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NOTE

Potential harm to the skin from unfiltered krypton chloride 'far-ultraviolet-C' lamps, even below an occupational exposure limit

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Abstract

Ultraviolet-C (UVC) radiation can effectively inactivate pathogens on surfaces and in the air. Due to the potential for harm to skin and eyes, human exposure to UVC should be limited within the guideline exposure limits produced by the International Commission on Non-Ionising Radiation Protection (ICNIRP) or the American Conference of Governmental Industrial Hygienists (ACGIHs). Both organisations state an effective spectrally weighted limit of 3 mJ cm^{-2}, although the spectral weighting factors of the two organisations diverged following a revision of the ACGIH guidelines in 2022. Using existing published human exposure data, the effective spectrally weighted radiant exposure was calculated for both unfiltered and filtered (to reduce UV emissions above 230 nm) krypton chloride (KrCl*) excimer lamps. The effective radiant exposure of the filtered KrCl* lamp was greater than 3 mJ cm^{-2} when applying ICNIRP or either of the revised ACGIH spectral weightings. This indicates that both guidelines are appropriately conservative for this specific lamp. However, the effective radiant exposure of the unfiltered KrCl* lamp was as low as 1 mJ cm^{-2} with the revised ACGIH weighting function that can be applied to the skin if the eyes are protected. Erythema has therefore been directly observed in a clinical study at an exposure within the revised ACGIH guideline limits. Extrapolating this information means that a mild sunburn could be induced in Fitzpatrick skin types I and II if that particular ACGIH weighting function were applied and an individual received an effective exposure of 3 mJ cm^{-2}. Whilst it is improbable that such an effect would be seen in current deployment of KrCl* lamp technology, it does highlight the need for further research into skin sensitivity and irradiance–time reciprocity for UVC wavelengths.

Ultraviolet-C (UVC) radiation is effective at inactivating airborne viruses and bacteria, including human coronaviruses [1, 2]. It is used to reduce human-to-human transmission of airborne diseases and has a long history of use in helping to prevent transmission of measles and tuberculosis [3, 4]. UVC is most effectively deployed indoors as either an upper-room (typically a low-pressure mercury lamp, peak emission 254 nm) or a whole-room (typically a krypton chloride (KrCl*) excimer lamp, peak emission 222 nm). Human exposure to UV radiation should be limited, and guideline exposure limits (or threshold limit values, TLVs®) are published by both the International Commission on Non-Ionising Radiation Protection (ICNIRP) and the American Conference of Governmental Industrial Hygienists (ACGIHs) [5, 6].

Both guidelines state that UV exposure should not exceed an effective spectrally weighted 3 mJ cm^{-2}; however, the intended application of each organisation is subtly different. ICNIRP state that within their limits 'nearly all individuals may be repeatedly exposed without acute adverse effects and, based upon best available evidence, without noticeable risk of delayed effects'. In contrast, ACGIH TLVs® apply to a

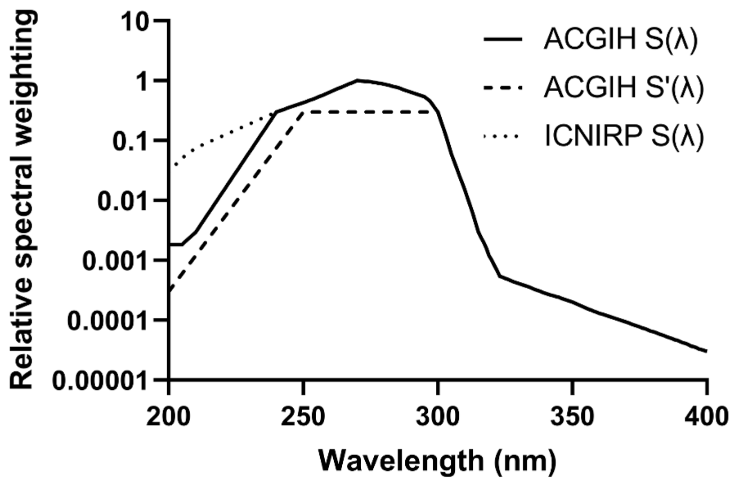

Figure 1. The relative spectral weighting functions as published by the ICNIRP and ACGIH.

supervised adult population of workers, and its occupational limits '… represent conditions under which it is believed that nearly all healthy workers may be repeatedly exposed without acute adverse health effects such as erythema and photokeratitis' and 'the TLVs should be used as guides in the control of exposure to UV sources and should not be regarded as fine lines between safe and dangerous levels'. Also 'the TLVs apply directly to the cornea of the eye and provide conservative guidelines for skin exposures'. Neither of these organisations' limits applies to individuals with abnormal photosensitivity.

Before 2022, both the ICNIRP and ACGIH advised the same spectral weighting factors, $S(\lambda)$, in the determination of the effective spectrally weighted exposure. To determine the effective UV exposure the spectral irradiance (mW cm^{-2} nm^{-1}) of the light source in question is multiplied by the spectral weighting factors; these (nm^{-1}) values are then summed together (integrated area under the curve) to give the effective irradiance (mW cm^{-2}), which is then multiplied by the exposure duration (seconds) to give the effective radiant exposure (mJ cm^{-2}, also commonly referred to as the 'dose'). If this effective radiant exposure is above 3 mJ cm^{-2}, then the exposure exceeds the guidelines and should generally not be permitted.

In January 2022 the ACGIH adopted new spectral weighting factors $S(\lambda)$ for unprotected exposure of the eyes and skin (hereafter referred to as ACGIH-2022). Furthermore, for the first time it created a second spectral weighting function $S'(\lambda)$ (read as: *S prime lambda*) for only skin exposure provided that the eyes were protected. The revised $S(\lambda)$ values are changed below 240 nm, whereas $S'(\lambda)$ weighting was also further reduced below 300 nm (figure 1). The overall limit for effective UV exposure remains at 3 mJ cm^{-2} within an 8 h period. The new ACGIH spectral weighting factors accounted for increasing evidence that shorter wavelengths of UVC, commonly referred to as 'far-UVC' (200–230 nm) do not penetrate as deeply into the skin or eye, and thus present a reduced hazard [7–9].

In vivo human studies have demonstrated that very high far-UVC exposure doses to the skin induced no acute effects of concern [10]. Whilst cutaneous induction of cyclobutane pyrimidine dimers (CPDs) occurs with 222 and 254 nm irradiation, 222 nm induces minimal CPDs found only in the uppermost non-proliferating layers, which are not thought to present any long-term hazard [7]. However, although the peak emission of KrCl* lamps is 222 nm, longer wavelengths emitted by these lamps can potentially cause harm to the skin. It was hypothesised by Woods *et al* that erythema on the backs of study subjects with Fitzpatrick skin types I and II was caused by these longer wavelengths and not the dominant 222 nm peak [11]. For context, relative to the minimal erythema dose (MED) on the back, the MED on the face and neck is approximately equal, while the MED on the arm is 2–2.5 times the back MED [12]. Using optical filters to limit emissions above 230 nm reduces the potential hazards from these longer wavelengths [7]. We therefore refer to KrCl* lamps as 'filtered' or 'unfiltered' depending on the presence of such filters; however, there is generally no agreed upon degree to which KrCl* lamps should be 'filtered'. In this work, we compare the outcomes of hazard assessments using 'filtered' and 'unfiltered' KrCl* lamps for ICNIRP and ACGIH spectral weighting factors, and put these into the context of the known effects of these lamp exposures from prior clinical studies.

The effective irradiances for two KrCl* excimer sources were calculated, one with an optical filter to reduce emissions above 230 nm (SafeZone UVC, Ushio Inc., Tokyo, Japan) and the other without such a filter (Sterilray™, Health Environment Innovations, Dover, NH, USA). Spectral irradiances from 200 to 400 nm

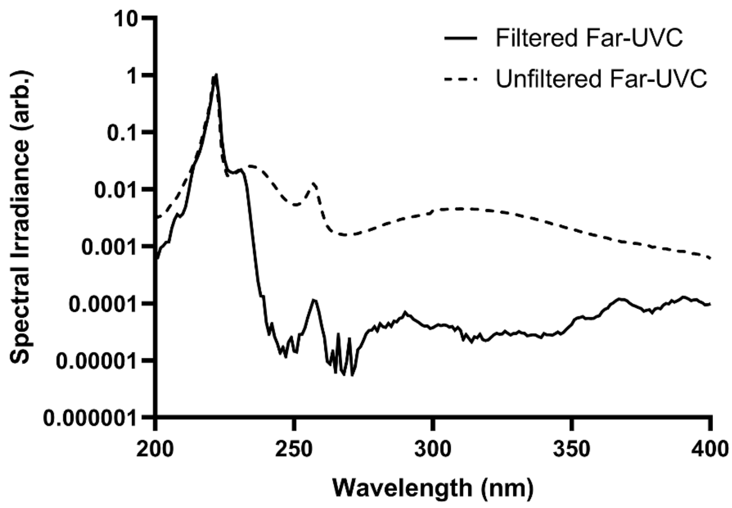

Figure 2. Spectral irradiances of the filtered and unfiltered far-UVC sources, normalised to 222 nm for comparison.

Table 1. Unweighted and $S(\lambda)$ and $S'(\lambda)$ average radiant exposures for a filtered KrCl* lamp (Eadie *et al*) and for a corresponding unfiltered KrCl* lamp (Woods *et al*). For each of the three radiation exposure weightings the recommended maximum exposure corresponds to 3 mJ cm^{-2}.

	Eadie *et al* [10] (filtered lamp)	Woods *et al* [11] (unfiltered lamp)
Outcome and unweighted radiant exposure (mJ cm^{-2})	No erythema at 1500 mJ cm^{-2}	Erythema at 40 mJ cm^{-2}
ICNIRP and ACGIH-2021 $S(\lambda)$-weighted radiant exposure (mJ cm^{-2})	194	6.1
ACGIH-2022 $S(\lambda)$-weighted radiant exposure (mJ cm^{-2})	29.1	2.3
ACGIH-2022 $S'(\lambda)$-weighted radiant exposure (mJ cm^{-2})	10.1	1.0

were taken from Eadie *et al* and Woods *et al* [10, 11], which were measured in each study using a calibrated double-grating spectroradiometer with traceability to national standards (IDR300, Bentham Instruments Ltd, UK). A normalised comparison is shown in figure 2. Each spectral irradiance measurement was weighted for the $S(\lambda)$ (ICNIRP and ACGIH-2021), $S(\lambda)$ (ACGIH-2022) and $S'(\lambda)$ (ACGIH-2022) spectral weighting factors.

There have been a number of measurements of far-UVC-induced erythema on human skin, both for filtered far-UVC lamps [10] and for unfiltered lamps [11]. Eadie *et al* delivered an unweighted radiant exposure of 1500 mJ cm^{-2} from a filtered lamp without inducing visible skin erythema [10]. By contrast Woods *et al* did induce visible erythema at an unweighted radiant exposure of 40 mJ cm^{-2} using an unfiltered lamp [11]. In the following we relate these two observations to the recommended maximum exposures that can be derived from the various ICNIRP and ACGIH recommendations discussed above and illustrated in figure 1.

Specifically, the spectral measurement of each lamp (figure 2) was combined with each of the three spectral weighting functions (figure 1), and the results compared with the 'universal' recommended maximum weighted radiation exposure of 3 mJ cm^{-2} per 8 h. These results are summarised in table 1. For the purpose of comparison with this value, we construct the scenario that the same radiant exposures are delivered over the course of an 8 h time period, as opposed to the relatively short exposure durations that were used in the respective studies. Inherent in this is the assumption that the biological effects of the UVC exposure (in this case erythema) are independent of the exposure time (the Bunsen–Roscoe law of reciprocity [13]). Whether this assumption holds is under debate, as whilse exposures from 1 s to 1 h have been shown to be equivalent there has, to our knowledge, not been any investigation at longer exposure times [13] and there is evidence for significant repair of UVC-induced damage to DNA over time frames of a few hours after a short (15 s) but intense (unweighted irradiance 0.01 mW cm^{-2}) exposure [14].

For the filtered lamp the results show that the weighted average exposure at which erythema was still not observed exceeds all the recommended weighted maximum exposures—implying that the recommended maximum exposures are appropriately conservative. This conclusion holds true whether the exposure weighting was performed as recommended by ICNIRP and ACGIH-2021 or whether the exposure weighting was performed using either of the two new ACGIH-2022 recommended weightings.

For the unfiltered lamp, the weighted radiation exposure at which erythema was observed exceeded the ICNIRP and ACGIH-2021 recommendations. However, for the newer ACGIH-2022 weightings the weighted radiation exposure at which erythema was observed was less than the recommended maximum weighted exposures. The special ACGIH $S'(\lambda)$ for the skin would not be exceeded until three times this radiant exposure from the unfiltered lamp was delivered, which would have produced mild sunburn (three to four times the MED) in the subjects reported in the study by Woods *et al.* For such unfiltered far-UVC lamps, these results suggest that the newer ACGIH-2022 guideline limits may not be adequate or 'conservative'.

This analysis demonstrates that unfiltered KrCl* excimer lamps will not cause harm to the skin within the ICNIRP exposure limits but that they do have the potential to cause damage to the skin without breaching the ACGIH-2022 $S(\lambda)$ and $S'(\lambda)$. In real-world settings, individuals will typically receive a fraction of the TLV® due to time and motion considerations [15] and are thus well protected if they follow the relevant guidelines; therefore actual harm is improbable. However, the possible adverse effects of unfiltered far-UVC on the skin, even when used within the recently revised guidelines, could cause a backlash against this important technology and limit the uptake of safer filtered far-UVC.

The point at which the spectra differ in figure 2, the studies referenced in this work and recent data [16] all indicate that wavelengths above 235 nm are most likely to be responsible for the erythema observed by Woods *et al*. The erythemal effectiveness of wavelengths below 250 nm is not adequately understood nor well defined as the standardised Erythema Reference Action Spectrum includes only wavelengths from 250 nm to 400 nm [17]. Thus, it is recommended that more research is carried out on monochromatic phototesting of exposures in the 200–250 nm region and on reciprocity of UV effects at exposures up to 8 h to help inform future guidelines. It seems clear that precautions should be taken to appropriately filter wavelengths above 235 nm in far-UVC sources.

Data availability statement

No new data were created or analysed in this study.

Contribution statement

PO: writing—original draft, formal analysis. KW: writing—review and editing. SI: writing—review and editing. EE: investigation, writing—review and editing.

Conflict of interest

The authors declare no conflicts of interest for this work.

Ethics statement

No ethical approval was needed for this study.

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References

[1] Eadie E *et al* 2022 Far-UVC (222 nm) efficiently inactivates an airborne pathogen in a room-sized chamber *Sci. Rep.* **12** 1–9
[2] Buonanno M, Welch D, Shuryak I and Brenner D J 2020 Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses *Sci. Rep.* **10** 1–8
[3] Wells W F, Wells M W and Wilder T S 1942 The environmental control of epidemic contagion: I. An epidemiologic study of radiant disinfection of air in day schools *Am. J. Epidemiol.* **35** 97–121
[4] Miller S 2002 Efficacy of ultraviolet irradiation in controlling the spread of tuberculosis (Atlanta) (available at: https://stacks.cdc.gov/view/cdc/11285) (Accessed 28 March 2022)
[5] ICNIRP 2004 Guidelines on the limit of exposure to ultraviolet radiation of wavelengths between 180 nm and 400 nm (incoherent optical radiation) *Health Phys.* **87** 171–86
[6] ACGIH 2022 *Threshold Limit Values (TLVs) and Biological Exposure Indices (BEIs)* (Cincinnati, OH: ACGIH)
[7] Buonanno M, Welch D and Brenner D J 2021 Exposure of human skin models to KrCl* excimer lamps: the impact of optical filtering *Photochem. Photobiol.* **97** 517–23

[8] Kaidzu S, Sugihara K, Sasaki M, Nishiaki A, Igarashi T and Tanito M 2019 Evaluation of acute corneal damage induced by 222 nm and 254 nm ultraviolet light in Sprague–Dawley rats *Free Radic. Res.* **53** 611–7

[9] Sliney D H and Stuck B E 2021 A need to revise human exposure limits for ultraviolet UV-C radiation *Photochem. Photobiol.* **97** 485–92

[10] Eadie E, Barnard I M R, Ibbotson S H and Wood K 2021 Extreme exposure to filtered far-UVC: a case study *Photochem. Photobiol.* **97** 527–31

[11] Woods J A, Evans A, Forbes P D, Coates P J, Gardner J, Valentine R M, Ibbotson S H, Ferguson J, Fricker C and Moseley H 2015 The effect of 222 nm UVC phototesting on healthy volunteer skin: a pilot study *Photodermatol. Photoimmunol. Photomed.* **31** 159–66

[12] Olson R L, Sayre R M, Everett M A and City O 1966 Effect of anatomic location and time on ultraviolet erythema *Arch. Dermatol.* **93** 211–5

[13] Meanwell E F and Diffey B L 1989 Reciprocity of ultraviolet erythema in human skin *Photodermatology* **6** 146–8

[14] Cipollini M, He J, Rossi P, Baronti F, Micheli A, Rossi A M and Barale R 2006 Can individual repair kinetics of UVC-induced DNA damage in human lymphocytes be assessed through the comet assay? *Mutat. Res.-Fundam. Mol. Mech.* **601** 150–61

[15] First M W, Weker R A, Yasui S and Nardell E A 2005 Monitoring human exposures to upper-room germicidal ultraviolet irradiation *J. Occup. Environ. Hyg.* **2** 285–92

[16] Welch D, Aquino de Muro M, Buonanno M and Brenner D J 2022 Wavelength-dependent DNA photodamage in a 3D human skin model over the far-UVC and germicidal UVC wavelength ranges from 215 to 255 nm *Photochem. Photobiol.* **98** 1167–71

[17] ISO/CIE 17166:2019 2019 *Erythema Reference Action Spectrum and Standard Erythema Dose* (International Commission on Illumination (CIE))