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Ultraviolet-C decontamination of a hospital room: Amount of UV light needed

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ABSTRACT

Introduction: Our primary aim was to investigate, using a commercial radiometer, the ultraviolet C (UVC) dose received in different areas in a burn ICU ward room after an automated UVC decontamination. The secondary aim was to validate a disposable UVC-dose indicator with the radiometer readings.

Methods: Disposable indicators and an electronic radiometer were positioned in ten different positions in a burn ICU room. The room was decontaminated using the Tru-D™-UVC device. Colour changes of the disposable indicators and radiometer readings were noted and compared. Experiment was repeated 10 times.

Findings: The UVC radiation received in different areas varied between 15.9 mJ/cm^2 and 1068 mJ/cm^2 (median 266 mJ/cm^2). Surfaces, at shorter distances and in the direct line of sight of the UVC device showed statistically significant higher UVC doses than surfaces in the shadow of equipment ($p=0.019$). The UVC-dose indicator's colour change corresponded with the commercially radiometer readings.

Conclusions: The amount of UVC radiation that is received in surfaces depends on their locations in the room (ie distance from the UVC emitter) and whether any objects shadow the light. In this study we suggest that quality controls should be used to assure that enough UVC radiation reaches all surfaces.

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1. Introduction

Numerous different ways to prevent and/or combat infections have been suggested and it has become obvious that the cleanliness of the personnel, equipment, and facilities is of utmost importance [1]. As well as following basic measures such as education, awareness, and proper hand hygiene (washing of hands followed by alcohol rinse in between contacts) healthcare professionals have started to use, as compliments, decontaminating tools such as specific detergents for manual cleaning, and automated hydrogen peroxide vapour or ultraviolet-C (UVC) irradiation.

Within the confines of distribution of ultraviolet light (10–400 nm) ultraviolet-C (100–280 nm) has the highest disinfectant capacity (with a peak-effect wavelength of 265 nm). The UVC light is absorbed by RNA and DNA in cells and microbes which induces changes (apoptosis) in the D-/RNA structures that result in their inability to replicate. Many microbes have proved to be

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susceptible to inactivation using UVC light including (in falling order of ease to inactivate) bacteria, viruses, fungi, and spores [2]. The amount of inactivation is directly proportional to the UVC dose, which is received, and this in turn is the result of its intensity and duration of exposure. The farther away the light source, the less UVC will reach the target, so only a quarter of the UVC remains when the distance doubles [3,4]. UVC radiation has a short wavelength and high energy, compared to other UV radiation, which enables for it to function the best in a direct line and at a short distance. Due to the high energy of the UVC radiation it is bound to the inverse square law where the propagation of light intensity decreases exponentially with increasing distance from the light source. This means that objects in proximity to the light source will have a higher exposure hence shorter disinfection cycles compared to objects further away. The reflection rate of UV radiation is also poor hence shadowed areas will most likely require a longer cycle time to reach the same level of disinfection as an area in direct line and on the same distance from the light source [5]. Any object that is between the light source and the target will block the UVC, resulting in shadowed areas. Conversely, to some degree, the UV light can reflect off surfaces to reach even the backside of objects. This capacity to reflect is highly dependent on the material of the surfaces. For example, organic material will absorb the penetration and block reflection of UVC, which is why surfaces should be cleaned manually to remove organic substances before decontamination [6].

Studies conducted with various UVC equipment such as: Pathogon (Pathogon UV Disinfection System, Steris Corporation, Mentor, OH, USA), Spectra 254 LLC (Spectra 254™, LLC, Danbury, CT, USA), XENEX™ (GERM-ZAPPING ROBOTS™, NY, USA), and Tru-D™ (Tru-D™ SmartUVC, Lumalier Corporation, Memphis, TN, USA) illustrate the efficacy of UVC irradiation in the decontamination of hospital rooms [7–9]. It has been claimed that UVC equipment has a disinfection rate of up to 4 $\log_{10}$, which is 99.99% eradication of, for example, *Clostridium difficile* — one of the more resistant bacteria [7,10,11].

While the market for UVC irradiation equipment is growing [3,12–15] questions about its efficacy have been raised. Its relatively short wavelength makes it most efficient only over short distances and in a direct line with the light source [3,4]. This in turn raises questions about shadowed areas, for example, and surfaces such as those behind furniture or the lavatory [16].

The mobile automated UVC device that we used in this study was originally developed for hospital room-decontamination and supposedly allows for quick, automated disinfection of rooms. It has been shown to be effective in the eradication of various pathogens, including multidrug-resistant strains, from hard surfaces [3,9,17,18]. Most devices have sensors that record the amount of UVC light that is reflected to the device from the surrounding surfaces during the decontamination process.

Emitted dose of UVC is not necessarily the same as the dose received in an area, as has been highlighted in some studies [11,14,16]. The UVC dose received in different areas of the room would therefore need to be measured to ensure that an adequate dose has been reached.

Different instruments are available to measure received UVC doses; UVC radiometers, such as biotechnical dosimeters, electronic and spectral radiometers, and different kinds of chemical dosimeters. Even though the electronic devices are accurate, they can be too expensive and difficult to be used as a routine in a clinical setting.

A disposable indicator has been developed (Intellego Technologies AB, Gothenburg, Sweden) that could be used in decontamination processes where UVC light is the source of radiation. The disposable indicator consists of a substrate with photoactive ink that reacts to the UVC dose received, and changes colour. The ink can be modified to respond (change colour) at different pre-set levels of energy. The change in the colour of the ink can be separated into several different "steps", with different tones showing at different accumulated energy levels (doses) (Personal communication, Lindahl, 20190115), or it can be read by a photometer.

As the disposable indicator is cheap (about <€0.5/unit) and easy to use- numerous indicators can be put on doubtful (shadowed) surfaces to make sure that a proper dose of UVC has been delivered to these areas. This will give increased quality control, and reassurance that the decontamination process is adequate.

Our primary aim was to investigate, using a professional commercially available radiometer, the UVC dose received in different areas in a burn ICU ward room after an automated UVC decontamination. The secondary aim was to validate a disposable UVC-dose indicator with the professional commercially radiometer.

2. Materials and methods

The principal experimental design of this pilot study has been described in detail elsewhere [19]. Briefly, disposable indicators and an electronic radiometer were positioned in different areas (locations and surfaces in frequent contact with the patient, staff, or both, and shadowed areas) in an unoccupied manually cleaned (as per ward routine) burn ICU ward room (36 m^2) at the Burn Centre. The room was arranged according to normal routine, ie ready to bring in a patient. The Tru-D™-device (Tru-D™ SmartUVC, Lumalier Corporation, Memphis, TN, USA) was centred in the room that was automatically disinfected as per manufacturer's instructions.

The Tru-D™ is a mobile unit that emits UVC light (254 nm) and, at the top of the unit, there are eight sensors that detect the UVC light that is reflected from the surroundings during decontamination. UVC light is emitted until a pre-set reflected dose of either 12 000 μWs/cm^2 (bactericidal) or 22 000 μWs/cm^2 (sporicidal) has been recorded by all the sensors. The sporicidal setting was used in this trial.

2.1. *Radiometer (electronic)*

For reference measurements, we used the RM-22 radiometer and UVC sensor (Opsytec Dr Gröbel GmbH, Ettlingen, Germany). RM-22 is a high-precision, hand-held instrument for measuring irradiation and levels and doses of illumination. The dose is calculated by integrating the irradiance, and ambient light is corrected by an automatic offset. We used the irradiance

Table 1 – Experimental set-up; location of dosimeter, distance from light source, measured UVC-dose received, conditions between the light source and dosimeter/indicators, and angle of the indicators (relative to the light source). Also, see Fig. 2.

Position	Description	Distance from the light source (cm)	mJ/cm^2	Shadowed	Angle of indicator
A	On the nurse's desk	144	560	No	Horizontal
B	On the bed	134	440	Partly	Horizontal
C	Under the bed	128	867	No	Vertical
D	In the basin	415	16	Yes	Horizontal
E	In the wardrobe	502	15,9	Yes	Vertical
F	On the ledge of the wall	430	424	No	Vertical
G	In the drawer of the left ceiling mounted pendant	97	108	Yes	Horizontal
H	By the infusion pump on the right ceiling-mounted pendant	230	1068	No	Vertical
I	On the writing surface on the right ceiling mounted pendant	275	45,8	Yes	Horizontal
J	Behind the desk chair	260	92	Yes	Horizontal

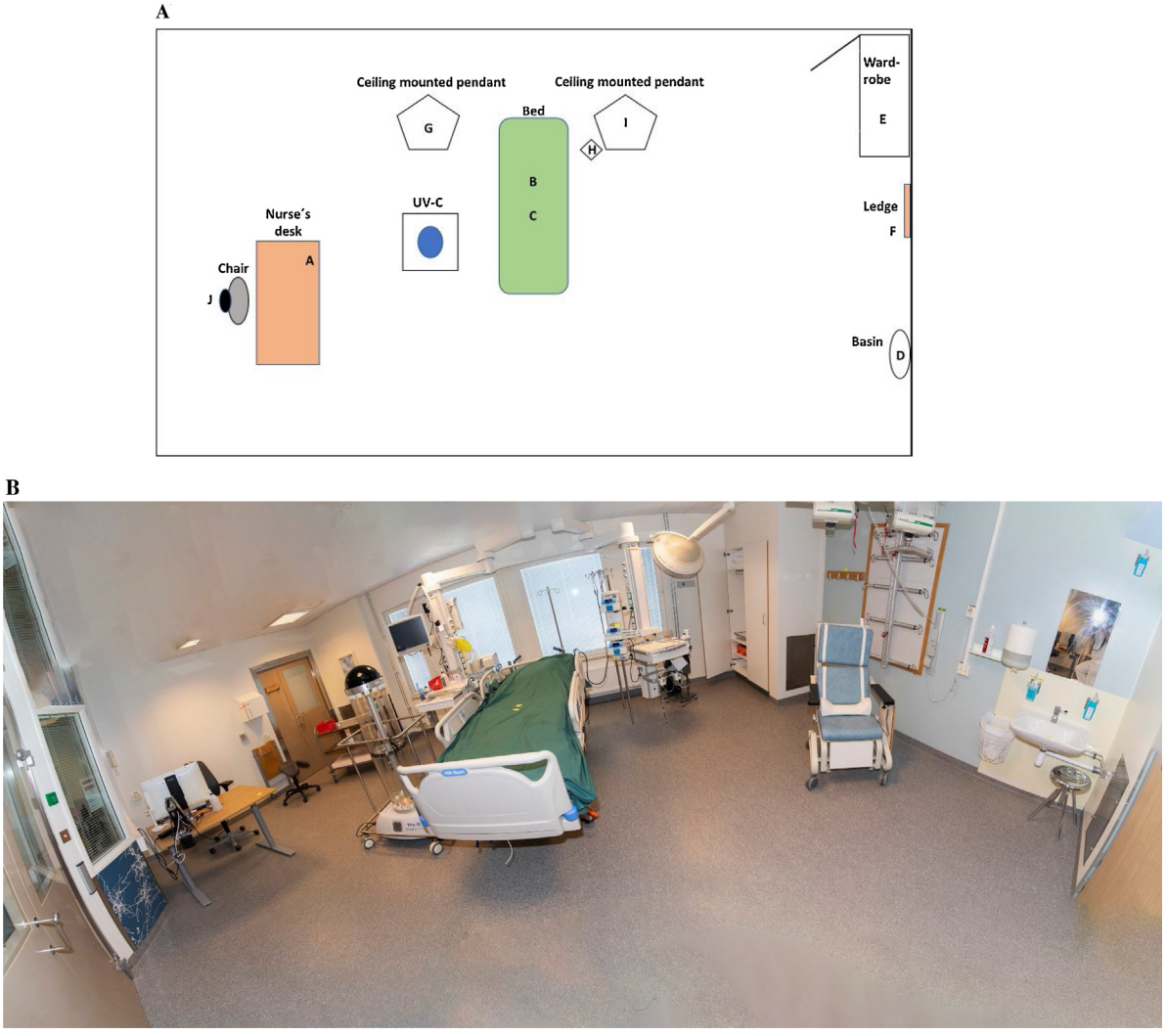

Fig. 1 – A) Room overview. Positions of indicators and radiometer (A) on the nurse's desk, (B) on the bed, (C) under the bed, (D) in the basin, (E) in the wardrobe, (F) on the ledge on the wall, (G) in the drawer of the left ceiling mounted pendant, (H) on the infusion pump, (I) on the drawing surface of the right ceiling mounted pendant, and (J) behind the desk chair. B) Panorama picture of the room in the burn ICU. Photo: Tony Lif.

measurement of 0.001 mW/s/cm^2 with the accumulated dose at a resolution of 0.001 mJ/cm^2. The range of dose was: 0–1 MJ/cm^2. The measurement range of illumination was 0–200.000 lx with a resolution of 1 lx. The spectral range of the UVC sensor was 200–280 nm.

2.2. *Disposable indicator*

We used a disposable indicator (developed by Intellego Technologies AB, Gothenburg, Sweden). The indicator's reactive technology is a mixture of a photo initiator and pH dependent pigment. The

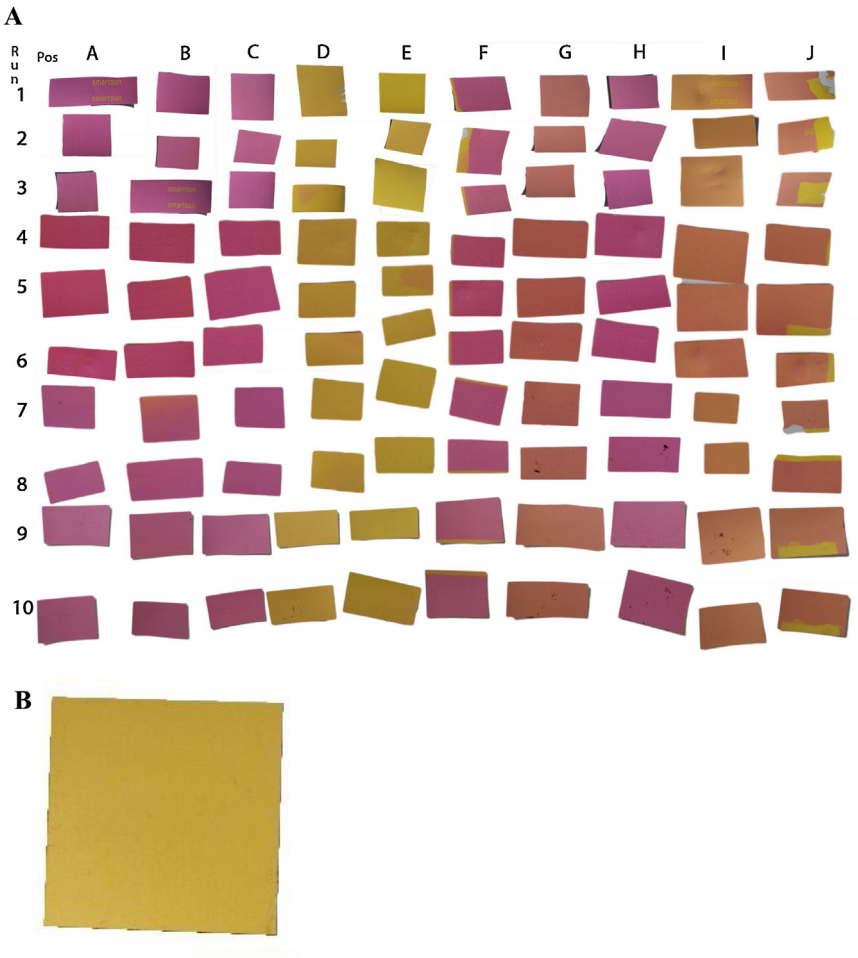

Fig. 2 – A) Representative picture samples of the disposable indicators' colour changes from different locations receiving different UVC doses. Positions A, B, C, F, and H (Pink); Positions G, I, and J (Orange); Positions D and E (Yellow). The letters indicate positions of the indicators (see Table 1). B) Original colour of indicator=yellow.

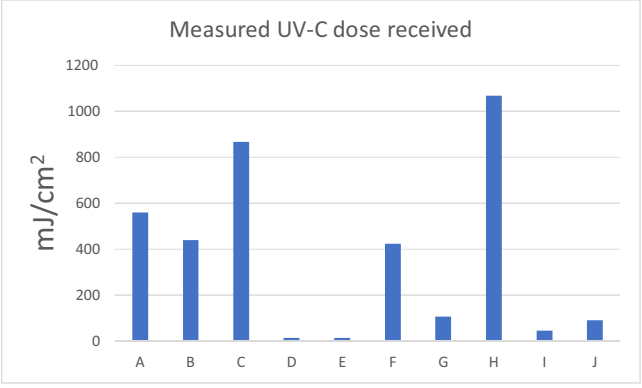

Fig. 3 – Measured UVC-dose received in different locations. (A) on the nurse's desk, (B) on the bed, (C) under the bed, (D) in the basin, (E) in the wardrobe, (F) on the ledge on the wall, (G) in the drawer of the left ceiling mounted pendant, (H) on the infusion pump, (I) on the drawing surface of the right ceiling mounted pendant, and (J) behind the desk chair.

chemical system reacts to the UVC radiation which induces a change in the pH. The change in pH affects the pH -dependent pigment that changes colours in separate steps depending on the energy levels to which the indicator has been adjusted.

The indicator therefore changes colour depending on the amount of radiation received. In this study colour changes were divided into; high, medium, and low, and were assessed (blindly) by the human eye (CL). The indicators had been verified by RISE (Research Institutes of Sweden, Borås, Sweden) that evaluated the colour shift for UV sensitive materials using two different irradiance levels at 254nm (Further details in Appendix 1).

2.3. *Experimental design*

The experiment was repeated ten times with the same design. For each repetition we placed 10 disposable indicators at separate locations in the room (Table 1,Fig. 1). The electronic radiometer was positioned next to a disposable indicator, at various locations for each repetition (Table 1).

The UVC emitting device was centred in the room, next to the bed (Fig. 1A and B). The decontamination process (22 000 μWs/cm^2, sporicidal setting) was started from outside the room using the remote control. The decontamination process proceeded until it automatically shut off when all sensors had received the set UVC dose.

3. Statistics

To analyse the correlations between the variable's "distance" and "dose of UVC", Spearman's rank order was used and probabilities of less than 0.05 were accepted as statistically significant. To analyse the significance of differences in median dose of UVC (continuous with respect to "shadowed"), the Mann-Whitney *U*-test (two-tailed) was used and again probabilities of less than 0.05 were accepted as statistically significant. Calculations were done using IBM SPSS Statistics for Windows (version 23, IBM Corp, Armonk, NY, USA), and results expressed as box and scatter plots.

4. Results

The results show that the doses of UVC radiation received by the radiometer varied widely in different areas in the room (Table 1, Fig. 2A and B, Fig. 3). There was a tendency for the variable's "distance" and "UVC dose" to correlate however, not showing any statistically significant correlation ($p<0.054$, Spearman) (Fig. 4).

Indicators (surfaces) in the direct line of sight and vertical to the UVC device showed a more distinct change of colour, thus indicating that the UVC dose received was higher than that received by indicators (surfaces) placed horizontally, or shadowed by equipment or furniture, or both (Fig. 2A). The pattern described was confirmed by the radiometer readings from the various locations (Table 1). A shown statistically significant lower UVC dose ($p<0.019$, Mann-Whitney *U*) was received at shadowed locations compared with those from

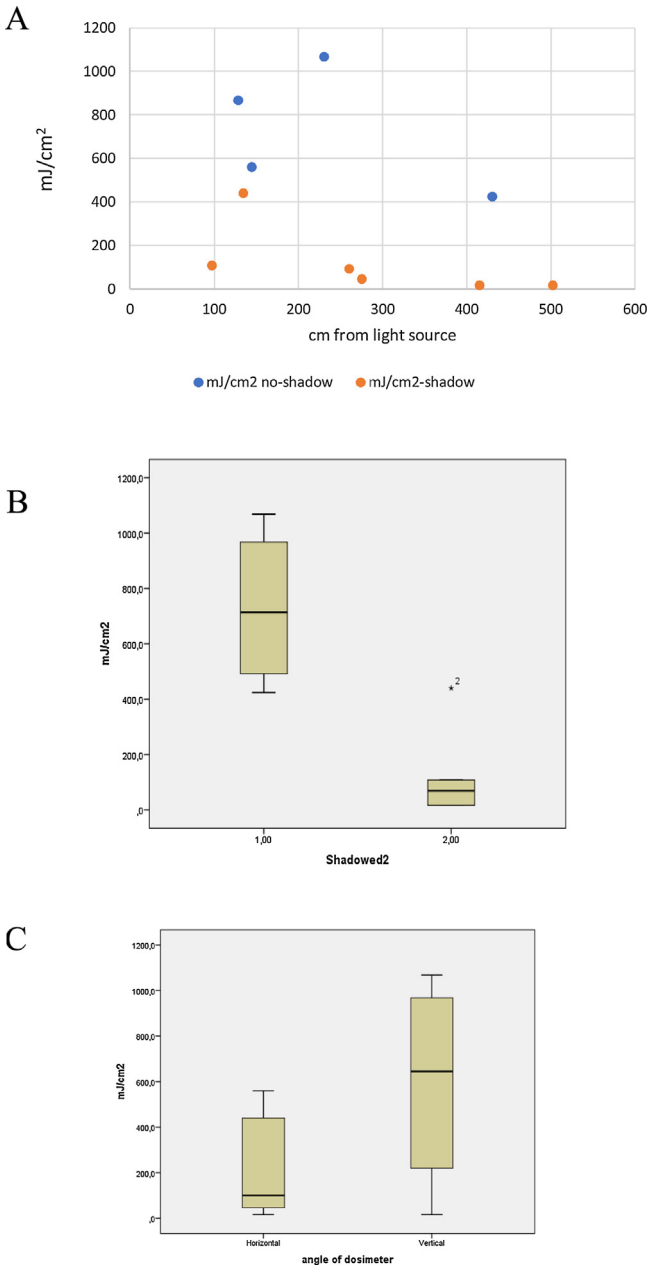

Fig. 4 – (A) Scatter plot of the received UVC-dose, position, and distance. Blue=no shadow, orange=shadow. (B) Box-and-whisker plot between shadowed area or not. Black line is the median. (C) Box-and-whisker plot of ratio of mJ/cm^2 in relationship to the angle of the dosimeter. Black line is the median.

locations in direct line of sight (Table 1), median 266mJ/cm^2 (range 15.9mJ/cm^2–1068mJ/cm^2). There was an obvious pattern that the more objects that were in the way, and the farther away the indicators were from the light source, the lower the dose received.

5. Discussion

We investigated the UVC dose received in different areas in a room after automated UVC decontamination using a mobile automated UVC light-emitting decontamination with the

sporicidal setting of 22000 μWs/cm^2. Manufacturers of decontamination devices based on UVC light claim that the UVC light emitted is reflected by surfaces to reach even areas that are not in direct line of sight, so reaching "everywhere".

The reflection of UVC light is obviously dependent on the type of surfaces and objects in the room. A recent study by Jelden et al. [20] proved that UV-reflective paint on the walls improved the decontamination of nosocomial bacteria on various surfaces, compared with standard paint on the walls. Boyce et al. [11] described a study like ours and their results correlate with ours. The achieved UVC dose varied related to the distance and shadowing objects. Several studies have proved the efficacy of bacterial decontamination by UVC-based devices [7,9,19] and there are many appropriate uses of this technology. Despite, our findings, along with others [21,22] suggest that one needs to be cautious and not rely only on the decontamination gained from

Table 2 – Published UVC-doses necessary for given log reductions for different microbes (adapted from ClorDiSys Ultraviolet Light Disinfection Data Sheet Rev. 10–213). Received UVC-dose not enough to reach X Log_{10} reduction for a specific microbe in locations: [D]- In the basin, [E]- In the wardrobe, [G]- In the drawer of the left ceiling mounted pendant, [I]- On the writing surface on the right ceiling mounted pendant, J- Behind the desk chair.

	UVC- dose (mJ/cm^2) necessary for a given log reduction						
	1 Log_{10}	2 Log_{10}	3 Log_{10}	4 Log_{10}	5 Log_{10}	6 Log_{10}	
Spores							Reference
*Bacillus subtilis*ATCC6633	**24**[D, E]	**35**[D, E]	**47**[D, E, I]	**79**[D, E, I]			α
Bacillus subtilis WN626	0.4	0.9	1.3	2			α
Bacteria							
Campylobacter jejuni ATCC 43429	1.6	3.4	4	4.6	5.9		γ
Citrobacter diversus	5	7	9	11.5	13		δ
Citrobacter freundii	5	9	13				δ
Escherichia coli O157:H7 CCUG 29193	3.5	4.7	5.5	7			ε
Escherichia coli O157:H7 CCUG 29197	2.5	3	4.6	5	5.5		ε
Escherichia coli O157:H7 CCUG 29199	0.4	0.7	1	1.1	1.3	1.4	ε
Escherichia coli O157:H7 ATCC 43894	1.5	2.8	4.1	5.6	6.8		γ
Escherichia coli ATCC 11229	7	8	9	11	12		ζ
Escherichia coli ATCC 11303	4	6	9	10	13	15	η.
Escherichia coli ATCC 25922	6	6.5	7	8	9	10	ε
Escherichia coli K-12 IFO3301	2.2	4.4	6.7	8.9	11.0		ε
Escherichia coli O157:H7	<2	<2	2.5	4	8	**17**[D, E]	ι
Klebsiella pneumoniae	12	15	**17.5**[D, E]	**20**[D, E]			δ
Legionella pneumophila ATCC33152	1.9	3.8	5.8	7.7	9.6		θ
Legionella pneumophila ATCC 43660	3.1	5	6.9	9.4			γ
Legionella pneumophila ATCC33152	1.6	3.2	4.8	6.4	8.0		θ
Pseudomonas stutzeri	**100**[D,E, I, J]	**150**[D, E, I, J, G]	**195**[D, E, I, J, G]	**230**[D, E, I, J, G]			λ
Salmonella spp.	<2	2	3.5	7	14	**29**[D, E]	μ
Salmonella typhi ATCC 19430	1.8	4.8	6.4	8.2			γ
Salmonella typhi ATCC 6539	2.7	4.1	5.5	7.1	8.5		ν
Salmonella typhimurium (from human feces)	2	3.5	5	9			μ
Salmonella typhimurium	**50**[D, E, I]	**100**[D, E, I, J]	**175**[D, E, I, J, G]	**210**[D, E, I, J, G]	**250**[D, E, I, J, G]		λ
Shigella dysenteriae ATCC29027	0.5	1.2	2	3	4	5.1	γ
Shigella sonnei ATCC9290	3.2	4.9	6.5	8.2			ν
Staphylococcus aureus ATCC25923	3.9	5.4	6.5	10.4			ν
Streptococcus faecalis (secondary effluent)	5.5	6.5	8	9	12		ξ
Streptococcus faecalis ATCC29212	6.6	8.8	9.9	11.2			ν
Vibrio natriegens	**37.5**[D, E]	**75**[D, E, I]	**100**[D, E, I, J]	**130**[D, E, I, J, G]	**150**[D, E, I, J, G]		λ
Yersinia ruckeri	1	2	3	5			β

The bold values are to where the received UVC dose is not enough to reach X Log10 reduction of the specific microbe.

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UVC light-based devices in areas that are not in a direct line of sight with the light source. During our testing we could see that several of the dosimeters in shadowed areas did show less of a colour change compared to the samples in direct line of sight. This was expected as the readings from the radiometer were significantly lower in these areas. For example, position G were within 100 cm from the light source but had not changed colour completely, which was confirmed by the radiometer reading.

For dosimeters further away, over 100 cm, but in a direct line from the light source, we could see that a full colour change occurred while the UVC dose was significantly lower compared to the position closer. Examples are the F and H position. F is further away and has a lower value than H. H is closer than F and has a higher value. One important note is that the dosimeters and radiometer angles were in a vertical position towards the light source and the radiation affects the colour change in the dosimeters and the radiometer simultaneously. Since UVC decontamination technology is being increasingly used in health care it is crucial to have access to tools that offer quality control and assurance that the decontamination process has been adequate. One option would be to use disposable indicators that are cheap and easy to use and can be put in questionable or crucial areas. The indicator validated in our study adequately detected the UVC dose received compared with the readings of the radiometer used.

The doses received in different areas ranged from 15.9 mJ/cm^2 to 1068 mJ/cm^2. Comparing our observed UVC-values with previously published levels needed to reduce different microbes, it seems that the biological effect may still be achieved for several of the more common microbes (Table 2). Moreover, we emphasise that quality control and assurance are essential during decontaminating a room using UVC light. One of the lowest radiations was found in the basin, one of the most frequent used places by the health-care workers in the room. The basin with its wet environment that can host a colonisation of bacteria, especially the gram-negative bacteria *Acinetobacter baumannii* is a well-known transmission pathway [23]. Compared to our previous study [19], most bacteria could be found in the wardrobe, and the measured radiation value in the wardrobe in this study was as low as in the basin.

We did not investigate the biological response of any microbials in the areas, and this should be done in future studies.

6. Conclusions

The UVC dose received in a normally equipped burn ICU room after decontamination with a mobile UVC-emitting unit varies depending on the distance between the light source and the irradiated area and any objects in between that shadows. One must assure that an adequate dose has been received in shadowed and/or critical areas. Disposable indicators can help ensure that an adequate dose has been received.

Source of funding

Intellego AB provided the disposable indicators and radiometer used. This research was funded by Uppsala County Council (ALF). Intellego AB (CL) was not involved in the study design, or in the collection, analysis, and interpretation of the data, in the writing of the manuscript, or in the decision to submit the manuscript for publication. Intellego AB (CL) did assist with setting up indicators and radiometer, and analysis and interpretation of RISE validation data of indicator. CL also helped draft the manuscript regarding the specifics on indicator, radiometer, and RISE validation data.

Authors' contributions

ML and FH analysed and interpreted data (exception as above), ML was responsible for data acquisition, ML, ET, and FH drafted the paper and revised it for important intellectual content after input from all other authors (exception as above). FH and ML were responsible for the concept and design of the study. All authors read, revised, and approved the final version of the paper (exception as above).

Conflicts of interest

None. CL had no input on the interpretation of critical data or decision to submit manuscript for publication.

CRediT authorship contribution statement

Marie Lindblad: Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Visualization, Writing - original draft, Writing - review & editing. **Eva Tano:** Conceptualization, Formal analysis, Methodology, Writing - review & editing. **Claes Lindahl:** Conceptualization, Visualization, Writing - review & editing. **Fredrik Huss:** Conceptualization, Formal analysis, Methodology, Project administration, Resources, Writing - original draft, Writing - review & editing.

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Appendix 1

The results from the RISE validation showed that the change in colours after a certain UVC exposure (dose) is similar for both the irradiance levels 90 and 760 μW/cm^2.

The samples were exposed to UVC-radiation at 254 nm wavelength using a UVP Transilluminator equipped with fluorescent UVC-tubes using two different irradiation levels (90 and 760 μW/cm^2 respectively). The irradiation level at the sample plane was established by a calibrated silicone detector with a precision aperture in front of the detector's photosensitive surface. An aperture was used to limit the exposure to a well-defined spot of about ⌀ 20 mm on the samples.

At certain times (corresponding to exposures of 10, 25, 50, 75, and 100 mJ/cm^2) the exposure was briefly paused and the colour of the exposed area was measured using a

Table A1 – Exposure with low irradiance (90 μW/cm²).” L*” is a measure of brightness, “a*” is a measure of reddish-greenish and” b*” is a measure of yellowish-bluish.

Exposure	CIE 1976 L*a*b* color coordinates			Colour difference
mJ/cm²	L*	a*	b*	ΔE*
0	82,2	−4,0	52,4	0,0
10	77,8	6,3	40,9	16,0
25	73,2	14,2	30,0	30,2
50	69,4	21,3	18,4	44,3
75	67,8	25,4	10,7	53,0
100	66,4	27,8	5,4	58,9

Table A2 – Exposure with high irradiance (760 μW/cm²).

Exposure	CIE 1976 L*a*b* colour coordinates			Colour difference
mJ/cm²	L*	a*	b*	ΔE*
0	83,0	−4,8	52,5	0,0
10	77,9	7,1	39,8	18,1
25	73,5	16,0	28,0	33,5
50	69,6	23,5	16,0	48,1
75	66,3	28,0	8,0	57,7
100	65,1	31,0	2,0	64,4

PR-735 spectrophotometer. A picture of the sample was also taken. The measurements and pictures were taken with the sample placed in a light booth using D65 illumination with high colour rendering index (>95).

The result from the testing showed that while the dosimeter was in a direct clear line from the UVC source, there was a clear change in colour up to 100 mJ/cm², whereas the change was hardly noticeable between 75 and 100 mJ/cm². At 100 mJ/cm² the colour had fully matured and almost stopped changing. For specific values of changes in colour, see Table A1 and A2).

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