The Inactivation of SARS-CoV-2 in Critical Hospital Settings by Means of Ultraviolet C Lamps: Examples of Their Use and Some Practical Advice

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Research Article

Keywords: SARS-CoV-2, Environmental contamination, UV-C disinfection, UV-C dosimeters, UV-C lamps

Posted Date: February 11th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-173176/v1

Abstract

Background

UltraViolet-C (UV-C) lamps may be used to supplement current hospital cleaning and disinfection of surfaces contaminated by SARS-CoV-2. Our aim is to provide some practical indications for the correct use of UV-C lamps.

Methods

We studied three UV-C lamps, measuring their spatial irradiance and emission over time. We quantify the error that is committed by calculating the irradiation time based exclusively on the technical data of the lamps or by making direct irradiance measurements. Finally, we tested specific dosimeters for UV-C.

Results

Our results show that the spatial emission of UV-C lamps is strongly dependent on the power of the lamps and on the design of their reflectors. Only by optimizing the positioning and calculating the exposure time correctly, is it possible to dispense the dose necessary to obtain SARS-CoV-2 inactivation. In the absence of suitable equipment for measuring irradiance, the calculated irradiation time can be underestimated. We therefore consider it precautionary to increase the calculated times by at least 20%.

Conclusion

To use UV-C lamps effectively, it is necessary to follow a few simple precepts when choosing, positioning and verifying the lamps. In the absence of instruments dedicated to direct verification of irradiance, photochromic UV-C dosimeters may represent a useful tool for easily verifying that a proper UV-C dose has been delivered.

Background

As the Covid-19 pandemic progressed, it became clear that hospitals can be significant epicenters of human to human transmission of the Severe Acute Respiratory Syndrome CoronaVirus 2 (SARS-CoV-2) for healthcare workers, patients and visitors alike. The spread of SARS-Cov-2 is thought mostly to be via the transmission of respiratory droplets and aerosol particles coming from infected individuals [1, 2], and this has led to the conclusion that social distancing and the use of face masks are the most effective tools for containing the transmission of the virus [3]. There is, however, evidence that SARS-CoV-2 can also be transmitted via contaminated surfaces when people touch these surfaces (and then subsequently touch their mouths or eyes), or when the virus on these surfaces becomes airborne again and is then inhaled [1, 4–6]. It should be noted that the use of gloves depends on local regulations and that it is strictly recommended only when cleaning or caring for someone who is sick [1]; presently, patients and visitors do not usually wear gloves in hospital settings.

A recent paper on contamination status of the Zhongnan Hospital of Wuhan University has confirmed that many surfaces in various patient care areas were contaminated with SARS-CoV-2 and that the virus was present on commonly used objects (such as hand sanitizer dispensers, desk surfaces and computer keyboards, coffee dispenser buttons, etc), and on medical equipment (such as pulse oximetry finger clips, oxygen masks, Computed Tomography (CT) scanner and personal protection equipment) [7]. Chin et al have recently investigated the stability of SARS-CoV-2 in different environmental conditions and on different surfaces [8]. They found that SARS-CoV-2 is relatively stable on smooth surfaces: the virus remained viable up to 1 day on cloth and wood, up to 2 days on glass, 4 days on stainless steel and plastic, and up to 7 days on the outer layer of medical face masks; compared to this, the virus was not present on printing and tissue paper after only 3-hours of having been contaminated. Like other coronaviruses, the SARS-CoV-2 virus is characterized by a fragile outer lipid envelope that makes it susceptible to standard disinfection methods. To date, the disinfection of hospital surfaces is carried out using products containing 0.1% chlorine (1000 ppm) or 70–90% ethanol and which are applied following a thorough cleaning with soap and water [9]. Whilst this should in theory be sufficient to eliminate the virus from surfaces, evidences widely reported in the literature [10–12] seem to indicate that the cleaning and disinfection carried out in hospitals may sometimes be suboptimal, resulting in residual contamination. Factors that contribute to the failure to fully sterilize surfaces include: the element of human error inherent in the manual cleaning process, the high turnover of cleaning staff (especially in the case of the outsourcing of cleaning services), incorrect disinfectant contact times, and the incorrect dilution of disinfectant solutions [10–12]. There is, therefore, an urgent need for an effective environmental disinfection strategy that can exist alongside (and additional to) these manual cleaning processes, a strategy that can be non-manual and therefore less susceptible to human error. Further, if this non-manual disinfection process were to take place before the manual cleaning process, this could lead to a safer working environment for the staff, and thus could also lead to cost savings (because the staff would be entering an already decontaminated area).

UltraViolet-C (UV-C) radiation (100-280nm) has been extensively used for many years for its germicidal effects [13]. Recently, numerous studies have been published on the possible application of UV-C in disinfecting contaminated surfaces by inducing photodimerization in the genomes of SARS-CoV-2 [4, 14–17]. We have used this research to explore the possibility of developing a protocol for the disinfection of potentially contaminated SARS-CoV-2 surfaces through UV-C radiation in our healthcare setting, which is an oncological hospital in Milan without an Accident and Emergency department. To do this, we did the following: we selected a number of potentially contaminated environments; we analyzed two commercially available UV-C lamps as well as a UV-C lamp specially assembled for the study; we built specific supports onto which the lamps could be attached; finally, we established the necessary exposure times to achieve disinfection, basing our calculations both with the use of a spectroradiometer to measure irradiance, and also in the absence of any suitable measuring instrument (i.e. using the manufacturer's stated measurements). In our opinion, the practical indications for the correct use of UV-C lamps (and in particular for the calculation of the exposure time) are scarcely reported in the literature. To calculate the exposure time correctly, direct irradiance measurements should be performed on the surfaces to be disinfected; however, these measures require tools and skills that are not always available in hospitals. We therefore tried to quantify the error that is committed by calculating the irradiation time based exclusively on the technical data of the lamps (that is, in the absence of technical skills and dedicated tools) or by making direct irradiance measurements. Finally, we tested specific dosimeters for UV-C, easily usable even by non-technical personnel, which can be used both to optimize the positioning of the lamps and to verify that the dose required for sterilization is actually delivered.

Direct verification of SARS-CoV-2 inactivation was not one of the objectives of our work. This verification requires skills and tools present in few hospital settings. Our aim was to provide practical advice so that even non-technical personnel devoid of dedicated tools can use the UV-C lamps correctly starting from the results of the SARS-CoV-2 inactivation tests reported in the literature.

Methods

Our protocol for the use of UV-C lamps is structured as follows: choice of the environment or the surface to be disinfected; choice and characterization of the lamps to be used; positioning of the lamps; definition of the UV-C dose; calculation of the exposure time in pre-selected reference positions (i.e. in positions where significant contamination is expected) and verification of the delivered UV-C dose in test positions (i.e. where there is doubt about the exposure to the full dose of irradiation that is, in partially shaded positions).

Choice of environments

There are many environments inside a healthcare facility that can potentially become contaminated with SARS-CoV-2 with various degrees of probability. Environments that have a high probability of being contaminated include the cubicles used for testing patients for SARS-CoV-2, rooms dedicated to Covid patients, and Covid specialized intensive care units. X-ray, CT and visiting rooms have a medium probability of contamination, whereas areas with a low probability of contamination include non-Covid departments and administrative offices. In each of these environments, there are specific surfaces and objects that have a higher probability of being contaminated and thus require utmost care during the disinfection process.

At the outbreak of the Covid pandemic in February 2020, three specific areas in our Institute were set up, which consisted of a) three cubicles for nasopharyngeal swab testing on patients, b) a walk-in clinic for the Covid testing on healthcare professionals working at the hospital, and c) a dedicated inpatient clinic occupying one floor of the hospital for the exclusive treatment of Covid patients. We selected two out of all the potential environments that required a specific disinfection protocol for SARS-CoV-2 to test our disinfection procedure: a cubicle for diagnostic tests (2.0 m width, 2.3 m length, 2.3 m height) and the waiting room for COVID-19 triage (5.5 m width, 10.0 m length, 2.3 m height). We also included in the study a surface with a high probability of contagion: the bed of the CT room (0.7 m width, 2.5 m length).

Selection and characterization of the UV-C lamps

Numerous studies are presently underway to evaluate the virucidal effects on SARS-CoV-2 of different wavelengths in the UV-C band [4, 14–17]. Considering how inexpensive the mercury lamps are and how easy they are to be procured and to use, we decided to focus our attention on performing tests with ozone-free low pressure mercury lamps producing 254 nm radiation. We tested two commercially available lights, the Sterilight-S72-UV-C (Arenaluci, CastelGoffredo MN, Italy) and the AirZing™ PRO5040 (OSRAM China Lighting Ltd), as well as the Deluxe110, a prototype lamp custom-built specifically for our study by ILT Italy s.r.l. (Albano Laziale Rome, Italy).

Table 1 shows the technical features of the three lamps used as transmitted by the manufacturer; the uncertainties on the nominal wavelength or on the nominal irradiance are not known.

Table 1
Technical features of the three UV-C lamps used in this study

Model	Deluxe110	Sterilight-S72-UV-C	AirZing™ PRO5040
Nominal wavelength [nm]	253.7	253.7	253.7
Nominal power [W]	2x55	2x36	1x36
Dimension [mm]	600x240x170	540x210x170	1363x54x78
Weight [Kg]	6.5	4.5	1.3
Nominal irradiance @1m [$\mu W/cm^2$]	600	220	140
Life time [h]	9000	5000	9000
Rear reflector	Yes	Yes	No
Side reflector	Yes*	No	No
*) Two side reflectors parallel to the luminous elements.			

The first task was the measurement of the emission stability over time. An irradiance measurement was carried out for each lamp at a distance of 1m from the geometric center of the luminous elements, with measurements taken at the following times after the lamps were switched on: 15 s, 30 s, 60 s, 120 s, 300 s, 600 s and 900 s. We subsequently mapped the spatial irradiance of the three lamps and their reflectors by performing irradiance measurements in different positions by locating a spectroradiometer on the orthogonal axis of the luminous elements at the following distances from the centre: 1 m, 1.5 m, 2 m, 2.5 m and 3 m. We then repeated the irradiance measurements, positioning the instrument on axes inclined at 45° and 60° with respect to the orthogonal axis, at 0.5 m intervals between 1 m and 3 m. The measurements were repeated both in the plane containing the major axis of the luminous elements and in the plane orthogonal to it. All irradiance measurements were performed 120 seconds after the lamps were turned on.

The spectral properties of the three lamps and their irradiance were measured using an Ocean Optics HR2000 + spectroradiometer (Ocean Optics Inc., Dunedin, USA), calibrated with reference to a deuterium–halogen source (Ocean Optics Inc. Winter Park, Winter Park, Florida) and in compliance with National Institute of Standards and Technology (NIST) practices recommended in NIST Handbook 150-2E, Technical guide for Optical Radiation Measurements. The detector of our spectroradiometer is a high-sensitivity 2048-element Charge-Coupled Device (CCD) array from Sony. The spectral range is 200–1100 nm with a 25 µm wide entrance slit and an optical resolution of 1.4 nm (Full Width at Half Maximum, FWHM). The cosine-corrected irradiance probe, model CC-3-UV-T, is attached to the tip of a 1 m long optical fibre and is coupled to the spectroradiometer [14].

Positioning of the UV-C lamps

The optimal positioning of the UV-C lamps and the decision as to whether they should be fixed on the ceiling, the walls, or on a mobile unit, depends on the size and shape of the room to be disinfected, but above all depends on the location of the objects in the room that have a high probability of being contaminated with the virus. The shape of the lamp and the type of reflector are also important factors in achieving a successful outcome. Although fixed lamps are easier to use for the staff, the use of mobile units for the lamps can optimize the irradiation and has the advantage of being adaptable to different environments (and therefore can be more cost efficient).

Definition of the disinfection UV-C dose

In our study we planned to deliver a UV-C dose of 3.7 mJ/cm^2 at 254 nm. This value correspond to the median of the dose values necessary to obtain the inactivation of SARS-CoV-2 resulting from the most recent experiments published on the subject [16]. Since dry biofilms (in which the virus is more resistant) may be present on the surface to be sterilized [11, 18], we believe it is advisable to multiply the dose verified under laboratory conditions by a factor of 10. So, the reference inactivation dose used in the following is 37 mJ/cm^2.

Calculation of the exposure time and verification of the delivered UV-C dose

In pre-selected reference positions, we calculated the exposure times using two different approaches: the first approach consisted of calculating the expected irradiance values using the nominal irradiance value provided by the manufacturer corrected by the inverse square law of distance; the corresponding exposure times were obtained by dividing the reference inactivation dose (37 mJ/cm^2) by the expected irradiance values. For the second approach, we directly measured irradiance over the 250–255 nm wavelength range in the same reference positions; the corresponding exposure times were then corrected to take into account the time needed for the lamp radiance to become fully operational. Finally, the differences between the exposure times calculated with and without direct measurements of irradiance were computed.

To verify that the dose required for sterilization was actually delivered on all exposed surfaces, semi-quantitative measurements of dosage were performed by using disposable UV-C indicators (UVC 100 by Intellego Technologies AB, Gothenburg, Sweden). The UVC 100 dosimeter features a layer of photoactive ink that reacts by changing color according to the amount of UV-C dosage it has been exposed to. The ink can be calibrated to show different tones according to the different dosages. UVC 100 dosimeters are designed to visually indicate an accumulated dose of UV-C of 25,

50, 75 and 100 mJ/cm². The photosensitive area, initially yellow, changes color from orange to dark pink as the dosage received increases, providing a semi-quantitative indication of the absorbed dose. UVC 100 were positioned where there was doubt about the exposure to the full dose of irradiation (test positions, other than reference positions).

Results

Characterization of the UVC-lamps

Figure 1 shows the spectral irradiance at 1 m of the three lamps evaluated in the study. As expected, the emission is a function of both the power of the tubes and the characteristics of the reflectors. The integrated irradiance for the Deluxe110, the Sterilight-S72-UV-C and the AirZing™ PRO5040 over the 250–255 nm wavelength range was, respectively, 645 ± 38, 383 ± 37 and 168 ± 12 μW/cm^2. The comparison of these values with those declared by the manufacturers shows a reasonably good agreement in the case of the AirZing™ PRO5040 (+ 16.7%) and the Deluxe110 (+ 7%). On the contrary, in the case of Sterilight-S72-UV-C, the measured value is + 42% greater than the declared value. This difference could be due to the fact that the value declared by the manufacturer is actually an average value at different angles from the orthogonal axis or an average value over the lifetime of the lamp.

Figure 2 reports the temporal variation of the emission of the three lamps in the first two minutes after being switching on. To facilitate the comparison, the emissions have been normalized to the maximum. The graph shows that the emission of the Deluxe110 lamp was equal to 88% and 98% of the maximum after 15 s and 30 s respectively. Compared to this, the emission of the AirZing™ lamp was only 62% after 15 s, while after 30 s it reached 88%. The Sterilight-S72-UV-C lamp had an intermediate behavior: its emission was equal to 78% and 95% of the maximum after 15 s and 30 s respectively. For all three lamps, the emission was stable within a variance of 3% after 120 seconds (and continued to be stable until the fifteenth minute, the duration of the test).

Figure 3 shows the integrated irradiance over the 250–255 nm wavelength range of the three lamps at 1 m distance from the center of the luminous elements in three different positions: on the axis orthogonal to the luminous elements, on an axis inclined at 60° to the orthogonal axis in the plane orthogonal to the major axis of the luminous elements and on an axis inclined at 60° to the orthogonal axis in the plane containing the major axis of the luminous elements. The spatial uniformity of the irradiance around each lamp strongly depends on the shape of the lamp itself and on the presence of rear and side reflectors. For example, in the case of the Sterilight-S72-UV-C lamp the absence of side reflectors and the position of the luminous elements (laterally shielded by the lamp structure) greatly limit the uniformity of spatial irradiance. As for the AirZing™ lamp, our results indicate that the spatial irradiance is quite uniform; this is due to the positioning of the luminous element, only rear shielded by the lamp structure. For this lamp, however, the absence of rear and side reflectors does not allow to recover the backscattered irradiance, limiting the useful power in the front part of the lamp.

Finally, the irradiance measurements carried out at different distances from the center of the luminous elements on the orthogonal axis, confirm the decrease in the emission approximately in accordance with the inverse square law of the distance. The deviation from this law increases the more the shape of the lamp differs from that of an ideal point source; the deviation also depends on the presence and geometry of side reflectors. The greatest deviation between the measured value and the expected one, equal to 19%, was recorded in the case of the AirZing™ PRO5040 lamp at a distance of 3 m from the luminous element.

Positioning of the UV-C lamps

We designed an aluminum support on wheels, equipped with telescopic rods and joints that would enable one or two UV-C lamps to be positioned at the necessary height and with the optimal inclination. The support was equipped with hooks for all the three lamps tested; in the case of the Airzig™ PRO5040, it is also possible to attach two lamps back to back to achieve a 360° exposure. Finally, the power supply of the lamps was connected to a safety circuit equipped with an alarm that sounds when emission begins, along with a timer to set the duration of the emission necessary for disinfection, with a delay function to allow the operator to leave the room in time.

To disinfect the bed of the CT room (the item with the higher probability of contagion in the room), we decided to use the mobile support equipped with an AirZing™ PRO5040 lamp. The positioning of the lamp oriented at an angle of about 20° with respect to the longitudinal axis of the bed and at about 80 cm from it, allowed to irradiate both the bed and the control panel on the gantry of the CT. To disinfect the waiting room for COVID-19 triage, we found that the best irradiation condition was obtained by fixing two Deluxe110 lamps on two opposite walls: the position and the power of the lamps were such as to allow disinfection of all potentially contaminated surfaces, included the underside of the arms of the chairs. If the lamps were placed on the ceiling, some surfaces would be likely to be shadowed and therefore not treated by UV-C. Finally, to disinfect the cubicles built to undertake the swab tests on patients, we used the mobile support with two back to back AirZing™ PRO5040 lamps placed vertically: the size of the room and the power of the lamps were such as to allow disinfection of both the bed and the medical chair. Also in this case, positioning the lamp on the ceiling would not guarantee disinfection of all potentially contaminated surfaces.

The calculation of the exposure time and the verification of the delivered UV-C dose

Table 2 shows the comparison between the irradiation times calculated with and without direct irradiance measurements in two reference positions (i.e. in positions where significant contamination is expected) for each of the three selected environments. The fourth column shows the irradiance values calculated by using the irradiance at 1 m, supplied by the manufacturer, corrected by the inverse square law of distance between each reference position and the source. The corresponding irradiation times, reported in the fifth column, were obtained by dividing the reference inactivation dose (37 mJ/cm^2) by the expected irradiance values. The uncertainty on the calculation of the irradiation times is less than 1% as the only source of error is the measurement of the distance between the lamp and the reference position. The sixth column reports the irradiance values measured at the reference positions; the corresponding irradiation times were reported in the seventh column. The uncertainty on the calculation of the irradiation time is, in this case, within 3%, which corresponds to the uncertainty of measurement of our spectroradiometer. The eighth column reports the time required to compensate for the emission to be fully operational and, finally, the ninth column reports the total irradiation times corresponding to the measured irradiance values.

Table 2
Irradiation times calculated with and without direct irradiance measurements

Position	Distance from the lamp[1]	Angle[2]	Expected irradiance from nominal data	Irradiation time corresponding to expected irradiance	Measured irradiance[3]	Irradiation time corresponding to measured irradiance	Time required to compensate for the emission not immediately fully operational	Total irradiation time corresponding to measured irradiance	Difference between measured and expected time
	[m]	[°]	[μWatt/cm^2]	[s]	[μWatt/cm^2]	[s]	[s]	[s]	
CT bed - Mobile support equipped with an AirZing™ PRO5040 lamp									
Side edge of the bed	0.90	20	165	224	160	231	19	250	10.4%
Headrest	1.40	45	71	521	46	804	17	821	36.6%
Cubicle for nasopharyngeal swab - Mobile support equipped with two AirZing™ PRO5040 lamps									
Medical chair	0.85	20	199	187	191	194	17	211	11.4%
Side edge of the bed	1.30	30	83	446	74	500	18	518	13.9%
Waiting room for COVID-19 triage - Two Deluxe110 lamps on the ceiling[4]									
First chair	1.90	0	166	223	196	189	10	199	-12.1%
Second chair	2.60	45	89	416	89	416	9	425	2.1%
Waiting room for COVID-19 triage - Two Sterilight-S72-UV-C lamps on the ceiling[4]									
First chair	1.90	0	61	607	109	339	13	352	-72.4%
Second chair	2.60	45	33	1121	30	1233	13	1246	10.0%
Waiting room for COVID-19 triage - Two Deluxe110 lamps on the walls[4]									
First chair	2.30	0	113	327	139	266	10	276	-18.5%
Second chair	4.60	45	28	1321	28	1321	9	1330	0.7%

[1]) The distance is calculated from the reference position to the center of the luminous elements.

[2]) Angle between the axis orthogonal to the luminous elements and the line joining the reference position and the center of the luminous elements.

[3]) Irradiance measurements were made two minutes after switching on.

[4]) Irradiance measurements were made by switching on only one lamp at a time.

In 8 out of 10 reference positions, the agreement between the irradiation times calculated with and without direct irradiance measurements is within 20%. In some cases, however, this agreement was achieved as a combination of two larger errors in opposite directions. For example, concerning the second reference position of the Sterilight-S72-UV-C, the overestimation of the irradiance that would be made in the absence of direct measurements at angles greater than 45° was partially compensated by the fact that the actual irradiance is, in the case of this lamp, much greater than the nominal. As can be deduced from the results reported in Table 2, if the time required to compensate for the emission to be fully operational is ignored, the error on the irradiation time is about 10% for exposures of a few minutes or negligible for exposures longer than ten minutes.

The semi-quantitative dosimetric verification carried out using the UVC 100 dosimeters consistently confirmed the achievement of the reference inactivation dose: the photochromic area changes color from yellow to different hues of pink, depending how far away the test position is from the lamp source (i.e. a lighter hue of pink the further away from the source).

Discussion

Healthcare infections are infections that patients and healthcare workers contract while in a health care setting. They can be caused by a range of microorganisms including bacteria, fungi and viruses present in the hospital environment and can result in serious illness including, since the beginning of 2020, COVID-19. Decontamination of environmental surfaces is critical in reducing and preventing the transmission of pathogens. Thus, in healthcare facilities appropriate cleaning and disinfection protocols need to be carefully selected with particular attention given to surfaces with a high probability of contagion. Given the limitations of manual disinfection methods, it is extremely important to introduce optimized automated non-touch disinfection methods, such as hydrogen peroxide vapor and UV-C irradiation. Automated non-touch methods avoid human error during the disinfection procedure, allows for frequently repeat disinfection cycles on high-touch surfaces (for example the CT bed and the chair needed to conduct nasopharyngeal swabs that need to be disinfected between one patient and the next), and to limit the risk of contaminating cleaning staff who perform manual disinfection after the automated cleaning has taken place.

In the ultraviolet spectrum, UV-C has the highest disinfection capacity with an efficacy peak at 265nm [13]. Presently, the radiation wavelength most used is that supplied by low pressure mercury lamps (254nm), which have the advantage of being cheap and easily available. The main drawback on their use is that there are strict environmental protocols on the disposal of mercury [19]. The 270-280nm radiation produced by LED is as effective as the 254nm radiation [20]. LED technology has the advantage that lamps can be produced with very small dimensions and customizable geometries and they don't contain harmful metals, although their main disadvantage is that they are very expensive to fabricate. Recently, the use of the 222nm radiation lamp has been promulgated with the idea that this shorter wavelength radiation might be less harmful to those exposed [15]. However, these lamps are still very expensive and very bulky, and they still require careful supervision to avoid damage to the skin and to the eyes. Numerous studies are underway to establish the disinfection power of the UV-B (280-320nm) and UV-A (320-400nm) bands. At the time of writing, there were very few published results [17] that indicate the effectiveness of these spectral bands to disinfect SARS-CoV-2 contaminated surfaces.

To date, only mercury lamps can therefore be used to disinfect surfaces in hospital environments. There are numerous mercury lamps available on the market, varying in power, geometry and the shape of the reflectors. To achieve the necessary disinfection, however, it is essential to choose the correct lamps for the environment they are going to be used in, and above all to position them in an optimal way, something that requires both suitable equipment and the adequate training of staff to be able to use this equipment; these conditions are often not present in healthcare facilities.

The intention of our study, therefore, was to present practical and simple advice for UV-C disinfection which includes guidance as to the choice and positioning of the lamps, a method to reduce the error on the calculation of the exposure time and provide a way to check irradiation by using proper UV-C dosimeters. The choice of the lamp depends on the type of environment or surface to be disinfected; in the case of smaller rooms or elongated surfaces (such as beds), low power lamps (32 or 36 W) with long tubes (120 or 150 cm) are to be preferred. In the case of large rooms, it is necessary to use more powerful (and thus more expensive) lamps (36x2 W or 55x2 W). In both cases, the presence of side and rear reflectors made of highly reflective material allows to significantly increase the spatial uniformity of the irradiance and to recover the radiation delivered in non-useful direction.

The positioning of the lamps also depends on the type of environment or surface to be disinfected: lamps on mobile supports seem generally better at disinfecting surfaces, whereas lamps fixed on ceilings or walls are preferable when whole rooms need to be disinfected. In choosing the number of lamps to be installed, attention must be paid to surfaces at angles greater than 45° with respect to the irradiation source; in this case, especially in the absence of side and rear reflectors, it is advisable to increase the number of lamps used. It is also important to remember that only surfaces that are exposed to the direct light from the lamp will be irradiated; the reflected component of the primary radiation from common materials contributes minimally to sterilization. This is certainly the main limitation of the UVC disinfection method which must therefore be proposed in addition to and not as a substitute for standard decontamination procedures.

It is the calculation of the exposure time for successful disinfection that poses the greatest challenge to establishing a disinfection protocol. The most recent studies on the subject provide the dose value necessary to obtain the inactivation of SARS-CoV-2. However, if the virus is present in dry biofilms deposited on surfaces, then the resistance to sterilization could be greater. Pending more studies on this subject, it is prudent to multiply the dose obtained in the laboratory by a factor of 10 in real-life environments. Once the disinfection dose is known, the irradiation time can be calculated by dividing this value by the irradiance of the lamp, obtained by applying the inverse square law to the irradiance value at 1m supplied by the manufacturer. In the absence of direct measurements of the irradiance, there are numerous reasons for error that can affect the irradiation time

calculated, the most significant of which seem to be the position of the object at angles greater than 45° with respect to the irradiation source (in the absence of proper side reflectors) and not compensating for the time required for the emission to be fully operational. In the case of lamps whose shape is very different from that of an ideal point source, also the application of the inverse square law of the distance can lead to a not negligible underestimation of the irradiation time. It is therefore considered precautionary to increase the calculated times by at least 20%. Our results suggest that even with this correction, significant underestimation of the irradiation time cannot be excluded; one method to easily verify that a proper UV-C dose has been delivered is to position photochromic UV-C dosimeters on any surfaces where there is doubt about the exposure.

Regarding the possible damage induced by UV-C on materials, it must be remembered that most of the organic based materials can become damaged if they are not properly protected to UV rays. This damage, called UV degradation, affects many natural and synthetic polymers including some rubbers, neoprene and polyvinyl chloride (PVC). With too much exposure, these materials can fade in color, lose strength, become less flexible and finally crack. Certain inks and dyes can be affected as well. This problem, called photodegradation or phototendering, causes objects like textiles, artwork and polymers to: change color, fade in color and produce a chalky surface. Not all materials become damaged by UV radiation. Many silicones are generally UV-stable, as well as acrylic and types of glass, etc. At the time of writing, damage to materials in the hospital environments due to UV-C light disinfection was not reported [11]. We have recently initiated a study to evaluate the photodegradation of wooden furnishings and the damage induced on the synthetic leather of the upholstery of the CT beds and of the swab armchairs. To date, the repetition of 700 disinfection cycles (25900mJ/cm^2) did not show any difference compared to the unexposed material. However, the study will be extended up to the delivery of 50000mJ/cm^2.

The main limitation of our study is not to have decontamination measurements on biofilms in which the virus may be embedded. A specific study on the subject has already been activated to verify UV-C induced inactivation on different surfaces.

Conclusion

Disinfection of surfaces potentially contaminated by SARS-CoV-2 with UV-C lamps can be achieved by following some practical rules: choose UV-C lamps of proper power and shape equipped with side and rear reflectors made of highly reflective material; increase the exposure time calculated using the nominal irradiance by at least 20%; verify that a proper UV-C dose has been delivered by positioning photochromic UV-C dosimeters on any surfaces where there is doubt about the exposure. The UV-C disinfection protocol must include a safety section that takes into account the consequences of UV overexposure on the skin and eyes of any operators present. Therefore, the use of the UV-C lamps and the possible presence of operators must be planned in accordance with the most recent guidelines on the matter [21, 22].

Declarations

Ethics approval and consent to participate. Not applicable.

Consent for publication. Not applicable.

Availability of data and materials. The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Competing interests. The authors declare no conflict of interest.

Funding. This study was partially supported by “Lega Italiana per la Lotta contro i Tumori (LILT)”.

Authors' contributions. Conceptualization: Manuela Lualdi, Adalberto Cavalleri and Andrea Bianco; Investigation: Manuela Lualdi, Adalberto Cavalleri, Andrea Bianco and Mara Biasin; Supervision: Mario Clerici, Giovanni Pareschi and Emanuele Pignoli; Writing – original draft: Manuela Lualdi; Writing – review & editing: Adalberto Cavalleri, Andrea Bianco, Claudia Cavatorta and Paola Galli. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

Acknowledgements. We acknowledge Fabio De Sisti, Sergio De Sisti and Davide Locatelli for providing the mobile support and one of the lamps included in the studio and above all for the very useful discussions on the subject of the article.

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Figures

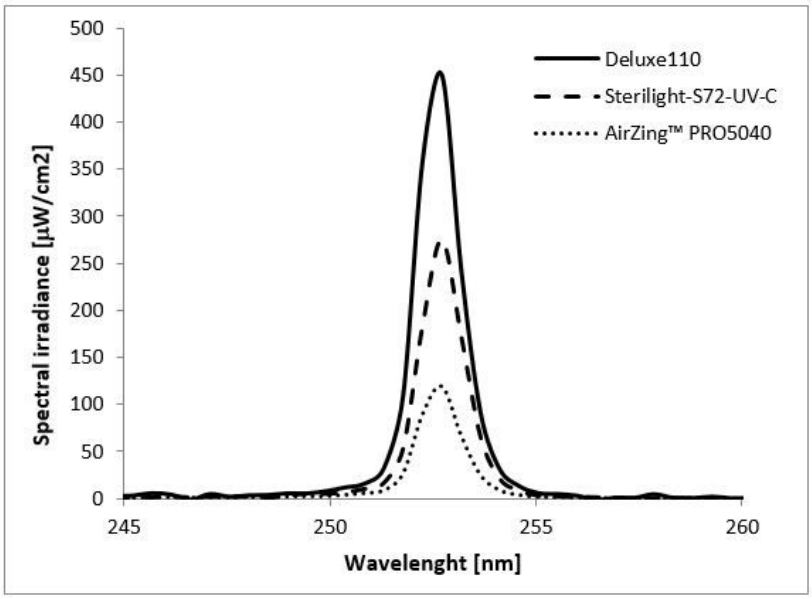

Figure 1

Spectral irradiance at 1m of the three lamps evaluated in the study. The measurements were made two minutes after switching on.

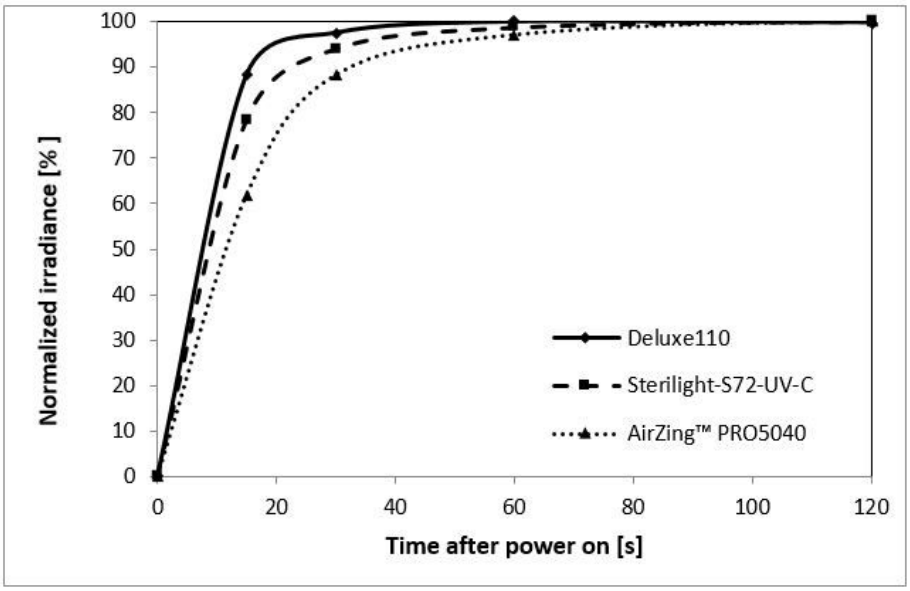

Figure 2

Temporal variation of the normalized integrated irradiance of the three lamps in the first two minutes after being switching on.

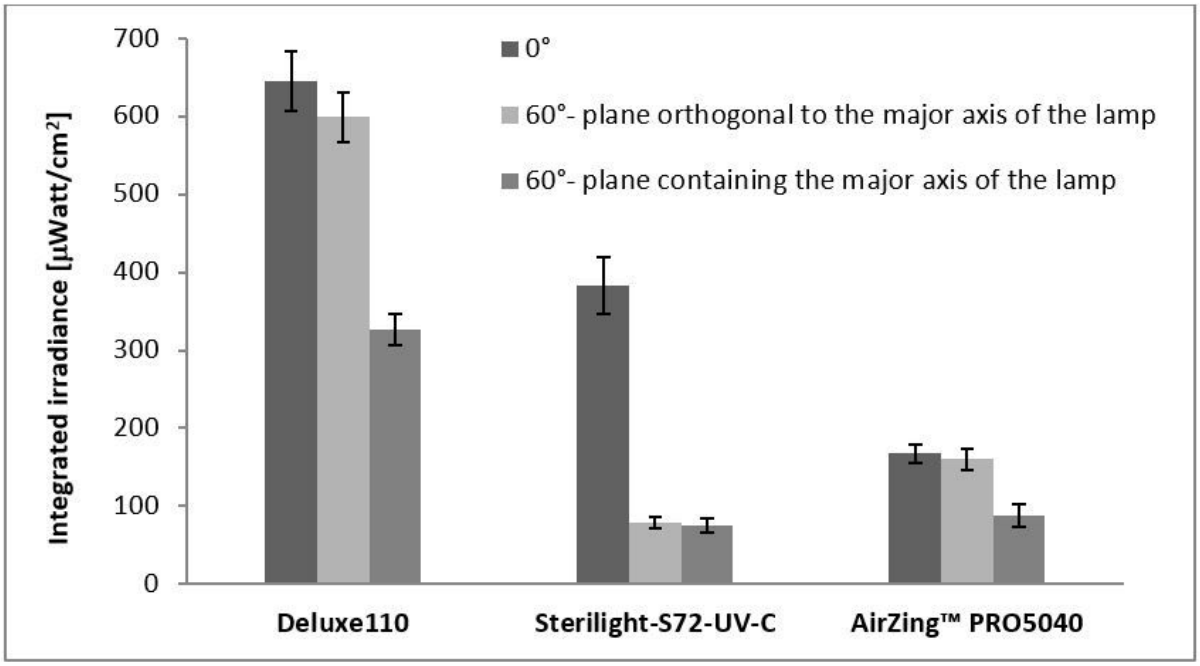

Figure 3

Integrated irradiance (mean and standard deviation of five measurements) of the three lamps at 1 m distance from the center of the luminous elements in three different positions: on the axis orthogonal to the luminous elements, on an axis inclined at 60° to the orthogonal axis in the plane orthogonal to the major axis of the luminous elements and on an axis inclined at 60° to the orthogonal axis in the plane containing the major axis of the luminous elements.