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Photon technologies as means to reducing bioburden in hospital environments

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Abstract

Background: Environmental cleaning and disinfection construct a base for infection prevention of hospital acquired infections.
Aims: This study aims to introduce photon disinfection technologies (PDT), to report their impact on inactivating the microorganisms, 3) to report their impact on preventing HAIs and 4) to create recommendations for their implementation in hospital settings.
Methods: An Integrated Literature Review completed in four data bases. The quality of 23 articles assessed with explicit tools, contents analysed in assistance of a spreadsheet according to PICOTT model.
Findings: The microbiological effectiveness of the PDT varied by microorganisms, settings and according to the devices used. The environmental cleaning was found crucial to complete prior the disinfection.
Conclusion: The implementation of the PDT in the hospital environments requires inquiry from viewpoints of microbiological, environmental, occupational, technical, and human safety. To enhance the safe implementation of PDTs the construction and use of evidence-based global standards for PDT are crucial.

Key words: Infection prevention and control, photon disinfection technology, ultraviolet light, blue light, hospital-acquired infection.

Introduction

Environmental cleaning and disinfection measures construct a base for clinical improvements in infection prevention and control (IPC) preventing harm to patients and others from healthcare-acquired infection (HAI) and infections with multidrug-resistant organisms (MDROs) (Linam, Trivedi and Schaffzin 2022). According to Suetens et al. (2018) and ECDC (2023), in Europe the adjusted prevalence of patients with at least one HAI was estimated at 6.5 % i.e., 3.8 million patients with at least one HAI, and 4.5 million infection episodes in 2016–2017. In United Kingdom (UK)-England, the HAI prevalence was 6.4 %, in UK-Northern Ireland 6.1%, in UK-Scotland 4.3% and in UK-Wales 5.7% respective. Of all the 19 624 HAIs reported by ECDC, the most frequent were respiratory tract infections (pneumonia 21.4 % and lower respiratory tract infections 4.3 %), urinary tract infections (18.9%), surgical site infections (18.4%), bloodstream infections (10.8%) and gastrointestinal infections (8.9 %). *Clostridioides difficile* (*C. Diff.)* infections accounted for 54.6 % of the latter and 4.9% of all HAIs. Like the microbial agents, also the IPC measures preventing the microbial spreading during the outbreaks are heterogeneous, highly depending on the setting and structural characteristics of the hospital wards (Medioli et al. 2022). The selection of effective environmental and other IPC measures against the spreading of microbial agents in hospital settings is difficult due to low quality or lack of controlled and microbial agent specific intervention studies (Medioli et al. 2022). The implementation of environmental IPC measures includes balanced ecological, economic, and non-harmful choices (Pereira et al. 2023). This study aimed to analyse photon disinfection technologies for IPC in healthcare settings. The study objectives were 1) Describe photon disinfection methods implemented in hospital and 2) to report their impact on inactivating the microorganisms on hospital surfaces, 3) to report their impact on preventing HAIs and 4) to create recommendations for implementing photon disinfection in hospital settings.

Background

Asymptomatic carriers, infected patients, healthcare workers and visitors contaminate surfaces, medical devices and human beings compromising the microbiological safety of healthcare facilities and services. In addition to that, livestock products can be potential reservoirs of microbes, in the worst case resistant to antimicrobial medication. Multi resistant *Staphylococcus aureus* is reported the most common microbe in pigs, goats, horses, sheep, buffaloes, cattle, rabbits, and poultry relating to the medical and non-medical use of antimicrobials in animal production farms and having potential to infect farm workers and products (Silva et al., 2023). In 2011-2012, in European acute care hospitals the most common microorganisms in HAIs were *Escherichia coli*, *Staphylococcus aureus*, *Enterococcus spp*. *Pseudomonas Aeruginosa*, *Klebsiella spp*., *Coagulase-negative staphylococci*, *Candida spp*. (ECDC 2023). In European hospitals, the fastspreading MDROs require immediate actions by mutual and multidisciplinary collaboration following their real-life routes of transmissions (de Brink 2021, v-ix).

Globally the *C. Difficile* infections are among the most common healthcare acquired infections (HAI), in the UK the *C. Difficile* ranked as third common anaerobic bacilli (ECDC 2023). Mean prevalence of 14.9% is reported in hospital environments, being the highest, 51.1 % in India, 17.8% in UK, 3.9% in Canada, and lowest, 1.6% in the USA (Borji et al. 2022). Birru et al. (2021) reported 71 (71%) of 99 inanimate objects and patient care equipment as contaminated in an Ethiopian hospital. Gram-positive bacteria, coagulase-negative *staphylococci,* CoNS, (52.2%) and *Staphylococcus aureus* (47.7%) were most common microbes followed by Gram-negative *Acinetobacter spp.* (28.5%) and *Klebsiella spp*. (23.8%). *Staphylococcus aureus* (100%) and CoNS (78%) showed resistance against penicillin. Of the *Acinetobacter spp.* bacteria found all were resistant to ceftriaxone and ampicillin. Alike, all the *Klebsiella spp.* bacteria were resistant to ampicillin and trimethoprim–sulfamethoxazole and of the *Citrobacter spp*., *Enterobacter spp*., *Salmonella spp.*, *Escherichia coli*, and *Serratia spp* bacteria all found 100% resistant to amoxicillin, ampicillin, and trimethoprim–sulfamethoxazole. The overall prevalence of MDRO was 57.7%.

In 2019, the antimicrobial resistance (AMR) estimated causing 4.95 million deaths globally, of the deaths 1.27 million were caused by bacterial AMR (Antimicrobial Resistance Collaborators 2022). In the EU/EEA, the annual number of cases of infections caused by bacterium–antibiotic resistance combinations ranged from 685 433 to 865 767 in 2019, with an annual number of attributable deaths ranging from 30 730 in 2016 to 38 710 in 2019 respective. Accordingly, also the disabilities harming the daily life of the infected people due to the resistant microbes increased from 2016 to 2019. Of the infections caused by antibiotic-resistant bacteria 70.9% were estimated HAIs. (ECDC 2022) According to Shahida et al. (2016) the HAIs rates are higher in low-income countries with limited resources than in the high-income countries. For example, in some Bangladesh hospitals, the HAI rates have exceeded 30%.

Conventional cleaning and disinfection measures

The Centres for Disease Control and Prevention (CDC 2003) recommend implementing “the Spaulding levels of disinfection” for devices and surfaces not requiring sterility for safe use. The highly toxic "high-level" disinfectants (e.g., hydrogen peroxide) inactivate all vegetative bacteria, mycobacteria, viruses, fungi, and some bacterial spores being appropriate for heat-sensitive, semi-critical instruments. The "intermediate level" disinfectant (e.g., sodium hypochlorite) does not kill bacterial spores, but inactivates for example the more chemical resistant *Mycobacterium tuberculosis* var. *bovis* than ordinary vegetative bacteria, fungi, and medium to small viruses with or without lipid envelopes. The "low-level" disinfectants (e.g., iodophors) inactivate ordinary vegetative bacteria, fungi, and enveloped viruses, such as human immunodeficiency (HIV), influenza viruses and some enveloped viruses.

The surfaces that require cleaning, disinfection, or sterilization are classified according to their potential to transmit an infection at the time of use (Quinn et al. 2015). According to the CDC (2003) the following factors influence the choice of the disinfection procedure for environmental surfaces: the nature of the item to be disinfected; the number of microorganisms present; the innate resistance of the microorganisms to the inactivating effects of the germicide; the amount of organic soil present, the type and concentration of germicide used; duration and temperature of germicide contact, and if using a proprietary product, other specific indications and directions for use. In hospitals, also the microbial activity, burden, and risks for the patients and personnel, as well as the number of people in the environment, amount of activity, amount of moisture, presence of material capable of supporting microbial growth, rate at which organisms suspended in the air are removed, and the type of surface and orientation, i.e. horizontal or vertical are important to consider. In practice, also the potential for direct patient contact; degree and frequency of hand contacts, and potential contamination of the surface with body substances or environmental sources of microorganisms (e.g., soil, dust, and water) are important for selecting strategies cleaning and disinfecting surfaces in patient-care areas.

The DCD recommendations (2003) highlight the cleaning as a basis for more specified disinfection measures by removing soil, organic contamination caused by microorganisms from surfaces and medical or care devices by scrubbing. The use of chemical surfactants or detergents, and water aims to wet, emulsify, or reduce surface tension improving the cleaning effect. It is important to define the residual, time and safety of cleaning and disinfection products and assess the conditions under which a one-step process with combined detergent-disinfectant is as effective for reducing contamination on surfaces compared as a two-step process in which cleaning is followed by disinfection (Quinn et al. 2015).

Photon disinfection techniques

The photon disinfection technologies (PDT) have potential in reducing bioburden in hospital surfaces in environmentally and occupationally safer manner than the conventional techniques. (Rangel et al. 2022; Pereira et al. 2023) The drugs, chlorination, ozonation and ultraviolet disinfection used in the sterilization of water, air, food, and other fields have unwanted effects. For example the by-products of ozonation and chlorination are potential risks for cancer, the energy consumption of the UV disinfection is high, and some microbes become naturally resistance to it. (Hu et al. 2022) Disinfectants have cyto- and neurotoxic, mutagenic, and even depressant effects on the central nervous system in human body (Pereira et al. 2023).

Photon disinfection occurs as a series of photophysical and photochemical reactions leading to a photodynamic inactivation of biomolecules by oxidizing the DNAs and RNAs of the microbial cells. PDTs with different ranges of light wavelengths are used to inactivate the pathogens on hospital environments' surfaces. (Cabral & Ag 2019) The effectiveness of disinfection depends on the radiation dose causing cellular damage by irradiation, the distance separating the radiation source from the contaminated surface, the nature and concentration of microorganisms, and especially the temperature and humidity of the environment. Different microorganisms have varying sensitivity to irradiation. (Rangel et al. 2022)

The electromagnetic spectrum (100–400 nm) of Ultraviolet (UV) rays occurs between the extreme of the visible region and the X-ray bands. The UV region can be divided according to their wavelength and energy: UVA region (315–400 nm), UVB region (280–315 nm), and UVC region (100–280 nm). The 200–290-nm range UVC irradiation of high energy and short wavelengths is reported possessing intensive potential for germicidal disinfection. (Bhardwaj et al. 2021) The common 254 nm UVC is considered harmful to human health, unlike the far-UVC at 222 nm reported safe for occupied spaces and effective for disinfection. (Pereira et al. 2023)

Methods

An Integrated Literature Review (ILR) completed according to five stages: 1) problem identification, 2) literature search; 3) data evaluation stage; 4) data analysis, and 5) presentation, of the ILR results of which we created recommendations for the implementation of PTD in hospital settings. (Whittemore & Knafl 2005; Torraco 2016). The PICOT-model (Duke University 2023) implemented in problem identification, the formulation of the study questions, data search and description of the selected studies. The type of research questions (T) according to the PICOT–model was: (P) What are the PDTs (I) implemented in hospital environments? 2) (P) What kind of impact (O) do PDTs (I) have on the microbial burden on hospital surfaces? (C) 3) (P) What kind of impact (O) do PDTs (I) have on the HAI rates of hospital patients? The time of reviewed publication (T) limited between 1st January 2010 and 28th April 2023. The data searches completed in 2021 and 2022 from CINAHL, PubMed, ProQuest and ScienceDirect data bases and reported as one search (Mohamed Naseer 2021), and the most recent search in 2023 completed from ProQuest and

Science Direct only reported in this study as one search (Figure 1).

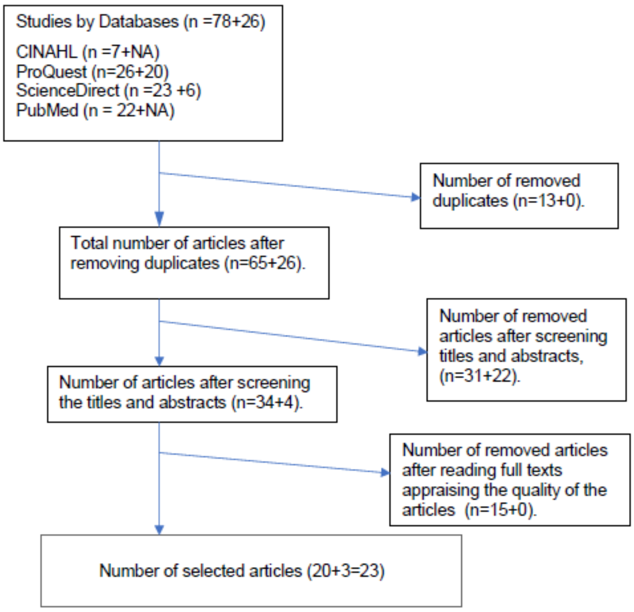

Figure 1. Flow chart of the selected articles.

Inclusion and exclusion criteria

Inclusion criteria for the selected studies were peer-reviewed scientific full text English language publications (qualitative, quantitative, mixed methods research, systematic literature review, integrative literature reviews), completed in hospital settings investigating the photon disinfection technology/methods, ultraviolet, blue light, blue-violet light, and catalytic coating. The exclusion criteria were thesis reports, newspaper articles, editorials, abstracts only, conference book proceedings, case reports, narrative literature reviews, commercial advertisements; studies in dentistry, oral care, elderly care, water processing, wound care, food disinfection, other than PDTs related disinfection technologies, and language other than English.

Appraisal of the article quality

Both authors appraised the quality of the articles independently to minimize the risk for inaccurate results

(Torraco 2016; Whittemore & Knafl 2005) by the STrengthening the Reporting of OBservational studies in Epidemiology, STROBE, (Knottnerus and Tugwell 2008) (n=20) and the systematic literature reviews gained in 2023 by an AMSTAR (n=3), a critical appraisal tool for systematic reviews that include randomized or non-randomised studies of healthcare interventions, or both (Shea et al. 2017). The quality of Anderson et al. (2018) trial assessed by the STROBE even it was a clinical trial. The quality of the study considered high. Differences in appraisal solved according to mutual discussion and decision-making. The results of all appraisals are reported in Tables 1 and 2. The authors set the 70% threshold for accepted articles. Articles below 70% considered low quality, 71-85% as moderate and over 86% as high-quality articles respective. (Knottnerus & Tugwell 2008.) Of the 24 articles 23 gained the required 70% level in quality rating. The rejected article of Lucciola et al. (2022) focused on the disinfection of keyboards only in hospital settings with low quality (62.5%).

Data extraction

The text of the articles (n=23) analysed according to the verification described by Whittemore and Knafl (2005) by displaying the articles according to the PICO questions as one data spread sheet and with reduced text. From the spread sheet, the descriptive information and the results of the articles compared and constructed as Tables 1 and 2. Finally, the summarized results concluded, and recommendations drawn by comparing the data with the CDC (2003) recommendations for conventional environmental cleaning and disinfection.

Results

Of the selected 23 studies ten were completed in the USA, one in Canada, one in Ecuador, four in the UK, two in Italy, one in the Netherlands, two in Japan, one in Thailand, and one in South Africa. In the articles the PDT devices evaluated, and microorganisms detected were reported inconsistently.

Photon disinfection methods implemented in healthcare settings

The most often reported PTSs were the PX-UV devises (n=15) with UVC or UVD radiation. In some papers the radiation type was not reported. The PX-UV, a non-touch device with a non-mercury Xenon flash lamp, reported as an efficient technology in disinfecting the floors and high touch surfaces, and it has proven the efficacy in eliminating MDROs from 95- 99% in healthcare settings. (Villacis et al. 2019; Dippenaar & Smith 2018; Casini et al. 2019). The other reported devices were e.g. Focused Multivector Ultraviolet (FMUV) system with shadowless delivery (n= 1), High-Intensity Narrow-Spectrum light Environmental Decontamination System (HINS-light EDS) (n=3). In the most recent studies, the UVC devices were reported as robots (n=2) and in the older studies mercury lamps (n=2). (Tables 1 and 2)

Impact of the PDT in inactivating the microorganisms

In the reviewed studies, the *Staphylococcal*-type organisms (N=9), *C. Difficile* (n=9) and Vancomycin resistant *Enterococci* (VRE) (n=5) were the most often screened microorganism. In several studies, the microorganisms were not clearly reported or were defined as CFUs. The microorganisms were often reported according to their importance in the study setting. For example in the study of Anderson et al. (2018) *C. Difficile*, MRSA, VRE, and MR *Acinetob. spp*. were screened in terminal room settings. The impact of the PDTs in inactivating the microorganisms varied. In some studies, the impact of 100% reduction (Casini et al. 2019) reported while in other studies no statistically significant reduction was found. The reduction in microbial burden by low-pressure mercury UVC devices were reported high by Wong et al. (2016) when Brite et al. (2018) did not find statistically significant reduction in *C. Difficile* and VRE burden. Bache et al. (2012) reported mean decrease from 22% to 86% in surface VRE bacteria during the HINS-light EDS and increasing from 78% to 309% after the light switched off. Also Maclean et al. (2010) reported the recovery of bacterial counts after switching off the HINS-light EDS when the microbial burden increased up to 126% and 39.5 CFU. Bache et al. (2018) reported reduction between 27% and 75% in burns inpatients' *Staphylococcal* CFU rates by HINS-light EDS. The reported reduction gained by PX-UVD varied from 31% in patient room for 90% in human milk preparation area. (Table 1)

The importance of pre-disinfection cleaning was reported for example by Armellino et al. (2019) and Casini et al. (2019). Villaci et al. (2019) reported the PX-UV being an efficacious technology when used after manual cleaning gaining a significant reduction of MDRO. Wong et al. (2016) reported UVC devices effective in addition to manual cleaning but limited to disinfect the high concentration of organisms in the presence of proteins. The FMUV disinfection reported reducing bioburden on hospital environment surfaces rapidly from all sides due to its high UV intensity (Armellino et al. 2019). The dose-calculating Tru-D SmartUVC device reported disinfecting vegetative MRSA and VRE and being sporicidal for *C. Difficile* (Wong et al. 2016).

Impact of the PDT in preventing HAIs

The impact of the PTD devices in HAI (or the transmission of the microorganisms) were reported in six studies (Table 2). In the trial of Anderson et al. (2018) in nine US hospitals with the baseline incidence rate of HAI 19.5 per 10000 patient days, no statistically significant decrease after standard (18.1%), UV (17.2%), bleach (17.5) or UV and bleach (17.4%) disinfection techniques measured according to the *C. Difficile*, MRSA, VRE and multidrug resistance *Acinetobacterium spp*. nor differences in HAIs between disinfection techniques reported. During the UV-radiation period the risk for the acquisition of *C. Difficile*, and VRE decreased. Schaffzin et al. (2020) reported no direct causation ship between PDT s and HAIs but the benefits of 2 LightStrike UV-C robots in the reduction of microorganisms. Vianna et al. (2016) reported 29% facility-wide reduction in *C. Difficile*, MRSA and VRE and 45%, 56% and 87% respective reduction in the rates in ICU, being statistically significant only in the VRE by PX-UV. Nagaraja et al. (2015) reported 22% reduction in hospital acquired *C. Difficile* rate during the Pulsed Xenon UV-D period, but the length of hospital stay due to the hospital acquired *C. Difficile*-infection remained unchanged in occupancy ICU. Sampathkumar et al. (2019) reported *C. Difficile*-infection rates decreasing significantly in the intervention units compared with control units during the six months of PX-UV disinfection. In the intervention units, also VRE acquisition reduced.

Discussion

This ILR is a theoretical study requiring no ethical review but the careful consideration of potential bias, lack of rigour and inaccuracy in selecting, reviewing, analysing, and reporting the combination and complexity of empirical and theoretical reports incorporating diverse methodologies (Whittemore & Knafl 2005).

Limitations of the study

The authors of this article selected an ILR as a method exploring the current status of the PDTs in infection prevention. Due to the selected method, the designs of the reviewed studies varied much which is typical for the ILR (Whittemore & Knafl 2005). Due to the variation in the tested PDT and the lack of standardized microbes it was difficult to compare the effect of the PDTs on microorganisms. In addition, all these factors were reported inconsistently. That is why the authors set the 70% threshold for accepted articles (Knottnerus & Tugwell 2008).

The implementation of the PICOTT-model turned out to be useful in summarizing and reporting the results. By the repeated data searches completed the authors aimed to increase the coverage of the selected studies. The databases varied between years. CINAHL, PubMed, ProQuest and ScienceDirect used in the initial search producing good number of hits. The last data search focusing only on the ProQuest and Science Direct considered updating the actual hits. The 2023 PubMed search excluded because it was considered too excessive with more than 1600 hits the most focusing on PDTs implemented to eliminate Corona viruses during the COVID-19 pandemic. The inclusion and exclusion criteria set before the data searchers were useful except the term "catalytic coating", it did not bring articles for the review. For the convenience reasons, the quality appraisal methods were kept in minimum by using only two tools, the STROBE (Knottnerus & Tugwell 2008) and the AMSTAR (Shea et al. 2017) and by reporting the quality of the article as percentages aiming to strengthen the face validity of the assessment.

The burden of HAIs for infection prevention and treatment

HAIs are a cascade creating great financial, economic, and human burden requiring excessive preventive and repairing measures. These costly measures bind the work force of hospital staff. According to Medioli et al. (2022) the most frequent IPC measures in controlling Carbapenem-resistant *Acinetobacter baumannii* (CRAB) in ICU settings are the "environmental disinfection (100%) performed with 10% sodium hypochlorite, implementation of hand hygiene with the alcohol-based hand rub (91%); contact precautions (83%); staff education (83%); additional active screening (83%); cohorting of staff and patients (75%); monitoring of environmental cleaning (66%); genotyping microorganisms (66%); daily chlorhexidine baths (58%); antimicrobial stewardship/monitoring of the antibiotic consumption (58%); active rectal screening (50%); environmental cultures (41%); and closing or stopping admissions to the ward (33%)".

PDTS as means to reduce the microbial burden and HAIs

The study of Anderson et al. (2018), was a clinical trial successfully comparing the impact of the standard disinfection procedure, the UV-radiation and bleach in different combinations in terminal rooms. In these studies the types of microorganisms and study settings were controlled showing significant reduction in hospital-wide risk for multidrug resistant *C. Difficile,* MRSA and VRE organisms. Bache et al. (2012; 2018) showed the effectiveness of the HINS-light EDS against VRE and Staphylococcal microbes but also its weaknesses in producing stable antimicrobial effect in hospital environments. Beal and associates (2016) reported the importance of the exposure time long enough in reducing the microbial burden. Required time, microbe-specific PDT and type of setting are all important factors to be taken into the consideration selecting and using the PDTs.

The review of selected studies, e.g. the study of Schaffzin et al. (2020) made visible the difficulties in showing the impact of PDTs against HAIs. Anderson et al. (2018) reported the impact of PDT against environmental microorganisms but not HAIs. The other four HAI impact studies (Nagaraja et al. 2015; Vianna et al. 2016; Sampathkumar et al. 2019; Schaffzin et al. 2020) reported reduction in transmission or HAI rates making the interpretation of their results challenging. For example, Morikane et al. (2020) did not report the reduction of HAIs but transmission of microorganisms. Nagaraja et al. (2015) reported reduction on *DC*-infections without showing differences in hospital stay between patients with hospital and community acquired C. Diff-infections.

The manual cleaning remains essential in preparing for the PDT measures. Armellino et al. (2019) reported the lack of thoroughness in the cleaning of contaminated surfaces being linked to an increased risk of infection to the next occupant in the hospital room. Implementation of manual cleaning prior to the use of PDT was reported important by CDC (2003) and several other reviewed studies.

Facilitators and barriers in use of PDTS

Usability of the PDTs were reported in a few studies. Bache et al. (2012) reported the HINSlight EDS having ability to be operated continuously in inpatient isolation rooms, being efficient, simple to run, unobtrusive, and being neither dependent on staff compliance nor requiring any additional staff time to implement. Brite et al. (2018) reported an automated data log recording the room number, environmental services operator identification, date, time, number of pulses delivered during device operation time and amount of energy emitted, as well as any error codes constructed to increase the compliance of housekeeping personnel in the utilization of PX-UV disinfection in a routine cleaning of terminal rooms. Armellino et al. (2019) identified the adoption of UV devices having challenges, for example selecting rooms benefiting most from the PDT, and with the time required for the terminal room disinfection. In addition, shadowing, sharp drop-outs in UV intensity with distance, and difficulties in disinfecting all sides of patient care equipment reported hindering the successful outcome of UV technology in hospitals. All of these barriers are possible to overcome by the shadowless delivery technology and performance of the Focused Multivector Ultraviolet (FMUV) system.

Safety of the PDT devices

Traditional chemical disinfection methods have been challenged due to their harmful impacts on human health and environmental safety. The HINS-light EDS emit blue violet light with white LEDs reported safer than the old mercury lamps (Wong et al. 2016). Beal et al. (2016) reported PX-UV devices not containing mercury bulbs, unlike some continuous UV decontamination devices, being occupationally and environmentally safe with no mercury disposal. The novel PDT devices make it possible for the staff staying in the room during the disinfection. For example, the FMUV devices enable the OT personnel conducting the manual cleaning in parallel with the UV disinfection process (Armellino et al. 2019). The motion sensors shut-off the device if any movement is detected inside the room being disinfected (Casini et al. 2019).

Current improvement in PDT devices

In addition to the measures developed for the disinfection of entire patient rooms also small-scale devices are constructed and tested for more limited use. Rangel et al. (2022) reported using a commercial shoe sole disinfection device with UV-C exposure time of 20 seconds showing 100% reduction in colony forming units (CFU) in *P. aeruginosa*, *S. enterica*, *E. faecalis*, *S. aureus*, *A.*

baumannii, and *E. coli* by. Blanchard et al. (2021) assigned the daily use of a bench top device for disinfecting high-touch items, such as ID-patches in 20 seconds. Implementing UV-C equipment that effectively decontaminates high bacterial load from daily items is an important addition to different disinfection strategies already in place (Rangel et al. 2022). Wang et al. (2022) designed of a robot capable to completely replace human beings in the complete disinfection of rooms with ability to climb stairs, distribute materials, conduct real-time monitoring, temperature measurement, and other functions.

Durango-Giraldo et al. (2019) improved the photocatalytic antibactericidal activity of UV disinfection against Escherichia coli and Staphylococcus aureus bacteria by UV disinfection with modified Titanium oxide (TiO2) and additional silver (Ag) in laboratory conditions. In addition to S-, C-, N- and other oxidant-based nanomaterials, also graphite-like carbon nitride and use of graphene as functional and environmentally safer non-metal nanomaterial are currently under investigation in developing electrode sterilization, disinfection filters and hybrid technology for disinfection and sterilization. In hospitals, popular air purification, disinfection and sterilization technologies are air filters, cleaners, and disinfectants. (Hu et al. 2022) in addition to base-line environmental cleaning and disinfections, intensive and expensive microbe-specific IPC measures are implemented in wards such as intensive care units (ICU).

Conclusions

Standardized evaluation methods were not implemented in any of the reviewed studies, so the results of this ILR are not necessarily scalable even into the similar hospital settings. The implementation of the PDT in the hospital environments requires consistent inquiry from the viewpoints of the microbiological, environmental, occupational, technical, and human safety. To enhance the safe implementation of PDTs the construction and use of evidence-based global standards for PDT are crucial. For the safe and effective

use of the PDTs devices more standardized research and education is important to deliver for all who are working in hospital environments including housekeeping, patient care and technical personnel.
Also, the more rigid effectiveness studies and cost analyses require standardized protocols to be able to improve evidence-based capability tackling HAIs.

Recommendations

It is recommended to classify the hospital surfaces requiring photon disinfection according to their potential to transmit an infection at the time of use.
The following aspects are important to take into the consideration:

- the nature of the item to be disinfected
- the burden of present microorganisms
- the activity of the present microorganisms
- the innate resistance of the microorganisms to the inactivating techniques
- the amount of organic soil present
- the presence of material capable of supporting microbial growth e.g. biofilm
- the number of people in the environment
- the type, duration, and amount of the radiation
- risks of the PDT for the patients and personnel
- the amount of the PDT activity
- the type of surface and orientation, i.e. horizontal or vertical are important to consider.

In practice, it is important:

- to equip the patient rooms only with necessary items, objects and patient care equipment
- to remove all unnecessary items and objects from the surfaces to be disinfected

- to remove organic soil from the surfaces to be disinfected

- to select the disinfection technology according to the potential or detected microorganisms

- to select the time, duration, and amount of the radiation according to the manufacturer’s instruction

- to consider the risk of PDT to the people present

- to use personal protective equipment according to the manufacturer’s instruction

- to select the time and disinfection technology according to the type, the orientation of the surfaces and room occupancy

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Table 1 The photon disinfection technologies (PDT) implemented in hospital settings and their impact on inactivating micro-organisms

Reference	The photon disinfection technologies and setting	Target organisms	Impact on inactivating the microorganisms	Quality scored by
Armellino et al. 2019. USA	Focused multivector ultraviolet (FMUV) system with shadowless delivery with a 90-second disinfection cycle for equipment at Operating Theatre.	Total pre-sample colony-forming units (CFUs) compared with post samples to assess reductions .	FMUV produced significant overall reductions of the microbial burden on patient care equipment in all study phases and independent of manual cleaning and chemical disinfection.	STROBE 35/44 = 79.54 %
Bache et al. 2018. UK	High-Intensity Narrow-Spectrum light Environmental Decontamination System (HINS-light EDS) efficacy in bacterial reductions in burn unit with an outpatient clinic.	V*ancomycin resistant enterococci* (VRE).	From 27% to 75% reduction in inpatients' CFU rates reported after use of HINS-light EDS. A rise of 48% recovering compared to pre-decontamination level after the HINS light switched off for two days.	STROBE 43/44 = 97.72 %
Bache et al. 2012. UK	High-Intensity Narrow-Spectrum light Environmental Decontamination system (HINS-light EDS) with 405 nm light in a burns' unit.	*Staphylococca*l-type organisms.	Mean decrease in surface bacteria from 22% to 86% reported during the HINS-light EDS and increasing from 78% to 309% after the light switched off. No correlation between bacterial kill and irradiance levels at sites but strong correlation between bacterial kill and exposure time.	STROBE 40/44 = 90.90 %
Beal et al. 2016. UK	PX-UV device at three room locations for a 5 min cycle each having at least one directly received UV cycle of disinfection in the line of sight with 25-minute mean time.	Total count of aerobic microbes, VRE.	The microbiological efficacy against VRE was limited with the three 5 min cycles of UV disinfection not ensuring total eradication of VRE. Longer periods of UV emission might increase the effectiveness.	STROBE 39/44 = 88.63 %
Brite et al. 2018. USA.	Ultraviolet disinfection (PX-UV) at a bone marrow transplant unit.	*VRE* and toxigenic *Clostridium Difficile (CD).*	Utilization of PX-UV disinfection to supplement routine terminal cleaning of rooms was not effective in reducing *VRE* and *CD*.	STROBE 43/44 = 97.72 %
Casini et al. 2019. Italy.	Pulsed xenon-ultraviolet light no-touch disinfection system (PX-UVC) for terminal room disinfection.	*Clostridium Difficile (CD)* spores, *Klebsiella pneumoniae, Achinetobacteria spp.*	After the PX-UVC exposure reduction of 12% obtained in patient rooms, of 8% in ICUs, of 93% in OTs with low turnover, and of 183% in OTs with high turnover.	STROBE 39/44 = 88.63 %
Casini et al. 2023. Italy.	UVC robots for disinfect high-touch surfaces in terminal rooms.		A total of 64.3% (103/160) of the sampling sites tested after standard cleaning as positive, whereas 17.5% (28/160) were positive after UV-C.	AMSTAR 13/16 = 81.25 %
Dippenaar & Smith. 2018. South Africa.	Pulsed xenon ultraviolet light device (PX-UVD) within neonatal and paediatric expressed human milk feed preparation areas.	*Acinetobacteria baumannii; Enterobacter cloacae; Stenotrophomonas maltophilia; Aeromonas hydrophilia; Enterococccus casseliflavus; Falvimonas oryzihabitans; Klebsiella pneumonia ozaenia; Klebsiella pneumoniae; Serratia marcescens; Serratia liquifaciens.*	A 90% reduction in surface bioburden was measured from the control period (544 CFU/cm$^{2)}$ compared to the PX-UVD period (50 CFU/cm^{2}). The number of organisms recognised during the control period decreased from ten to five: *Acinetobacteria baumannii; Acinetobacteria ursingii; Klebsiella teringa* during the PX-UVD period.	STROBE 40/44 = 90.90 %

Gostine et al. 2016. USA.	Automated mercury-bulb UVC lamps over computer keyboards and mice tested in ICU.	*Identified microbes: Staphylococcus*, *Streptococcus*, *Enterococcus*, *Pseudomonas*, *Pasteurella*, *Klebsiella*, *Acinetobacter*, and *Enterobacter*.	193 of the 203 base-line samples (95.1%) were positive for bacteria with a median of 120 CFUs per keyboard. Of the 218 post-installation samples, 205 (94%) were sterile. Comparison of pre- and post-UV decontamination median CFU values (120 and 0, respectively) revealed a >99% reduction in bacteria.	STROBE 32/44 = 72.72 %
Green et al. 2017. USA.	Portable pulsed xenon ultraviolet disinfection (PPX-UVD) in ICU.	Colonies were counted and identified. If the isolate was potential HAI pathogen, defined as *S. aureus, Enterococcus spp*.	Before the PPX-UVD exposure samples from bathroom hoppers, bedside monitors and door handles were most heavily contaminated. The post-exposure total samples (both touch and settle plates) with any growth significantly decreased (48% vs 31%), alike the surface growth (51% vs 33%).	STROBE 40/44 = 90.90 %
Kitagawa, Mori et al. 2021. Japan.	PX-UV disinfection in isolation rooms.	The CFUs of *Clostridium Difficile.*	Before bleach cleaning 27.8% and 31% CD rates found before PX-UV disinfection. Before and after both disinfection methods the bedrails and toilet seats were the two most common surfaces contamined with *CD.* Bed-side tables were the third most contaminated surfaces. Both manual bleach cleaning and PX-UV disinfection in addition to nonbleach cleaning reduced the overall *C. diff.*-positive samples and *C. diff*. CFU count. No significant differences found in baseline *C. diff*. CFU between groups.	STROBE 34/44 = 77.27 %
Maclean, et al. 2010. UK.	High-intensity narrow-spectrum light (HINS) system in isolation rooms in burn unit.	*Staphylococcus aureus* with testing for meticillin resistance.	The pooled data over the three phases showed a 62% mean percentage reduction in total contact-plate counts after use of HINS-light EDS with a mean plate reduction of 51.3 CFU. The mean reduction in presumptive *S. aureus* counts after HINS-light EDS was 50% with a mean plate count reduction of 18.4 CFU. Recovery of bacterial counts after switching off the HINS-light EDS increased 126% and 39.5 CFU. The presumptive *S. aureus* counts recovered by 98%, 18.0 CFU. For the on/off study, on average 56.5% of the presumptive *S. aureus* proved to be *S. aureus, of them* 73.1% were MRSA. After extended use of HINS-lights ~50% of tested isolates were S. aureus. In the empty-rooms, 3%.	STROBE 39/44 = 88.63 %
Morikane et al. 2020. Japan.	PX-UV device in an ICU.	MRSA and two drug resistant Achinetobacteria (2DRA).	The rate of the microbiological burden after manual cleaning was 81%, a further 59% reduction was achieved by PX-UV.	STROBE 40/44 = 90.90 %
Sathitakorn et al. 2023. Thailand.	Pulsed xenon UV (PX-UV) in intensive care units.	Gram-negative microorganisms.	Rooms with positive Gram-negative microorganisms were reduced by 50% after terminal manual cleaning and disinfection and 100% after PX-UV disinfection. On five nursing station sites, colony counts of Gram-negative contamination decreased by 100% after PX-UV exposure while decreasing by 65.2% in the control arm after terminal manual cleaning and disinfection. The in-room time use was 15.6 min per room. A PX-UV device significantly reduced the level of Gram-negative microorganisms on high-touch surfaces in intensive care units.	AMSTAR 12/16 = 75 %

van der Starre et al. 2022. Netherlands.	Automated whole room disinfection (WRD) devices by aHP, H2O2 vapour, UVC and PX-UV were compared.	Norovirus, *Acinetobacter*, carbapenemase-producing *Enterobacteriaceae* (CPE), extended spectrum beta-lactamase (ESBL) producers, *MRSA*, VRE, *Clostridium Difficile (CD)* and *Candida auris*.	Articles (n=54) consistently showed that automated disinfection using any of the four types of WRD is effective in reducing environmental and clinical outcomes. Despite the large variation in the included studies, the four automated WRD systems are effective in reducing the number of pathogens in hospital environment.	AMSTAR 15/16 = 93.75 %
Villacís, et al. 2019. Ecuador.	PX-UV disinfection in OR, ICU, internal medicine, Neo-ICU, Neo-Infectology, and microbiology lab surfaces.	*MRSA*, *E. faecium* (Van B), *Pseudomonas aeruginosa* (VIM), *and Klebsiella pneumoniae* (KPC) endemic strains to the hospital were tested.	A total of 3569 CFU detected from 124 surfaces after manual disinfection decreased to 889 CFU in 80 surfaces after PX-UV disinfection showing statistically significant 75% reduction in the surface and environmental contamination after PX-UV compared to manual cleaning and disinfection. The statistically significant decreases in CFU counts of high touch surfaces found in OR 87% and patient rooms 76%. After five minutes of PX-UV exposure all cases in four rooms an 8-log reduction was achieved presenting serine carbapenemases confirmed by PCR and sequencing.	STROBE 36/44 = 81.81 %
Wong et al. 2016. Canada	Low pressure mercury UVC light devices in tertiary care academic hospital.	Methicillin-resistant *Staphylococcus aureus* (MRSA), vancomycin-resistant *enterococci* (VRE), and *Clostridium difficile (CD).*	Totally 61rooms and 360 surfaces screened. Pre-cleaning the rate of MRSA contamination was 34.4%, VRE 29.5% and CD 31.8%. The post-cleaning contamination rates were not statistically significantly lower, 27.9%, 29.5% and 22.7% respective. The UV-C disinfection further reduced the MRSA contamination to 3.3%, the VRE contamination to 4.9%, and the CD contamination to 0%. All these reductions were statistically significant. The CFUs in surfaces excluding floors, decreased from 88.0 to 19.6 after manual cleaning. The UVC disinfection reduced it significantly to 1.3 CFU. The contaminations of floors increased from 241.4 CFU before manual cleaning to 591 CFU after it. The UVC exposure reduced this to a mean of 8.8 CFU. Prior to cleaning, MRSA, VRE, and CD contaminated 13.8%, 11.4%, and 7.2% of surfaces, respectively. The UVC disinfection further reduced the bioburden by 8-to 10-fold.	STROBE 38/44 = 86.36 %
Zeber et al. 2018. USA.	Portable PX-UV device with roughly 15 minutes (3 x 450 flashes).	MRSA or aerobic bacteria colonies (ABC).	Totally 70 samples were collected. The PX-UV device reduced MRSA and ABC counts by 75.3% and 84.1%, respectively, versus 25%-30% reduction after manual cleaning at control sites. Adjusting for baseline counts, manually cleaned rooms had significantly higher residual levels than PX-UV sites. Combined analyses revealed an incident rate ratio of 5.32, with bedrails, tray tables, and toilet handrails also showing statistically superior PX-UV disinfection.	STROBE 38/44 = 86. 36 %

ESBL = *extended spectrum beta-lactamase*; *CD = Clostridium difficile*; CDI = *Clostridium difficile*-infection; MDRO = *multidrug-resistant organisms*; MDR GNR = *Multi drug resistant gram-negative rods;* MRSA = *meticillin-resistant Staphylococcus aureus*; VRE= *vancomycin-resistant Enterococcus faecium*; MR *Acinetob. spp*. = multi-resistant *Achinetobacter;* 2DRA = two-drug resistant *Acinetobacter baumannii*; OR(T)= *operating room (theatre)*; CFU = *colony forming unit*; ICU = *intensive care unit*

Table 2 The photon disinfection technologies (PDT) implemented in hospital settings and their impact on hospital acquired infections (HAI)

Reference	The photon disinfection technologies and setting	Target organisms	Impact on decreasing the rate of hospital acquired infections	Quality Scored by
Anderson et al. 2018. USA.	Comparison of disinfection methods: With or without UV-C, UV-C, Bleach, Bleach and UV-C in terminal room settings.	*C. diff., MRSA, VRE; MR Acinetob. spp.*	No statistically significant difference in the hospital-wide risk of target organism acquisition between the standard disinfection and the three disinfection strategies for all target multidrug-resistant organisms reported but during the UV-radiation period the risk for the acquisition of *CD*, and VRE decreased. The HAIs were not reported.	STROBE (Sic!) 40/44 = 90.90 %
Morikane et al. 2020. Japan.	PX-UV device in an ICU.	MRSA and two drug resistant Achinetobacteria (2DRA).	The baseline incidence of MRSA transmission decreased from 13.8 to 9.9 (29% decrease) per 10,000 patient days % and Achinetobacteria (2DRA) from 48.5 to 18.1 (63% decrease) respective by PX-UV.	STROBE 40/44 = 90.90 %
Nagaraja et al. 2015. USA.	Pulsed xenon (PX-UV-D) in occupancy ICU in a tertiary care hospital.	*Clostridium difficile (CD).*	All together 525 HA and non-HA CD-infections found (274 in pre-UV-D period and 251 in UV-D period. The overall CDI rate was similar during the two periods. The hospital acquired CDI rate was 22% less during the UV-D period than before it. The separately calculated length of hospital stay of the HA CDI and the CA CDI patients remained unchanged between the two period.	STROBE 38/44 = 86.36 %
Sampathkumar et al. 2019. USA.	Pulsed xenon (PX-UV, 200-300 nm, 60 HZ) disinfection in haematology-bone marrow transplant and medical-surgical units.	*Clostridium difficile (CD).*	Pre-intervention CD-infection rates in the units were similar. During the six months of UV disinfection the CD-infection rates decreased significantly in the intervention units compared with control units (11.2 per 10,000 patient days, compared with 28.7 per 10,000 patient days, P = 0.03). In the intervention units also VRE acquisition decreased.	STROBE 37/44 = 84.09 %
Schaffzin et al. 2020. USA	UV disinfection by 2 LightStrike UV-C robots.	MDROs excluding methicillin-resistant *Staphylococcus aureus*. and *Clostridium difficile (CD)*.	The baseline median HAI rate was 3.63 / 1,000 inpatient days reported decreasing to a median of 3.04 / 1,000 inpatient days, 16.2%. The baseline median house wide HA-CDI rate was 0.45 / 1,000 inpatient days increasing to 0.94 / 1,000 patient days from March 2016 and decreasing to 0.75 / 1,000 patient days. Baseline median HAI-MDR-GNR of 33% decreased to 5.6%. The direct causation ship was not possible to infer between disinfection coverage and HAI rates, but that UV disinfection contributed to preventing HAIs.	STROBE 38/44 = 86.36 %
Vianna et al. 2016, US.	A pulsed xenon full-spectrum ultraviolet (PX-UV) flashlamp disinfection system in ICU.	*Clostridium difficile (CD), MRSA, VRE.*	A 29% facility-wide reduction reported in *CD; VRE* and *MRSA.* In the ICU, *CD*, MRSA, and VRE rates decreased by 45%, 56%, and 87%, respectively but the only statistically significant reductions found for VRE. In non-ICU areas, the reduction of 40% for *CD* and 52% increase for *MRSA* found. Compared to base-line data 36 fewer infections in the	STROBE 38/44 = 86.36 %

			whole facility and 16 fewer infections in the ICU found during the intervention period than would have been expected.	

ESBL = *extended spectrum beta-lactamase*; *CD = Clostridium difficile*; CDI = *Clostridium difficile*-infection; MDRO = *multidrug-resistant organisms*; MDR GNR = *Multi drug resistant gram-negative rods;* MRSA = *meticillin-resistant Staphylococcus aureus*; VRE= *vancomycin-resistant Enterococcus faecium*; MR *Acinetob. spp*. = multi-resistant *Achinetobacter;* 2DRA = two-drug resistant *Acinetobacter baumannii*; OR(T)= operating room (theatre); CFU = colony forming unit; ICU = intensive care unit; HA = hospital acquired; CA = community acquired.