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Original article

An overview on the use of ultraviolet radiation to disinfect air and surfaces

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Abstract. *Background and aim:* Ultraviolet radiation (UV) is the portion of the electromagnetic spectrum of wavelengths between 200 and 400 nm divided into three bands called UVA, UVB and UVC. Due to its well-described antimicrobial activity, UVC can represent a useful tool for disinfecting surfaces, water, and air. This study aimed to illustrate the studies over time of ultraviolet germicidal irradiation (UVGI) to disinfect air and surfaces. *Methods:* Articles on Scopus published until April 14, 2023, were considered. Many issues involving UV were deepened crosschecking with e.g., "air", "surfaces", "disinfection", "bacteria", "fungi", "operating theatres". According to the case, the following variables were considered: years and related number of articles, subject areas, type of document published, type of journal, and nationalities of the authors. *Results:* Since '30s, 287 448 articles on UV have been published. Among UVGI, 22 159 articles covered bacteria issues, followed by fungi and viruses with about 12 000 both. UVGI was addressed by 1941 and 931 articles for surfaces and air, respectively. Of these, 122 were performed in operating theatres. Since 1987, works have been published on spacecraft and, since 2000, on the use of UVGI robots for disinfecting air and surfaces. *Conclusions:* Our study shows the studies on UVGI and related issues. It also shows the most recent perspectives about possible applications e.g. during prolonged human-crewed missions on spacecraft, to inactivate microorganisms in environments where the exchange of air is impossible. (www.actabiomedica.it)

Key words: UV radiation, air and surfaces, operating theatres, disinfection

Introduction

Ultraviolet radiation (UV radiation) is the portion of the electromagnetic spectrum of wavelengths between 200 and 400 nm (nanometres). Towards the longer wavelengths, UV radiation borders on the shorter wavelength visible light, perceived by humans, of a violet colour, hence the denomination "ultraviolet radiation". UV radiation is divided into three bands of different wavelengths, called UVA, UVB and UVC. The exact wavelengths by which the three bands are defined vary according to the specific fields of study. However, the most used subdivision is the following: UVA: 400-315 nm; UVB: 315-280 nm; UVC: 280-200 nm (1). The most important natural source of ultraviolet radiation is the sun. The emission is linked to the transformation of the thermal energy produced by nuclear and chemical reactions taking place inside and on the surface of the star, into radiant energy. The atmosphere of the earth, through processes of absorption and diffusion, acts as a filter against radiation. In particular, UVC radiation (the most harmful to life due to its high energy content) is completely absorbed by the ozone and oxygen of the highest layers of the atmosphere; UVB radiation is also largely absorbed, but a non-negligible percentage (about 15-20%) reaches the earth's surface; UVA radiation manages to a large extent (about 55-60%) to reach the earth's surface.

In summary, the UV radiation that reaches the earth's surface is about 9% of the solar radiation at the top of the atmosphere and is distributed between UVA (90%) and UVB (10%). Artificial sources derive from various types and fields of application. Among the most widespread, there are germicidal lamps which are used to reduce microorganism contamination of devices and hospital environments. The standard source of UVC in commercial systems is low-pressure mercury vapor lamps. In the handcraft and industrial fields, the use of electric arc welders and some lasers that operate at wavelengths included in the ultraviolet range is frequent. Another use of UV lamps is in beauty salons to promote tanning. Based on the scientific literature, World Health Organisation (WHO) (2) has identified the diseases closely related to exposure to ultraviolet radiation (skin melanoma, squamous cell carcinoma, basal cell carcinoma, squamous cell carcinoma of the cornea or conjunctiva, keratoses, cortical cataract, pterygium).

One of the main uses of UV radiation is the disinfection of surfaces, air, and water. Ultraviolet germicidal irradiation (UVGI) uses short-wave ultraviolet energy (UVC) to inactivate viral, bacterial, and fungal organisms, making them unable to replicate themselves and spread diseases (1). Reed et al. describe the studies on UVGI in the air (3). As early as 1845, it was known that microorganisms respond to light (4). In 1877 it was observed that sunlight prevented the growth of microorganisms, and, upon increased exposure durations, the test tubes remained bacteria-free for several months (5-10). Between 1914 and 1930 some articles provided the first analytical bactericidal action spectrum of UVGI (11-14). Some studies suggested that nucleic acids may be the genetic material and responsible for cell death-proteins, as was a common belief at the time (15). In 1960, it was demonstrated that UVC radiation results in the formation of dimers from adjacent pyrimidines, accounting for "a large part of the effects of ultraviolet radiation on biological systems" (16).

Derived from the droplet theory put forth by Flügge (17), the concept arose of airborne infection by droplet nuclei and the use of UVGI to disinfect the air (18-19). Some studies of airstream disinfection using UVGI in HVAC systems were performed (20-21). After some initial mistakes (22), some studies reported a reduction in the postoperative wound infection rate from 11.62% without the use of UVGI to 0.24% with the use of UVGI (23-28). Throughout the 1940s, extensive work provided further evidence for the efficacy of UVGI, and guidelines for UVGI air disinfection systems and applications were proposed (29). The effectiveness of UVGI to disinfect exhaust air was also demonstrated, including the first use inside an air conditioner (30-31). In 1955, Wells published the Air Contagion and Air Hygiene (32), deemed a "landmark monograph on air hygiene" by Nardell (33). Riley followed with his Airborne Infection: Transmission and Control (34) and the concept of UVGI effectiveness was extended to the prevention of tuberculosis (TB) (35). Moreover, it was extended to airborne transmission of influenza, during the 1957 pandemic. The infection rate was only 1.9% in an irradiated ward, while it was 18.9% in a non-irradiated ward (36).

Although the early successes in the effectiveness of UVGI, it was neglected in the following years (37-38). The inability to reproduce the success in preventing the spread of measles (39-41) or cold and bacterial illness (42-46) can help to explicate that, but also the increasing use of antibiotics at that time and the hope that viral diseases could be controlled by vaccines. In the meantime, concern about the health effects of UVC exposure and ozone production from germicidal lamps was highlighted.

Despite that, the evaluation of UVGI effectiveness in operating theatres to reduce post-surgical infections continued (47). In 2003, the Commission Internationale d'Eclarage (CIE) (48) published a technical report on UVGI air disinfection, summarising the state of knowledge of that time.

The Centers for Disease Control and Prevention (CDC) expanded their previous recommendation (49-50) about UVGI adding TB infection control in healthcare settings. Afterward, CDC produced the first comprehensive guideline for UVGI in the control of TB in healthcare settings (51) and a clinical trial was published (52).

Considering healthcare–associated infections (HAIs), and, among these, surgical site infections (SSIs) (53-58), the CDC provided recommendations for environmental disinfection (59), and particular attention was dedicated to environments for paediatric immunocompromised patients (60).

UVGI technology has been increasingly used in healthcare settings to prevent infection by disinfecting surfaces, water, and air (61-67). Some studies demonstrated the effectiveness of UVGI in the environmental fight against multidrug-resistant organisms (68-71). Recently, a new issue was added to UVGI; prolonged human-crewed missions on the Moon are foreseen as a gateway for Mars and asteroid colonization in the next decades could expose crews to health risks related to airborne biological contaminants and long-time permanence in space. A possible way to perform pathogens' inactivation could be by employing the shortest wavelength range of solar ultraviolet radiation. This could be a new challenge for the future (72).

This study aimed to illustrate the studies overtime on the use of ultraviolet radiation to reduce air and surface contamination with particular reference to the operating theatres providing a picture of the spread of this topic among the scientific community.

Methods

Based on our recent studies (73-74), we searched Scopus for articles published until April 14, 2023, using the string TITLE-ABS-KEY (UV AND radiation OR ultraviolet). Only Scopus was considered as it covers a wider range of journals, aiding in both keyword research and citation analysis (75). Articles written in all languages were included. Many issues involving ultraviolet and air or surfaces contamination were deepened by crosschecking with i.e., "disinfection/sanitisation/sterilisation" (in figures and in the text reported as disinfection, "bacteria", "molds/fungi/fungal", "virus/viruses", "prions", "surgical site/wound infection", "operating theatres/rooms".

According to the case, the following variables were considered: years and related number of articles, subject areas, type of document published, type of journal, nationalities of the authors, and institutions to which the authors belonged.

Results

From 1933 to April 14th, 2023, 287 448 articles on ultraviolet radiation were published (Figure 1) by authors from 160 countries (Figure 2). The top ten include the United States, China, India, Germany, Japan, United Kingdom, France, Italy, South Korea, and Spain, with 232 264 authors representing 63.2% of all authors.

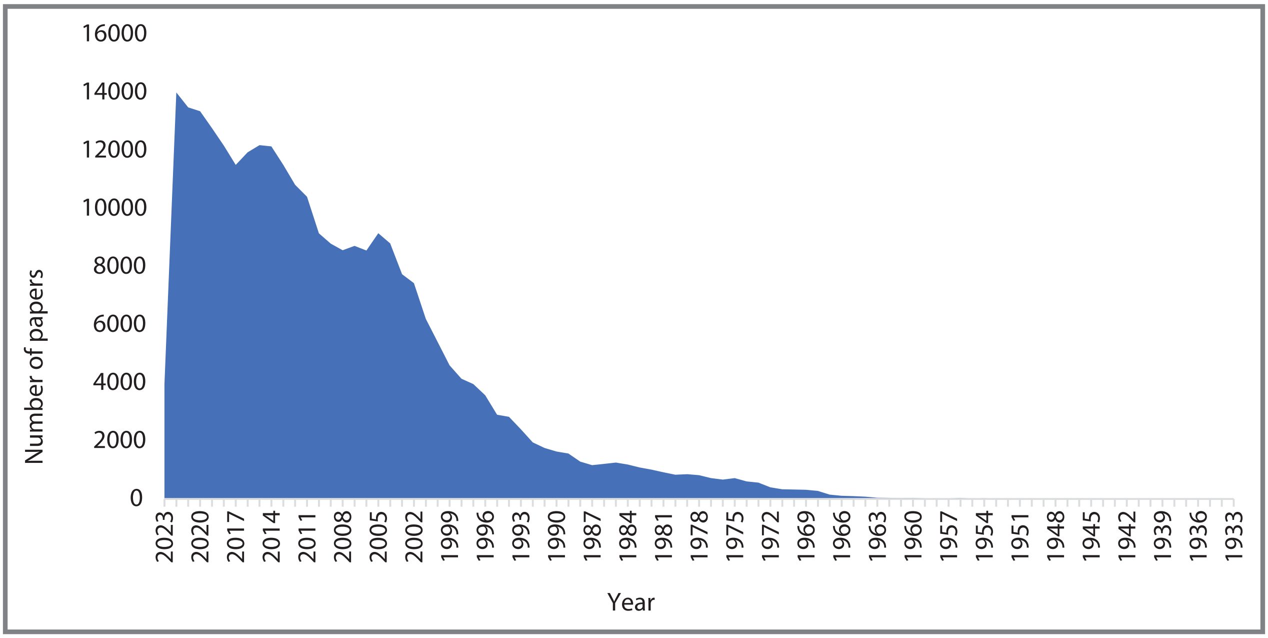

Figure 1. Papers published from 1933 on ultraviolet radiation.

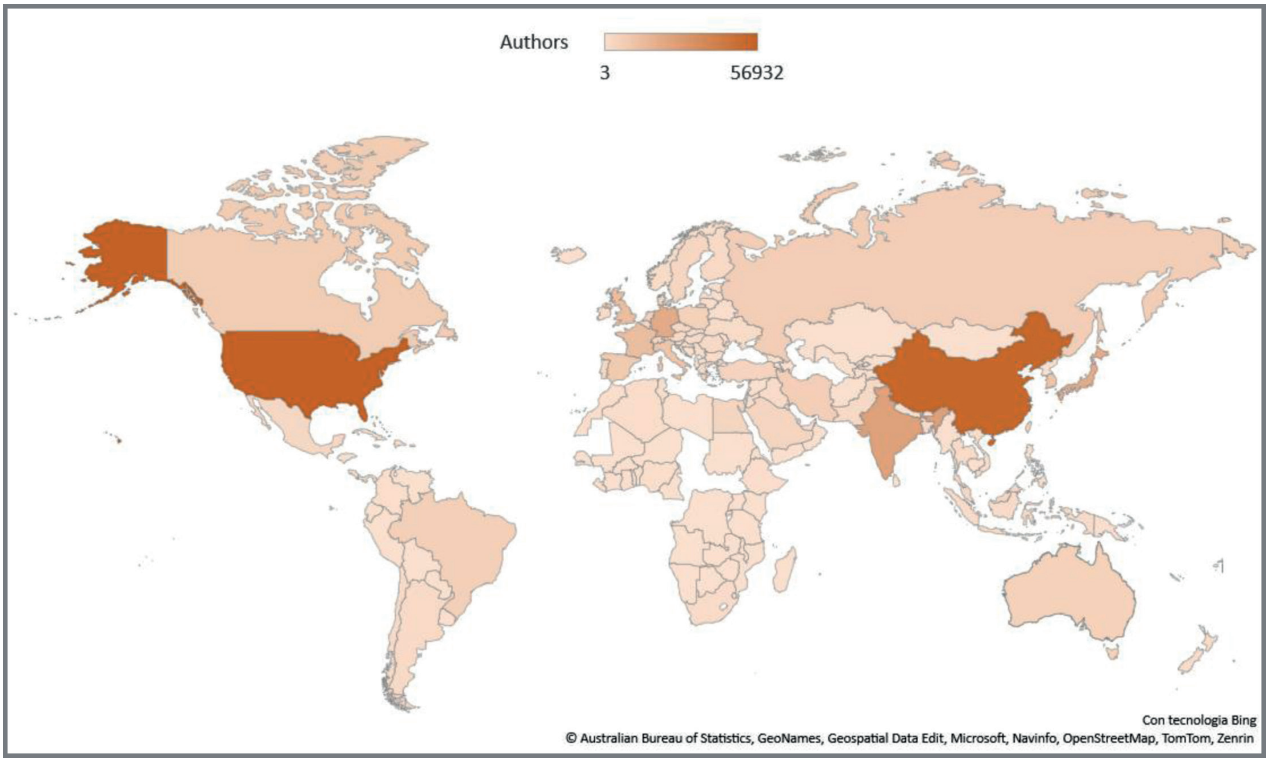

Figure 2. Countries of authors involved in ultraviolet radiation studies.

Regarding UV radiation and microorganisms, bacteria were the topic covered since 1931 by 22 159 articles. On ultraviolet radiation and viruses 11 356 articles were published since 1935, while since 1920, 11 824 articles appeared on fungi, 1 210 on algae, and only 196 articles on prions and 135 on protozoan (Figure 3).

Since 1941, 1 941 articles have addressed TITLE-ABS-KEY (uvc OR uv-c OR ultraviolet AND surfaces AND disinfection OR sanitisation OR sterilisation), and 931 articles have addressed TITLE-ABS-KEY (uvc OR uv-c OR ultraviolet AND air AND disinfection OR sanitisation OR sterilisation) (data not shown). The studies on ultraviolet radiation about operating theatres, TITLE-ABS-KEY (uvc OR uv-c OR ultraviolet AND operating AND theatres OR rooms AND disinfection OR sanitisation OR sterilisation) were 122 (65 on air and 33 on surfaces) (Figure 4).

The principal area of interest of the journal publishing UVGI papers was medicine (Figure 5).

The use of UVGI to reduce SSI was evaluated in 171 papers since 1959 (Figure 6) with an increase in the last seven years and with authors mainly from the United States, followed by the following countries: United Kingdom, Japan, Germany, India, Italy, Canada, United Arab Emirates, Finland, Norway (Figure 7).

Since 1987, 34 studies have been published on TITLE-ABS-KEY (uvc OR uv-c OR ultraviolet AND spacecraft OR space AND station AND air OR surfaces AND contamination) of which 9 only focused on air, starting from 1992 until 2010. After that date, no data are available.

Since 2000, 19 articles have been published on the use of robots for disinfecting air and surfaces using ultraviolet radiation (80), and 21 articles dealt since 2017 with drones in the field of decontamination.

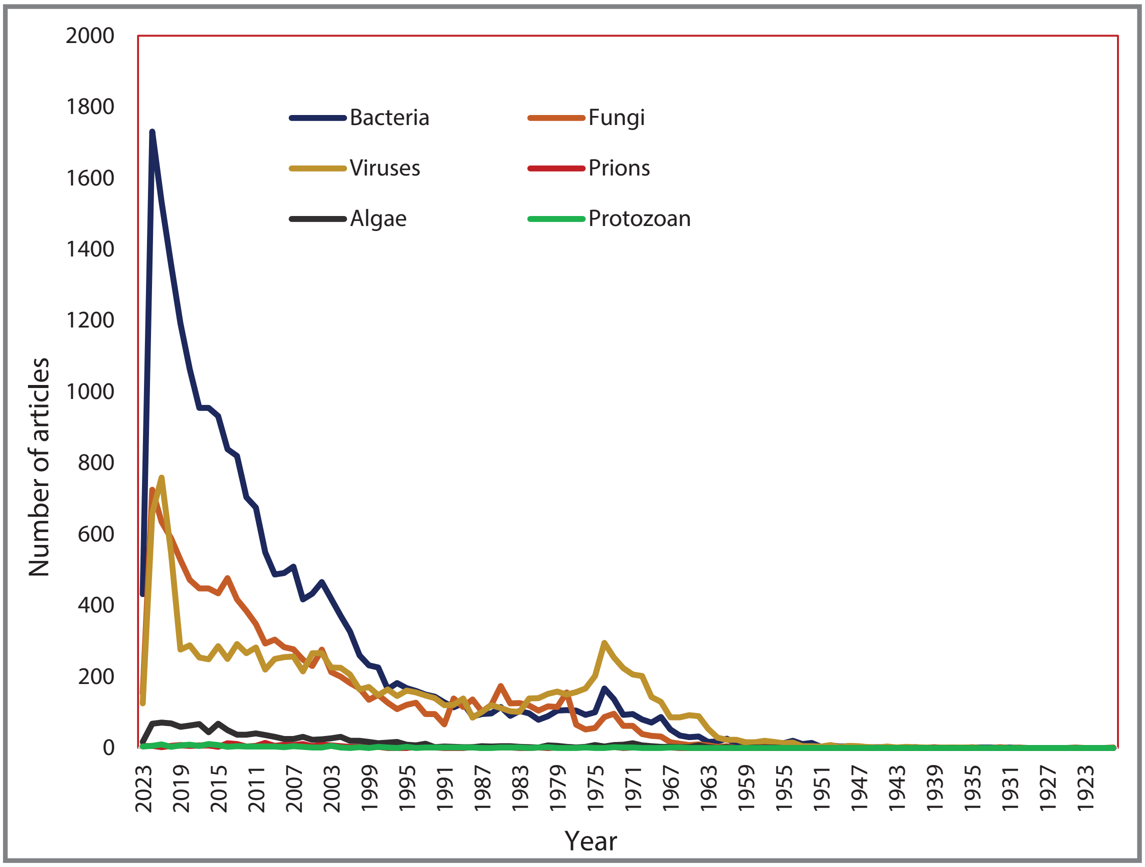

Figure 3. Papers published over time on UV radiation and bacteria, fungi, viruses, prions, algae and protozoan.

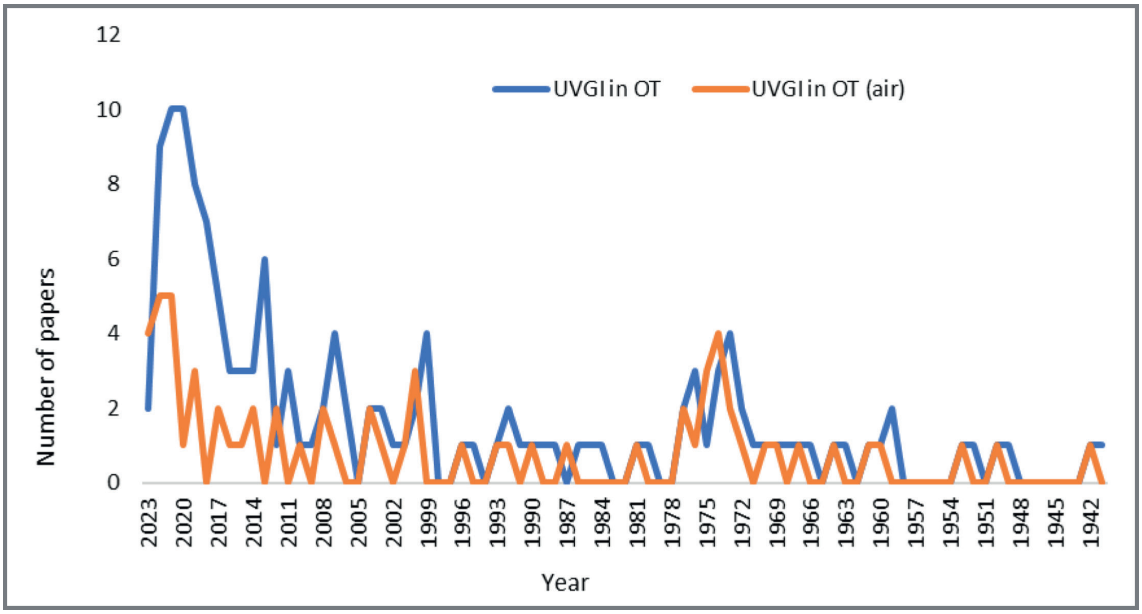

Figure 4. Number of papers published on air and surfaces disinfection in operating theatres.

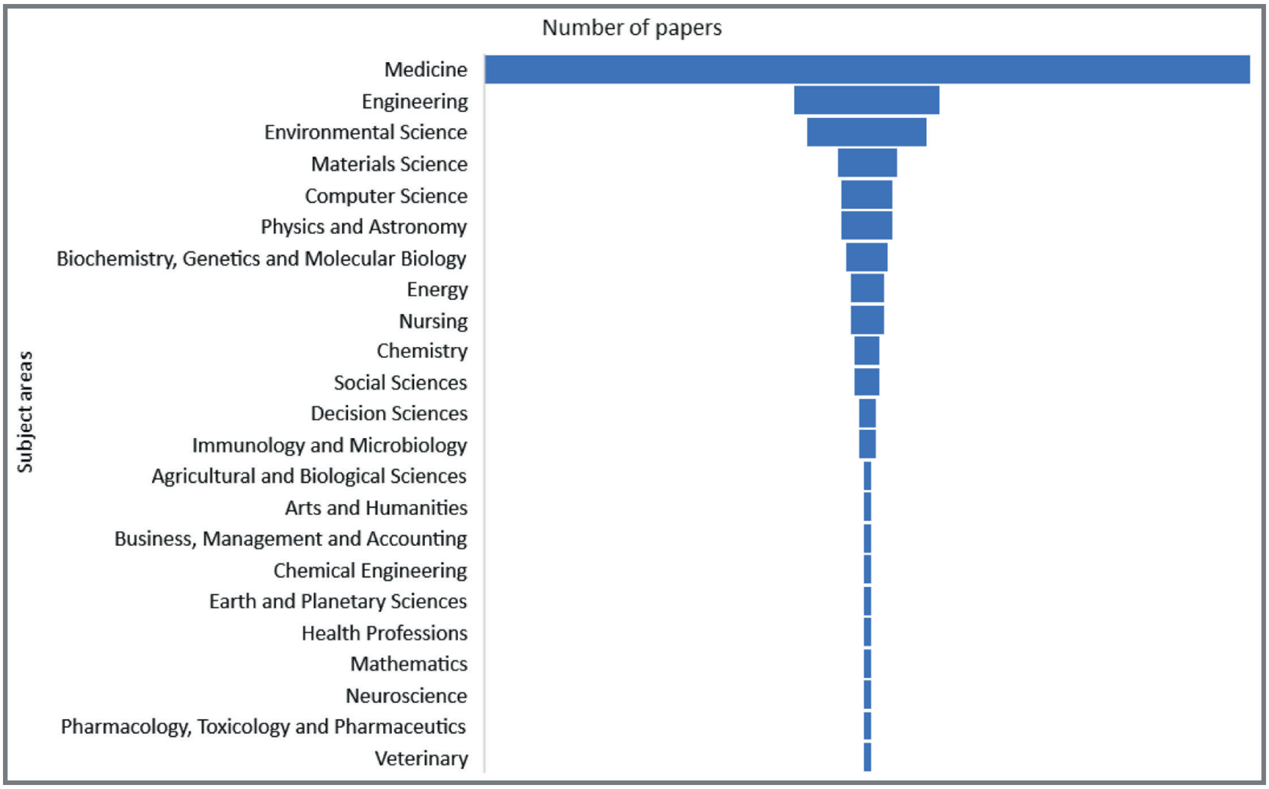

Figure 5. Subject areas involved in UVGI studies in operating theatres.

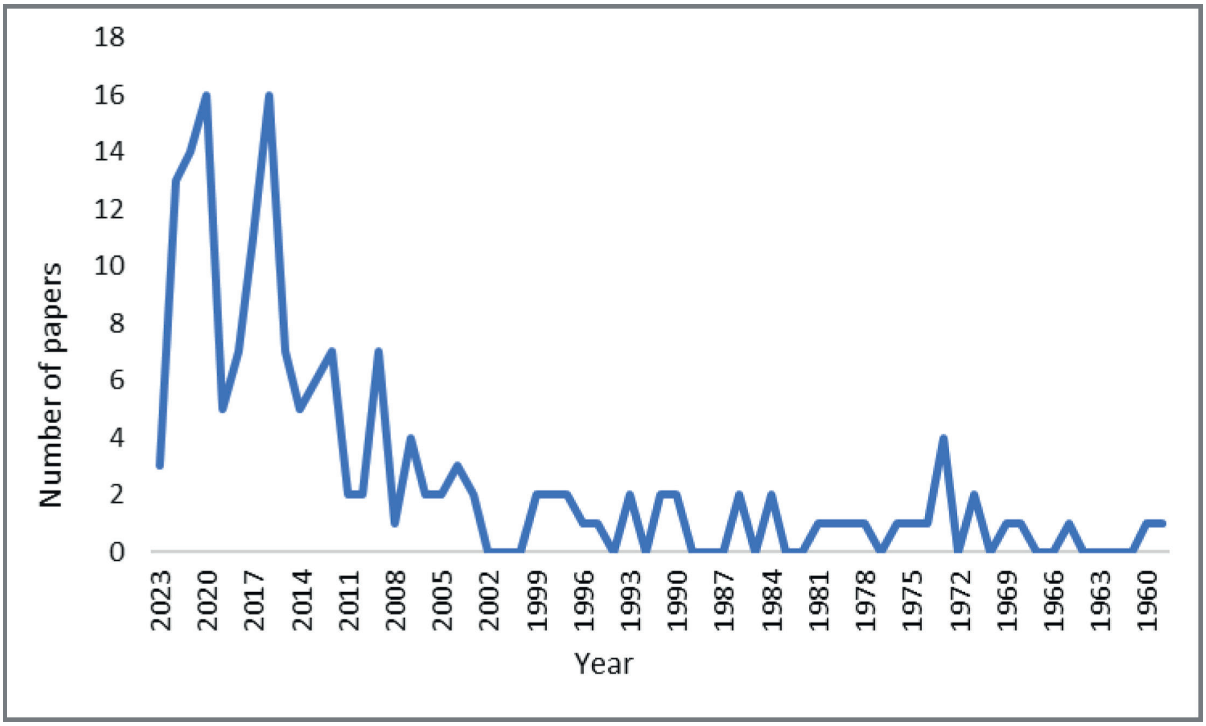

Figure 6. The trend of articles published on UVGI and reduction of surgical site/wound infection.

Figure 7. Countries of authors involved in studies about reduction of surgical site/wound using UVGI.

Conclusions

The studies on the use of UVGI are undoubtedly numerous. The efficacy of UVGI disinfection has been established for a long time. Some studies included the measurement of bioburden;most of these also indicated that UVGI led to reduction of healthcare-associated infections, but with a lack of standardisation and the presence of confounding factors (76). However, the number of studies regarding practices in contexts where their effectiveness can lead to benefits seems to be relatively small; for example, in operating theatres where the reduction of the incidence of surgical site infections and in any case the reduction of the infectious risk also for healthcare workers are an important objective.

Due to its well-described antimicrobial activity, UVC can be a useful tool to replace traditional general-purpose surface disinfectants (70). However, manual cleaning is a prerequisite for the use of UVC disinfection. Evidence also suggests that manual cleaning and disinfection are often inadequate and result in residual contamination (77).

Interest in technologies, such as robotic devices that perform surface and air disinfection procedures using UVGI, has recently increased dramatically. UVGI complements rather than replaces physical environmental disinfection. The use of disinfection protocols plays a significant role in preventing and containing the spread of infectious diseases, a reality highlighted during the COVID-19 pandemic (78).

Delivery times for single rooms in hospitals must be short given the high bed occupancy levels in many countries. UVC robots will need additional time that interferes with daily hospital routines. Therefore, their use must be integrated into the hospital workflow. The advantages of UVC robots are (77): (1) The robotic disinfection will work in an unmanned and standardized way, without the need for continuous human presence at the disinfection site. Thus, exposure of healthcare workers to harmful UV radiation can be avoided during the process. (2) The application of UVC as a final disinfection step after manual cleaning and manual disinfection provides an additional hygienic benefit to reduce cross-transmission and healthcare-associated infections. (3) UV light leaves no residue, making it an environmentally friendly disinfection method.

This new technology could be used to complement current hospital cleaning and disinfection practices (77-81).

This study is not a systematic review and is based only on the Scopus database, therefore some documents may have been lost. However, we believe that the analysis of the results of our study provides a useful tool to know the evolution of studies on the use of UV radiation to reduce air and surface contamination mainly in operating theatres to raise awareness towards better sharing of objectives, approaches, and results, above all in the interest of patients and health services. It also shows more recent perspectives on the use of UVGI for future application, for example during extended manned missions to the Moon envisaged as a gateway to colonisation of Mars and asteroids in the coming decades, to perform pathogen inactivation employing the shortest wavelength range of solar ultraviolet radiation as a natural source.

Conflicts of Interest: Each author declares that he or she has no commercial associations (e.g. consultancies, stock ownership, equity interest, patent/licensing arrangement etc.) that might pose a conflict of interest in connection with the submitted article.

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