INTERIM INDICATIONS FOR THE USE OF UV GERMICIDAL IRRADIATION IN THE CONJUNCTURE OF COVID-19 PANDEMIC

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Abstract

The ultraviolet radiation in the range 100 -280 nm (UV-C) has a well-known germicidal efficiency due to the disruptive mechanism on the nucleic acids, RNA and DNA, of microorganisms. The UV-C based disinfecting technology is commonly used, for example, in biosafety cabinets in hospitals and laboratories. Although the UV-C would be useful for its germicidal action, caution must be used when the UV-C use could imply human exposure. The phototoxicity of the UV-C radiation can induce damage to most external organs, eyes and skin and exposure limits for acute effects must be respected in order to protect the human health and safety. In addition, the UV-C radiation is known to have stochastic effects and for this reason has been classified by the IARC (International Agency for Research on Cancer) as a class I carcinogenic agent.

The COVID-19 pandemic outbreak raised the question of disinfecting living and working environments especially when they are shared by many people, this issue being particularly urgent in hospitals where the viral concentration due to patients affected by Covid-19 can be very high. Although the hospitals are the environments that most need disinfection, also transport means, markets, schools, commercial centers have to be disinfected in order to control the spreading of the infection. The effectiveness of the UV-C against microorganisms aroused a great interest during the pandemic outbreak, and several new devices for disinfection, based on this technology, have been proposed in the market with different use. Although there is lack of studies determining precisely the lethal UV-C dose in the case of COVID-19, many studies have been carried out in the recent past regarding the UV-C inactivation efficiency against very similar microorganisms, such as those causing the SARS and the MERS belonging to the same family Coronaviridae. The effectiveness of UV-C radiation in killing microorganisms, including respiratory viruses that were found relatively highly susceptible, is well assessed, but caution must be used when the use of UV-C based technology implies human exposure. The right compromise between effective disinfection objective and human health protection must be found, quantitatively evaluating each specific situation. The limit of human exposure must be respected and an accurate cost/benefit ratio must be evaluated in the case of doses well below the exposure limits for acute effects. In this work, the concepts of lethal dose in terms of irradiance and exposure time are discussed in the light of the human exposure limits with respect to different UV-C radiation practical applications.

Examples are drawn by the literature and by the direct experience of the authors.

This work is addressed, in particular, to medical physicists and biomedical engineers. Technical personnel with adequate expertise could use these indications for developing and maybe sharing specific experiences. Further research is recommended at the aim of improving the disinfection techniques based on optical radiation. Beyond the epidemic conjuncture, this work could be useful also in fighting the increasing spread of multiresistant bacteria in hospitals reducing healthcare personnel exposure to complex mixtures of disinfectants.

Introduction

On May 2020, the Italian Institute of Health (ISS), issued its Report 19 n. 25/2020 [1] addressing interim recommendations on cleaning and disinfection of non-healthcare settings.

In this report (in Italian), is clearly stated that the UV-C radiation can be safely used in enclosed environments to disinfect surfaces or objects if no risk of human exposure occurs.

Before COVID-19 sanitary emergency, the use of UV-C radiation, although the germicidal effectiveness was well known and widely described in literature, was basically limited to health care and research workplaces in order to keep sterility of the work plane in biosafety cabinets (BSCs). The risk, arising from human exposure to UV-C radiation, in facts, discouraged use of UV-C lamps, even when technical precautions could have been easily taken in order to minimize the human exposure itself. Although the use of UV-C sources did not develop much in Italy in living and working environment, a lot of different UV-C technical applications have been proposed, some of them with possible human exposure occurrence, other without any possibility of human involvement.

In fact, the problem of improving the indoor air quality in presence of possible microbiological contaminants raised long before the COVID- 19 epidemic outbreak.

The issue of improving the indoor air quality inactivating bacteria, fungi, viruses at the aim of protecting workers and inhabitants, especially the most susceptible due to some immunodeficiency, is object of a large scientific literature and technical solutions are continuously proposed.

The selection of particularly harmful strains of antibiotic-resistant bacteria causes many deaths in hospital setting, making particularly crucial the bacteria inactivation in the air breathed by fragile patients.

Solutions have been also studied in the scenario of bioterrorist attacks to large buildings in which a lot of people are simultaneously contaminated by pathogenic agents, circulating through the ventilation and air conditioning systems. Although the HAVC (Heating Ventilation and Air Conditioning) systems could contribute to spreading infections, if technical requirements are not kept into account for preventing such occurrence, simply preventing the recirculation of air as suggested for the coronavirus contrast [2], could not be sustainable in the long term.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), which is an important reference for the best practices about aeraulic systems, in a 2019 position document [3] considers the use of germicidal UV-C radiation as a suitable and reliable solution.

The UV-C technology could be particularly useful in disinfecting the air flux in ventilation and air conditioning installations. In this case, the UV-C only irradiates the air flux inside close ducts so that the human exposure cannot occur. A complete and updated review about this issue is reported in [4].

After the COVID-19 outbreak, and even more in view of the re-opening of normal activities with sanitization requirements to be fulfilled, a very large number of UV-C based devices are being proposed to the market.

In this document, the safety concerns addressed in the ISS Report [1] are considered in more detail with brief considerations and references about the different technologies proposed so far.

Reference values and calculation examples, taken from the literature and authors experience, are provided in order to help trained staff, of the health physics and clinical engineering departments, both in Italy and other countries touched by a global enduring outbreak, to set up safe and effective solutions.

The possible safe use of UV-C radiation, in cases of highly contaminated environments when a fast, simple and effective disinfectant method is needed, is also addressed. The possible use of UV-C for disinfecting personal protective equipment (PPE) in case of shortage, is also considered with all the necessary precautions.

D_{90} and metrics for microorganisms inactivation

The germicide properties of the UV-C radiation is well known, and described in literature.

When a population of N_0 microorganisms is irradiated with constant power density (better, irradiance, in W/m^2), the number of surviving ones N_s decreases exponentially with time.

The integral of the irradiance over time is called radiant exposure or H_0, expressed in J/m^2.

In the literature, radiant exposure is often defined also fluence or dose, since it is the total energy density hitting the target.

Following the technical standard of the International Commission on Illumination CIE 155:2003, [5], the following relation holds:

$$\frac{N_s}{N_0} = e^{-k \cdot H_0} \quad (1)$$

If we define D_{90} as the UV dose that we need to inactivate the 90% of the microorganisms, $N_s/N_0 = 0.1$ and the decay constant k, the inverse of the dose at which the population is reduced of $1/e$, derived from (1) is

$$k = \left| \frac{ln(0.1)}{D_{90}} \right| \quad (2)$$

Many publications report the D_{90} expressed as radiant exposure, otherwise, the logarithm in base 10 of N_0/N_s is reported versus the dose in J/m^2 .

A log inactivation of n=4, for example, means that a fraction of 10^{-4} of the initial population survived the germicide effect or, equivalently, that 99.99% of the microorganisms are inactivated.

For a given D_{90}, from (1) it is possible to compute the dose needed to attain a log inactivation of n simply by multiplying by n the D_{90}

$$D_n = D_{90} \frac{ln(10^{-n})}{\ln(0.1)} = nD_{90} \quad (3)$$

Wavelength dependence

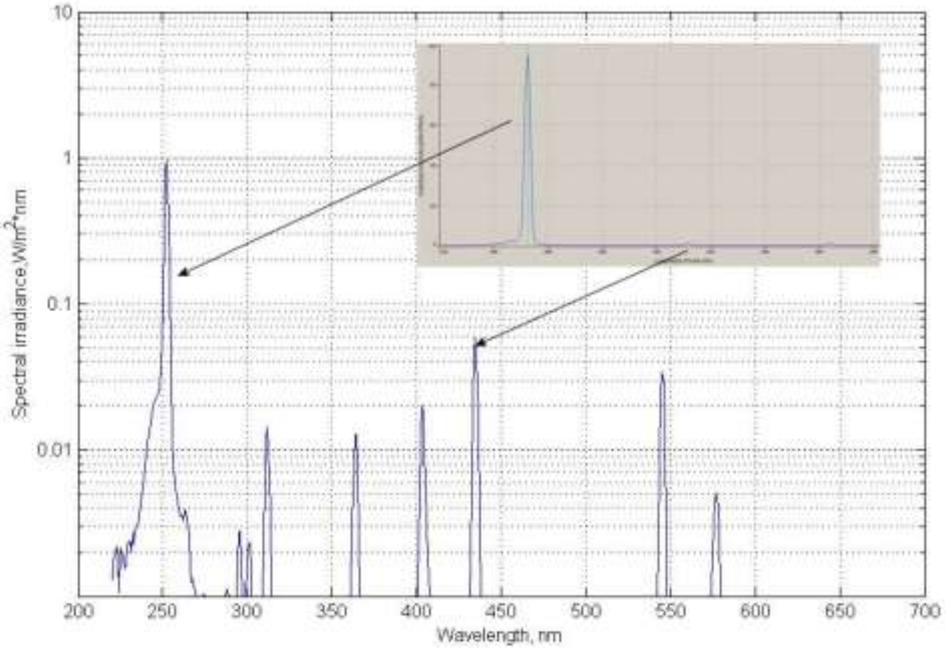
The log inactivation depends on the wavelength of the radiation, but extended research on this topic has been limited so far by the availability of radiation sources capable to emit the proper amount of non-ionizing radiation in the range of UV-C.

In 2014, Beck et al [6] studied the inactivation of a number of different microorganism species comparing the effect of the irradiation with a wavelength tunable laser to that of the most widely used source since then, i.e the mercury vapor discharge UV lamp.

Actually, most of microorganisms show a certain sensitivity around 260 nm, even if below 240 nm the microorganisms susceptibility has been shown to increase at decreasing wavelengths.

Figure 1, shows the spectrum of an UV lamp mounted in a BSC: the peak wavelength is at 253.7 nm. Other UV peaks are at 311 and 365 nm but they are comparable in intensity with the visible light emission, whilst the UV-C peak is so intense that, in linear scale, only the 434 nm visible emission can be distinguished.

Figure 1: spectrum of a germicidal lamp mounted in a biosafety cabinet, in logarithmic and linear scale



Photobiological safety issues

Health effects of the human exposure to UV radiation are addressed in the guidelines of the International Commission on Non Ionizing Radiation Protection (ICNIRP) [7].

The exposure limits (ELs) reported in the ICNIRP guidelines were implemented as exposure limit values for workers in the European Union Directive 2006/25/EC. In Italy, other EU countries and UK, it has the force of law for the protection of workers against the risks arising from artificial optical radiation.

The exposure of unprotected eye and skin to UV-C and UV-B radiation must not exceed, in an 8 hours work-shift (Texp8h), the dose of 30 J/m^2, calculated as the effective radiant exposure H_{eff}, given by:

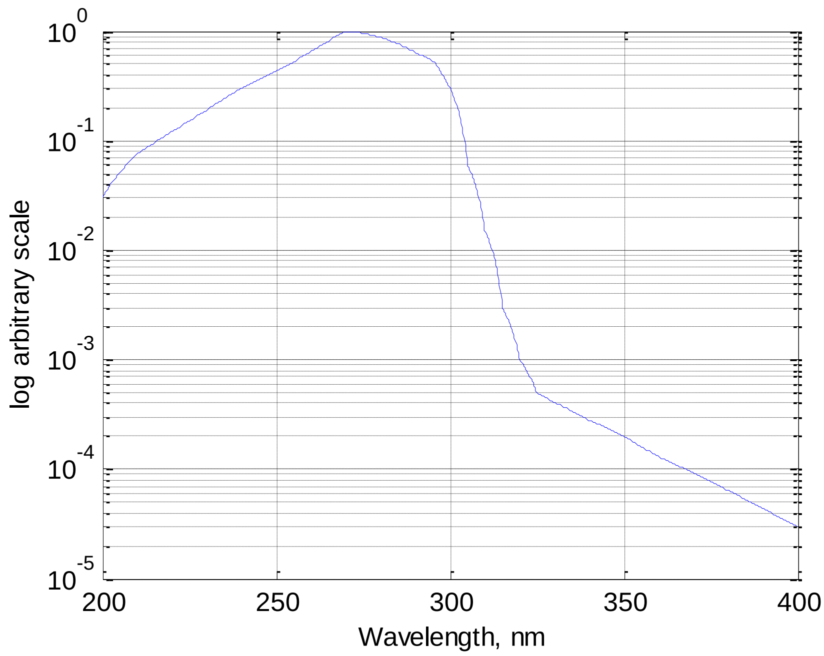
$$H_{eff} = \int_0^{Texp8h} E_{eff} \cdot dt \quad (4)$$

where E_{eff} is the spectral irradiance weighted on the action spectrum for hazard assessment S_λ, derived upon the envelope of action spectra that considers both ocular and skin effects, and integrated over the wavelength:

$$E_{eff} = \sum_{\lambda=180\ nm}^{\lambda=400\ nm} E_\lambda \cdot S_\lambda \cdot \Delta\lambda \ (5)$$

The effective radiation spectrum S_λ, tabulated by ICNIRP, is shown in Figure 2

Figure 2: effective action spectrum S_λ for the protection of eye and skin, ICNIRP 2004 [7]



The limit described by (4) should be considered as an absolute limit for ocular exposure.

In facts, the ICNIRP ELs were developed by considering lightly pigmented populations (i.e., white Caucasian) with greatest sensitivity and genetic susceptibility for skin cancer.

ICNIRP states that *occasional exposures to conditioned skin may not result in adverse effects*.

In Directive 2006/25/EC , the limit has been set for the protection of eyes and skin against some of the effects that can occur as a result of excessive UV exposure: "photokeratitis, conjunctivitis, chataractogenesis, erythema, elastosis, skin cancer".

For the protection of the eye from the risk of photochemical cataract, the UV-A irradiance

$$E_{UVA} = \sum_{\lambda=315\ nm}^{\lambda=400\ nm} E_\lambda \cdot \Delta\lambda \quad (6)$$

must also be limited so that, in a 8-hours shift, H_{UVA} < 10 kJ/m^2.

It is important to notice that, in the literature, when the microorganisms inactivation dose is under consideration, H_0 is normally related to the integral over the time of the irradiance around the most effective germicide peak at 254 nm. The energy flux in other ranges is not kept into consideration in the calculation of the D_{90}.

When safety issues are addressed, the irradiance of interest E_{eff} is derived by convoluting the Irradiance spectrum with the relative biological efficacy curve plotted in Figure 2. However, when the germicide lamps are under consideration, since almost all the germicidal power of the spectrum is concentrated in the mercury emission line, centered at 254 nm, in practice, H_{eff} can be easily derived simply multiplying H_0 by 0.5 which is the value of S_λ at 254 nm.

Alternative sources to mercury vapor lamps

The use of different sources has been proposed, such as light emitting diodes (LEDs), with different spectral characteristics.

In principle, LEDs could be fabricated with the peak emission at the desired wavelength, and the environmental issue, due the mercury, contained in germicidal lamps, would be spared.

However, UV LED technology is not yet as "mature" as that of the corresponding visible LEDs and is not yet competitive with the most common low-pressure mercury vapor lamps, [8] thus limiting, so far, the actual ability of LED-based devices to the sanitization of small objects, e.g. smartphones.

A number of applications of this type are being proposed to the market; considering the great variety in the performance of LEDs and the high demand caused by the pandemic, it is not simple to assess effectiveness and safety of these devices. In facts, manufacturers of products using UV sources for the purpose of disinfecting objects, should clearly provide spectroradiometric information and the actual germicidal effectiveness of their products.

Notice that, due to the logarithmic scale of Figure 2, a slight shift of the wavelength could result in different germicidal effectiveness of the radiation; it should be noted that the values of D_{90} generally refer to the radiation at 254 nm of common mercury vapor lamps.

As an alternative to mercury containing lamps, systems based on pulsed xenon lamps are being proposed [9]. Xenon lamps have a continuous emission spectrum extending from UV to IR, so, in order to achieve sufficient germicidal efficacy without risk to the user, they must be pulsed and the emitted radiation must be properly filtered.

Again, results are strongly dependent on actual spectrum and average irradiance, therefore in the literature the effectiveness of these systems is still under discussion [10]. Anyway, pulsed xenon UV based system are normally designed to operate in absence of human subjects.

However it must be pointed out that most of the transparent windows in workplaces are effective in shielding UV-C, so that mercury lamps, having a weak visible emission, are widely used in BSCs. Pulsed UV xenon spectrum, instead, is, in principle, accompanied with strong visible light. Fast pulses of intense visible light can cause annoyance and even hazard for sensitized subjects [11].

All optical radiation sources, to varying degrees, may represent a potential risk to exposed human subjects depending on their emission spectrum, their biological effectiveness and the intensity of emission in the different spectral bands. Ultraviolet rays in the UV-C band, which are recognized as having the highest germicidal efficacy, although they are the highest energy spectral component, are less dangerous to humans than their closest UVB and UVA "cousins", at least from the point of view of known deterministic effects. Therefore, low-pressure mercury vapor lamps, which concentrate most of their radiant flux in the UV-C band, are relatively less dangerous for the same total power output than their xenon counterparts with significant UVB-A and visible emissions.

As reported in literature, UV irradiation is effective only on the surface of the objects in the line of sight to the source, so its use in the sanitization of thick fabrics or any object with shadowed surfaces is not recommended.

Another important issue with UV sanitization of objects, is that UV radiation is a main cause of ageing of most of materials; a number of test methods are established [12],[13], in order to test consumer products against solar irradiation. Since germicidal UV has a very different spectrum, lacking of specific testing, the effect of repeated treatments cannot be foreseen.

The use of the so-called far UV-C could be promising, as well, as sensitivity of viruses [14] around 220 nm has been demonstrated, comparable to that at 254 nm. In this range, however, the action spectrum in Figure 2 is worth about 0.12 vs 0.5 at 254 nm. Therefore, compared to common mercury lamps, it is possible, within the ELs for eye and skin, not considering the possible stochastic effects, to increase the germicidal dose and, consequently, the log inactivation value.

The study [14] was conducted on laboratory-generated aerosol, exposed to radiation emitted by excimers lamps (Kr-Cl). These lamps have a broader emission spectrum compared to mercury lamps and had to be filtered for the experiment.

Further research is needed because one of the main reason for the skin safety of the radiation at 220 nm, is the strong absorption in water; the effectiveness of this wavelength on viruses encapsulated in droplets should be confirmed. Moreover, below 250 nm, the amount of ozone, generated by photochemical processes, increases, as the ozone production efficiency is an increasing function of photon energy. In 155:2003, CIE made warnings against the ozone production by the far UV-C short wavelength sources even if they have interesting disinfectant properties; the authors of the study [14], reported indeed a very low ozone concentration (< 0.005 ppm) .

A very recent study (Szeto et al. 2020) [15] showed that the combination of Vacuum-ultraviolet (VUV) light at 185 nm and the UV-C at 254 nm, both emitted by the low pressure Hg vapor lamps, increases the germicidal effectiveness of the single emission at 254 nm. This occurrence can be explained both by the stronger ionizing power of the VUV with respect to the UV-C light and by the ozone production that could interact constructively in the germicidal effectiveness of the UV radiation. The authors showed the disinfectant efficacy of VUV combined with UV-C on different microorganisms such as influenza viruses and Mycobacterium tuberculosis (MTB). The inactivation efficiencies of UV-A (365 nm), UV-C (254nm) and UV-D (180nm) were compared in Wang et al. [16]. The authors studied both the inactivation of airborne *Escherichia coli* and the endotoxin removal. The UV-C and UV-D resulted largely more effective than UV-A as regards the inactivation of airborne *Escherichia coli*, only the UV-D was able to degrade and remove the endotoxin most likely because of the ozone production.

The advantages and disadvantages in the use of ozone are beyond the objectives of this work.

In the following, only the use of UV-C germicidal lamps with peak wavelength at 254 nm will be addressed.

Practical uses of UV in COVID-19 emergency

As many researchers are committed in realizing devices aimed at disinfecting equipment or workplaces, in this work we report a few literature reviews with references to the germicidal dose.

Kowalsky et al. [17] report an average D_{90} for coronaviruses of 67 J/m^2 (7 – 241 J/m^2); in order to attain log 4 inactivation, according to equation (3), a radiant exposure of 268 J/m^2 is required.

Meechan and Wilson [18] use a reference dose of 300 J/m^2 as reported from the manufacturer of their BSC for spore forming organisms, which are less sensitive than viruses. They also report a series of measurements of irradiance in various positions near germicidal lamps even considering the effect of personal protective equipment (PPE).

Normal clothing textiles have very different degrees of attenuation of UV radiation depending on the composition and specific mass.

Tests conducted in Pavia have resulted in the fractions of the transmitted irradiance at 254 nm reported in Table 1.

Table 1: Fraction of irradiance at 254 nm transmitted through different clothing and PPE

	Transmitted irradiance fraction at 254 nm
Disposable operating room sterile coat	0.051
Face mask	0.003
Nitrile glove (double)	0.003
Standard nursing uniform	0.003

The lowest fractions reported in Table 1 (0.003) comply with the value obtained by Meechan and Wilson who, using an irradiance of 2.82 W/m^2 measured the transmitted fraction through a Tyvek coverall; the irradiance transmitted through the Tyvek coverall was about 10^{-2} W/m^2, which is also the sensitivity of the instrument (Ocean Optics HR 4000).

Other measurements are taken from a report (in Italian), available on the Italian website, managed by the Italian Workers' Compensation Authority (INAIL) and Southern/Eastern Tuscany Health Agency [19].

In the present work, we calculated the lower limit exposure time (maximum permitted exposure time) to reach the EL with and without protective equipment, reported in Table2, in seconds and in minutes, respectively, as function of different common irradiance, also reported in Table2. The maximum permitted exposure times, given from a radiation protection perspective are compared to the minimum time for microorganism (coronaviruses in our report) inactivation. The minimum time is calculated to reach a germicidal dose of 300 J/m^2 (log 4 inactivation) and the maximum permitted exposure times are calculated according to the dose limit of 30 J/m^2 for H_{eff}.

The maximum permitted exposure times are calculated assuming a linear attenuation of 0.003 for the UV – C radiation reaching the skin due to the PPE wearing.

Table 2: minimum time to attain log 4 inactivation and maximum permitted exposure time for different germicidal irradiances. The maximum permitted exposure times are also reported assuming a 3*10^{-3} attenuation due to the PPE wearing. The minimum time for inactivation is of the order 1-2 minutes whilst the maximum permitted exposure times are greater than half an hour.

Source and viewing condition	***E* W/m^2**	**E_{eff} W/m^2**	**t minimum (s) for log4 inactivation**	**t max (s) for EL without PPE**	**t max (min) for EL with PPE**
Wall mounted fixture, 55 cm [19]	3.60	1.80	**83**	17	**93**
BSC, 20 cm from the opening [19]	1.60	0.80	**188**	38	**208**
BSC work surface, arms exposure [18]	2.82	1.41	**106**	21	**118**

Considering that the times in the last column are expressed in minutes whilst the minimum times for inactivation are expressed in seconds, working under direct germicidal UV-C, even if not advisable in normal operating condition, could be an option in emergency when the PPE are worn during the whole work-shift.

Even taking into consideration the greater transmittance of the disposable operating room sterile coat (0.051), as the only garment worn by the operator, the EL exceeding time would still be of the order of a few minutes, still comparable with the minimum time for a log4 inactivation.

This could be the condition inside COVID-19 hospitals, e.g. in common areas. As the personnel working in the intense care units (ICU) or sub-intensive care units cannot remove protective equipment during their permanence in the common areas, being these last highly contaminated and being the clothing removal a very dangerous operation that should not be repeated during the work-shift, wearing the PPE during the whole work-shift can be a common condition.

It is worth noticing that, even with the PPE, under effective germicidal irradiances, no more than 30 minutes of exposure are permissible.

In a 2012 case report [20], an incident is described about two nurses that had been working for about 1 hour directly exposed to the germicidal lamp of a BSC during an hospital drug preparation.

The post incident investigation, demonstrated an exceeding of the EL by 126 times to the eyes and by 194 times to the skin of the face. In fact, in a normal working task, direct observation of the lamp occurs only for a fraction of the time.

Severe symptoms were reported for the eyes and facial skin but nothing to the fore arms which were covered by garments.

Exposure with PPE is computed in Table 2 assuming an attenuation of a factor $3*10^{-3}$, which could be overestimated due to the sensitivity of measurements. However, Table 1 itself shows that great difference in UV attenuation could exists between different materials and no certification about this issue is available so far from manufacturers.

However, the measurements reported are taken at distances well below 1 meter while the work spaces may generally be larger. Therefore, the personnel, wearing PPE, moving in rooms, at variable distance from the sources, could be suitably protected against UV-C, even if, in highly contaminated areas, the germicidal lamps are kept continuously operating.

What is discussed so far is an emergency scenario, what we should keep in mind is that, as the exposure to radiation effective in killing microorganisms is potentially very harmful for humans, the use of germicidal lamps in presence of occupants should always be avoided.

If the disinfection of surfaces and objects is necessary, instead of installing lamps in fixed position, the modern technology makes available more sophisticated solutions such as the installation of lamps on board of drones, which can treat specific rooms under pre-defined protocols.

PPE Irradiation

In general, PPE can be reused only if expressly foreseen by the manufacturer and following its sanitization protocol.

World Health Organization considers among others [21] the use of UV-C in reprocessing PPE under severe shortage. In designing methods and devices for UV-C reprocessing units the same problems are to be faced as above discussed about small objects disinfection, considering that some surfaces could not receive the required germicidal dose.

However, with UV-C irradiation, no chemicals, that, due toxic residues, should require control, are needed and the germicidal dose can be in principle achieved in very short times.

The use of ultraviolet radiation for the sterilization of PPE (gloves, glasses, face shields, gowns, filtering facepieces) is still something to investigate. For reusable PPE, manufacturers must provide precise and safe procedures for their sanitization which may or may not include the use of UV. For the non-reusable PPE, however, although the use of UV is in many cases among the most promising decontamination methods, it is still highly dependent on the dose and, of course, on the wavelengths used. A brief overview of the issues for each device is shown below.

Gloves

Gloves are among the most common and inexpensive protective devices. The usefulness of the gloves is given by the barrier that provides the material of which they are made. Therefore, the sterilization methods used for the gloves should always guarantee the integrity of these materials. The disposable gloves used in healthcare can be of various materials (nitrile, latex, polyethylene); these materials normally degrade easily by UV [22, 23, 24] causing loss of elasticity and tensile strength of the gloves [25]. However it would be interesting to investigate more deeply on the UV exposure not only in terms of doses (J/m^2) but also in terms of spectral characteristics of the UV radiation, in order of evaluating the effect of the different wavelengths on the different materials.

The data in the literature show that the degradation of materials exposed to UV radiation for disinfection purposes, occurs faster than it would have been due to the simple use of the same gloves.

Goggles, safety glasses and face shields

Droplets of liquid and, potentially infected, splashes directed towards the eyes can be blocked by specific glasses (goggles or safety glasses) or by a shield covering the face up to the chin. The optical part, that is the lenses for the glasses, is normally composed of polycarbonate for their optimal optical and mechanical characteristics. Like many plastic materials, even polycarbonate, if exposed to UV radiation, is susceptible to photodegradation processes [26, 27] which cause yellowing, loss of toughness, embrittlement and breakage [28]. Also in this case, as for gloves, it remains to be assessed for what doses the photodegradation effects reach levels for which the alteration of the optical or mechanical characteristics reduces the effectiveness of the protective device to unacceptable levels. In this regard, the European certification standard regarding the personal eye-protectors (EN 166:2000) guarantees, for those certified devices, a certain UV resistance without specifying the doses involved. The standard, in fact, requires the UV irradiation of the device with a high pressure xenon lamp with a power between 400 W and 500 W and a spectral transmission of the lamp carrying at least 30% of the power in the UV-C, for 50 hours and at a distance of 30 cm. The light transmission factor of the irradiated device must not differ by more than 5% from the initial value. According to the standard, the certified eye-protectors are guaranteed against a UV-C dose of about $2.39*10^7$ J/m^2 .

Disposable respirators with facial filter

Disposable filtering facepiece respirators (FFR) are designed to reduce the exposure to the inhalation of particulate contaminants (such as droplets or aerosols). The filtering action is carried out through the particular non-woven fabric (polyethylene and/or polypropylene) of which the FFR is composed. FFRs were among the most used devices during the health emergency from CoVid-19 and those of which we have a great shortage. Several studies evaluated the possibility of reusing the FFR after different types of decontamination, then retesting their efficiency. It has been observed that the use of UV is among the most promising decontamination methods but the effectiveness is highly dependent on the dose that can penetrate the filtering tissue [29] and on the shape of the FFR [30]. Some studies have found a significant reduction in vitality (> log3) by irradiating different types of FFR contaminated with droplets of H1N1 influenza at doses of UV-C between 10 and 18 kJ/m^2 [31, 32]. Acceptable filtration performance and respiratory resistance have been recorded for different FFR models exposed to various doses ($5*10^3$-$9.50*10^2$ J/m^2) of UV-C [30, 33, 34, 35, 36, 37, 38]. One study [29] also revealed problems of elastic straps integrity.
As also supported by the WHO, the different methods and results found in literature do not lead to define a protocol that takes into account all the parameters [38].

Gowns

The medical gowns can be made of different materials depending on their reusability. The reusable disposable gowns are made of cotton while the disposable gowns are generally made of plastic material (propylene or polypropylene). Although the use of UV for the disinfection of cotton gowns could be effective and not lead to an appreciable deterioration of the fibers [38], the elective disinfection treatment for cotton gowns remains that with hot water, soap and disinfectants, such as chlorine [39]. Furthermore, as in the case of FFR, it is not sure that UV could kill all the pathogens on gowns because of the shadows produced by the folds of the fabric.

Heating Ventilation and Air Conditioning UV-C disinfection

Upper air UV-C sources.

This is the simplest solution for UV-C air disinfection. The UV-C lamps are positioned in the upper part of the room and the irradiation is directed towards the ceiling. In this condition, the eyes and the skin of the occupants are outside the propagation direction of the direct radiation flux and are only exposed to the diffused radiation field. This solution has been proposed for hospitals, medical waiting rooms but also in schools to reduce the measles spreading. Recently, during the COVID-19 pandemic, upper-air lamps have been proposed inside airplanes, trains, and buses, in order to disinfect the air. The upper-air UV-C irradiation for airborne microorganisms inactivation is based on the physical phenomenon of convection. The air currents flow from bottom to top and vice versa, and air mixing ensures disinfection of the total volume. Ventilation systems are often added to ensure good air circulation and mixing. The upper air UV-C lamps should operate continuously, making these systems highly energy consuming. In addition, health effects coming from the exposure to UV-C radiation must be prevented. In the ASHRAE guidelines a maximum irradiance of E_{upper_air}= 4 mW/m2 at the height of the eye is considered an acceptable engineering standard, and the guideline states that at these radiation levels no adverse health effects have been observed.

It must be reminded that with the E_{upper_air} irradiance of 4 mW/m^2, the maximum permissible dose of UV-C radiation on the unprotected eyes and skin is reached in about 4 hours. This exposure time must not be exceeded. In conclusion, the system must be sized in such a way that the maximum permissible dose of UV-C radiation of 30 J/m^2 is not exceeded, considering the maximum exposure time of one or more occupants.

The upper air UV-C sources are a good solution when the exposure time of the occupants is not very extended, for example in trains, subway cars, buses, planes. This solution should be avoided if workers are present during the whole, or a large fraction of, the work-shift. Chronic exposure to UV-C radiation must be avoided, also if the acute effect maximum exposure dose is not exceeded, due to the carcinogenetic effect of UV-C.

In–duct disinfection

In the in-duct disinfection systems no human exposure to UV-C radiation could occur if not during the maintenance. Due to the air velocity inside the duct, the available time for disinfection is very short, of the order of 1 s or less. As consequence, the irradiance of the sources must be very high to reach an effective disinfection. The ASHRAE indicates a range for the germicidal irradiance from ten to hundreds of W/m^2. In order to increase the irradiance level and uniformity inside the duct, it is suggested the coating of the duct internal surfaces with materials characterized by high reflectivity in the UV-C range such as the aluminum. The ASHRAE assumes a typical air velocity of 2.5 m/s. Assuming this velocity, a disinfection zone with a length of 2.5 m reaches an exposure time of 1 s. The in-duct systems are designed with exposure times greater than 0.25 s. If the disinfection length is 5 m, we have 2 s of exposure time. In this condition, assuming a germicidal dose of 400 J/m^2, an irradiance of 200 W/m^2 would be necessary.

Laboratory studies, mainly conducted on inactivated microorganisms, have shown the efficacy of disinfectant system for moving airstreams. The most important limit of these systems is that they must be operating all the time and can be quite expensive.

References

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