	——	——	——
	After manual cleaning with HPA	5	**98.42% (1-log)** *	1477	**87.06% (0-log)**	——	——	——	——
	After UV-C in addition to manual cleaning with HPA	2	**99.38% (2-log)** *	686	**93.99% (1-log)** *	——	——	——	——
	At baseline	1157		12,862		——	——	——	——
	After manual cleaning with QAC	145	**87.46% (0-log)**	9797	**23.80% (0-log)**	——	——	——	——
	After UV-C in addition to manual cleaning with QAC	0	**99.9999% (6-log)** *	4859	**62.22% (0-log)**	——	——	——	——
	At baseline	209		10,863		——	——	——	——
	After manual cleaning with chlorine-based disinfectant (SH 10%)	2	**99.04% (1-log)** *	1160	**89.32% (0-log)**	——	——	——	——
	After UV-C in addition to manual cleaning with a chlorine-based disinfectant (SH 10%)	0	**99.9999% (6-log)** *	701	**93.54% (1-log)** *	——	——	——	——
	At baseline	442		11,818		——	——	——	——
	After manual cleaning with DT	102	**76.92% (0-log)**	12,954	**9.61% (0-log)**	——	——	——	——
	After UV-C in addition to manual cleaning with DT	11	**97.51% (1-log)** *	8208	**30.54% (0-log)**	——	——	——	——
Rutala 2018								**Median**	
	At baseline	——	——	——	——	——	——	——	——
	After manual cleaning with QAC	——	——	——	——	——	——	60.8	—— **(0-log)**
	After UV-C in addition to manual cleaning with QAC	——	——	——	——	——	——	3.4	94% **(1-log)** *
	At baseline	——	——	——	——	——	——	60.8	
	After manual cleaning with QAC and chlorine-based disinfectant	——	——	——	——	——	——	11.7	81% **(0-log)**
	After UV-C in addition to manual cleaning with QAC and chlorine-based disinfectant	——	——	——	——	——	——	6.3	90% **(1-log)** *
Beal 2016				**Median**					
	At baseline	——	——	50.3		——	——	——	——
	After manual cleaning with DT in warm water	——	——	8.5	83.10% **(0-log)**	——	——	——	——
	After UV-C in addition to manual cleaning with DT in warm water	——	——	1.6	96.81% **(1-log)** *	——	——	——	——
Hosein 2016			**Percentage**						
	At baseline	——	——	——	——	——	——	——	——
	After manual cleaning with a chlorine-based disinfectant	——	——	——	——	——	——	——	——
	After UV-C in addition to manual cleaning with a chlorine-based disinfectant	——	**99.999% (5-log)** *	——	——	——	——	——	——
Wong 2015				**Mean (SD)**					
	At baseline	——	——	88.0 (274.3)		——	——	——	——
	After manual cleaning with HP	——	——	19.6 (779.1)	**78% (0-log)**	——	——	——	——
	After UV-C in addition to manual cleaning with HP	——	——	1.3 (20.4)	**99% (1-log)** *	——	——	——	——

UV-C, Ultraviolet-C; HPA, Hydrogen Peroxide with Peracetic Acid; HP, hydrogen peroxide; QAC, Quaternary Ammonium Compounds; HPV, Hydrogen Peroxide Vapor; DT, Detergent; SH, Sodium Hypochlorite; MDROs, Multidrug-resistant Organisms; AB, Aerobic Bacteria; EPIs, Epidemiologically Important Pathogens.
* ≥ 1-log reduction (≥ 90%).
[a] an overall of nosocomial pathogens loads.

difference in efficiency between 1- (90%) and 2- (99%) or 6-log reduction (99.9999%).

In laboratory experiments, the disinfection with germicidal UV-C spectrum (200–280 nm) achieved 2-log to 6-log for different infectious agents in ≤ 10 min [38,39]. These results can vary in real-life scenarios, probably due to the interference of some variables such as the distance from the light source, shadows, time of exposure, the device used, the applied UV-C dose, and also a suboptimal manual cleaning performance [40,41]. Although all the included studies in our review reported an enhanced reduction when UV-C was implemented, the significance of this improvement depended on the UV-C device used, the manual cleaning protocol of choice, and the type of microbe found positive in

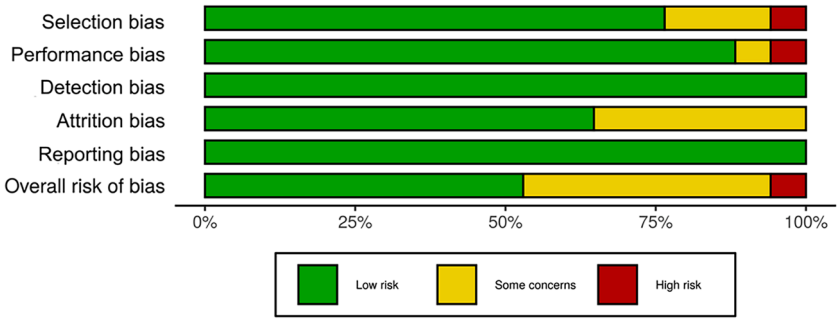

Fig. 2. Risk of bias graph illustrating the proportion of studies with each of the judgments.

Table 3
Risk of Bias for individual studies and overall judgment.

Study	Selection bias		Performance bias		Detection bias	Attrition bias		Reporting bias	Overall RoB judgment
	Sample calculation	Standardization of sampling method	Standardized manual disinfection or blinding of operators	Standardization of the UV-C performance	Blinding of outcome assessment	Incomplete outcome data before intervention	Incomplete outcome data after the intervention	Selective outcome reporting	
Kitagawa et al., 2020	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**
Kitagawa et al., 2019	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**
Zeber et al., 2019	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**
Casini et al., 2019	Some concerns	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Some concerns	Low RoB	**Some concerns**
Rutala et al., 2018	High RoB	Low RoB	High RoB	No information	Low RoB	Some concerns	Low RoB	Low RoB	**High RoB**
Zeber et al., 2018	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**
Beal et al., 2016	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**
Hosein et al., 2016	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Some concerns	Low RoB	**Some concerns**
Wong et al., 2015	Low RoB	Low RoB	Low RoB	Some concerns	Low RoB	Low RoB	Low RoB	Low RoB	**Some concerns**
Ghantoji et al., 2015	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**
Jinadatha et al., 2014	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**
Havill et al., 2012	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	Low RoB	**Low RoB**

RoB, Risk of Bias.

samples. Better results were observed using a xenon lamp after manual cleaning with a chlorine-based disinfectant or QAC reaching from 0-log (<90%) to 2-log (99.9%) reduction for MRDOs in approximately 10 to 25 min in most of the studies. One study also reported the effectiveness of PX-UV in the absence of manual cleaning [31].

Three studies reported a 5-log (99.999%) [34] and 6-log (99.9999%) reduction [30,31] after UV-C intervention in addition to manual cleaning even when MDROs were positive in samples. The three trials assessed the PX-UV device following the manufacturer protocol: 5 min disinfection cycles with minimal distance from high-touch surfaces and multiple positions; for operating rooms recommends 10 min cycles. The PX-UV uses xenon lamps to produce a full germicidal light spectrum (UV-B and UV-C). Also, the authors described a standard protocol of manual disinfection with chlorine-based disinfectant [30,31,34] or QAC [30]. Hosein et al. [34] prepared the chlorine disinfectant (0.1%) using an effervescent tablet mixed with 1 L of water to produce a hypochlorous and disinfectant solution with detergent (triclosan sodium). Casini et al. [31] used a disinfectant with 2800 mg/L of active chlorine, and Zeber et al. [30] used bleach germicidal wipes containing SH 10%. The three studies reported a reduction from 0-log to 1-log after the chlorine-based disinfectant, and this reduction was enhanced significantly after UV-C intervention (5-log to 6-log). This synergistic effect of UV/chlorine has

Table 4
Level of evidence by the GRADE approach. Question: UVC disinfection in addition to manual cleaning compared to manual cleaning alone for disinfection on surfaces.

Certainty assessment							Impact	Certainty
Nº of studies	Study design	Risk of bias	Inconsistency	Indirectness	Imprecision	Other considerations		
Comparison of CFU counts between groups in controlled before-after studies								
5	Controlled before-after trials (309 samples versus 299)	not serious	serious [a]	not serious	not serious	none	4 studies reported a superior pathogen reduction performing pulsed xenon ultraviolet light intervention in addition to manual cleaning vs manual cleaning alone, however, the significance was dependent on the disinfectant used. In 1 study, the reduction was superior using a hydrogen peroxide vapor system in addition to manual cleaning with sodium hypochlorite 10% or quaternary ammonium compounds, in this study a low-pressure mercury UV-C device was used.	⨁⨁⨁◯ MODERATE
Comparison of CFU counts between groups in uncontrolled before-after studies								
7	Uncontrolled before-after trials (5112 samples versus 5152)	not serious	serious [a]	not serious	serious [b]	none	The 7 studies demonstrated an additional pathogen reduction after UV-C intervention in addition to manual cleaning, presenting better results when the manual cleaning was performed using sodium hypochlorite 10% and quaternary ammonium compounds.	⨁⨁◯◯ LOW

Explanations.
a. Heterogeneity related to manual cleaning protocols and pathogens tested in each study.
b. The CFU counts were assessed before and after intervention without a separated control group.

also been demonstrated in drinking water and wastewater disinfection [42,43].

Zeber et al. [30] also assessed UV-C intervention after manual cleaning with other disinfectants such as QAC, obtaining a 6-log reduction after UV-C intervention; even though when manual cleaning was performed with hydrogen peroxide with peracetic acid and with a detergent followed by UV-C disinfection, only 2-log and 1-log reduction, respectively were reached.

One study assessed UV-C technology and the HPV system in separate groups. Both non-touch systems demonstrated an enhanced log reduction compared to manual cleaning alone (QAC or bleach germicidal wipes SH 10%). However, UV-C was inferior to HPV (0-log vs. 2-log) [28]. In this study, UV-C intervention was performed using the Tru-D Smart device that emits low-pressure mercury UV-C light in the 254 nm range and uses a specific dose for the type of bacteria (i.e., vegetative bacteria or spores). As with the PX-UV device, effectiveness is limited by shadowed areas of the room, but the Tru-D Smart system disinfects rooms from a single location by using sensors to measure the amount of UV-C reflected [44]. For sites that were out of the direct line of sight, UV-C exposure was less effective [28].

Some studies recommended the incorporation of UV-C to dental cleaning routine [45,46], but the clinical trials performed in dental offices did not meet our inclusion criteria and were excluded. Most practicing dentists worldwide are preventing the transmission using enhanced PPE protocols and other measures such as preoperative mouthwash to reduce the oral microbial load in patients' saliva [8]. Dental professionals are aware of the need to develop complementary disinfection methods considering blocking the transmission routes is the best way to reduce the risk of being infected [47].

Despite UV-C being a promising technology, some devices present limitations related to the inefficiency in shadowing areas, portability, cost, and preventing damage to operators and materials. Recently, there are two major ways to explore the efficiency of UV-C robots in shadowing areas; the first one is to embark on a mobile platform to cover the room entirely, alternating between exposure and movement from a unique point of emission. The second one uses an intelligent robot with a pair of 3D cameras to locate itself and map the room to recognize high-risk surfaces using AI and image processing algorithms but still has cost limitations [48]. To improve cost and portability has also been proposed to design a portable ultraviolet C device based on the core principles of origami—the ancient Japanese art of paper, to make the device more portable and less expensive [49].

In addition, as pointed out before, safety warnings must be strictly considered using portable or fixed UV-C devices to avoid inappropriate usage and human exposure. The use of protective UV-C goggles, gloves, clothes, and motion sensors for fixed devices to switch off the power is essential to diminish the risk of accidental exposure [17,50]. Although the Threshold Limit Value (TLV) for human UV exposure can be higher for some ranges of radiation (270 nm TLV=> 3mJ.cm^{-2}, 254 nm TLV => 6mJ.cm^{-2}, 220 nm TLV=> 25mJ.cm^{-2}) without inducing sunburn or eye damage [17,18], far UV-C (200 –225 nm range) can generate ozone via photolysis of environmental oxygen molecule and increase ozone concentration in a room which could mean a health risk in the presence of humans [51].

5. Limitations

Although we applied a rigorous eligibility criterion to gather similar methodologies, the high heterogeneity across the included studies persisted and made it impossible merging of data to perform a meta-analysis. The grade of success of the UV-C devices depended on several physical and biological factors specific to the different environments and pathogens assessed.

6. Conclusions

The evidence we gathered points out the effectiveness of UV-C technology to enhance manual cleaning failures improving the logarithmic reduction of pathogen colonized on surfaces. However, the certainty of this evidence was classified as moderate and low due to the high heterogeneity across studies. The absence of a meta-analysis limited our review to a qualitative analysis of the methodologies and results from each study and a narrative summary of the certainty of evidence.

Although UV-C technology could be considered in dental and medical clinics to reduce manual cleaning failures, safety concerns to avoid human exposure are paramount. The applied UV-C dose should be balanced to achieve a valid inactivation value (more than 90%) and avoid exposure damage to personnel and surfaces. The effectiveness of any UV light device will depend on various factors, whether physical or

biological. Its use must be preceded by a judicious project under the supervision of a physicist or other trained professional to scale the space for a specific office or hospital area, the number of lamps to be used, observe the shaded areas, and ensure the maximum safety of the people involved. Dental and medical practices must be cautious in selecting a device, obtaining third-party evidence, and looking for a certification of its components by regulatory organizations worldwide.

We encourage conducting further controlled before-after trials assessing lower cost, more portable, and safer UV-C devices to ease their application in healthcare facilities. Also, the synergistic effect of UV-C and chlorine-based disinfectants should be considered in the cleaning protocols to achieve optimal disinfection on high-touch surfaces. For non-bleach cleaning, quaternary ammonium compounds can also be an option.

CRediT authorship contribution statement

María Olimpia Paz Alvarenga: Writing – original draft, Visualization, Investigation, Data curation, Project administration, Methodology. **Sirley Raiane Mamede Veloso:** Writing – original draft, Investigation, Data curation, Project administration, Methodology. **Ana Luisa Cassiano Alves Bezerra:** Writing – original draft, Investigation, Data curation. **Benoît Paul Trindade:** Writing – original draft, Project administration, Methodology. **Anderson Stevens Leonidas Gomes:** Writing – original draft, Writing – review & editing. **Gabriela Queiroz de Melo Monteiro:** Writing – original draft, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors have no conflict of interest to disclose. The funders had no role in study design, manuscript preparation, or the decision to publish.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jpap.2021.100096.

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