Photochemistry and Photobiology, 2021, 97: 485–492

Special Issue Invited Review

A Need to Revise Human Exposure Limits for Ultraviolet UV-C Radiation†

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Received 31 December 2020, revised 28 January 2021, accepted 9 February 2021, DOI: 10.1111/php.13402

ABSTRACT

The COVID-19 pandemic has greatly heightened interest in ultraviolet germicidal irradiation (UVGI) as an important intervention strategy to disinfect air in medical treatment facilities and public indoor spaces. However, a major drawback of UVGI is the challenge posed by assuring safe installation of potentially hazardous short-wavelength (UV-C) ultraviolet lamps. Questions have arisen regarding what appear to be unusually conservative exposure limit values in the UV-C spectral band between 180 and 280 nm. We review the bases for the current limits and proposes some adjustments that would provide separate limits for the eye and the skin at wavelengths less than 300 nm and to increase both skin and eye limits in the UV-C below 250 nm.

INTRODUCTION

The International Commission on Illumination (the CIE) has defined the short-wavelength ultraviolet region, the UV-C photobiological spectral band, as 100–280 nm (1). Since the wavelengths less than approximately 180 nm are highly attenuated in air but can be transmitted effectively in a vacuum, the 80 nm region from 100 to 180 nm is generally termed "the vacuum ultraviolet." Because there are effectively no realistic exposures of the skin and eyes to the vacuum ultraviolet (UV), exposure limits of the American Conference of Governmental Industrial Hygienists (ACGIH®) and the International Commission on Non-Ionizing Radiation (ICNIRP) currently provide UV-C limits only from 180 to 280 nm. These guideline limits evolved from an initial ACGIH® proposal in 1971 for an "envelope" action spectrum that covered both ocular and skin thresholds for acute damage, i.e. well below the thresholds for both erythema (skin reddening) and photokeratitis (i.e. "welder's flash" or "snow blindness") as shown in Fig. 1 (2). In 1972, ACGIH reduced its initially proposed Threshold Limit Value (TLV®) of 100 mW cm^{-2} in the UV-A (315–400 nm) down to 1.0 mW cm^{-2} for lengthy exposures; and in 1973, the final proposed limit was formally adopted. By 1985, the International Non-Ionizing Radiation Committee (forerunner of ICNIRP) had adopted essentially the same guidelines (3), and in 1988, ACGIH® extended the limit down to 180 nm (3,4). By 2004, ICNIRP had updated the earlier INIRC guidelines, supported by a World Health Organization (WHO) Criteria Document (5), which differed from the ACGIH® TLV® only in the UV-A; the ICNIRP UV-C guidelines were essentially the same as those in the 2020 ACGIH® (4). There have been only editorial clarifications and flow charts added by ACGIH® since that time (4). In the early 1990s, the Illuminating Engineering Society in the US applied the ACGIH® TLV®s in the first photobiological safety standards for lamps (6); then, the CIE adopted the same emission limits in 2002 for its lamp safety standard, and in 2006, the

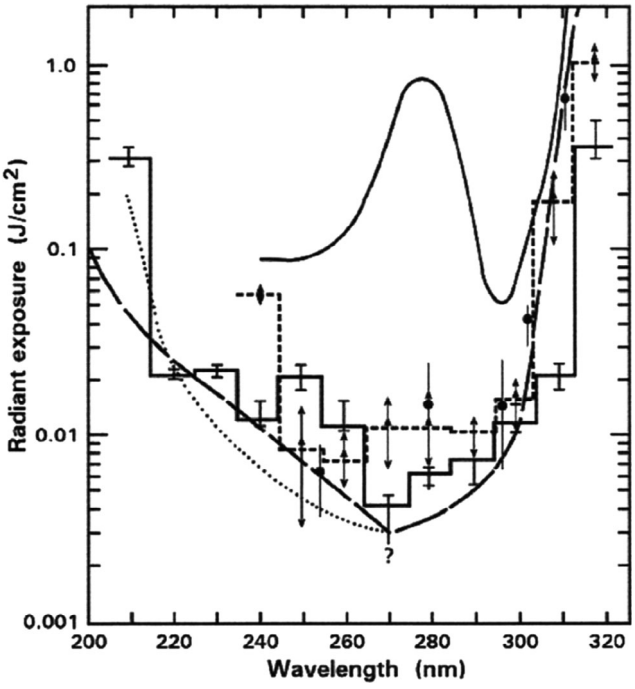

Figure 1. Envelope action spectrum (absolute) formulated in the 1970s for UV-C and UV-B. The histogram of threshold data along with the uncertainties show the wide bandwidths of some of the data that had to be adjusted for a spectrally resolved set of limits and hazard function $S(\lambda)$. (Adapted from Sliney, 1972 (2)).

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†This article is part of a Special Issue dedicated to the topics of Germicidal Photobiology and Infection Control.

International Electrotechnical Commission (IEC) adopted the CIE standard as a joint-logo standard, IEC 62471:2006 (7). In 2004, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) had formally adopted UV exposure guidelines that were the same as ACGIH® for UV-B and UV-C spectral bands (8).

The ACGIH® broadband TLV®s within the UV-C spectral band from 200 to 280 nm have hardly changed since the values were first proposed in 1972, although ACGIH® extended its TLV® down to 180 nm in 1990 after threshold photokeratitis and other studies were conducted with argon–fluoride laser radiation at 193 nm (9). Because of complaints from ophthalmologists using ArF lasers for refractive surgery, ACGIH® proposed an increase in the more conservative laser TLV® for UV-C wavelengths shorter than 260 nm in 2020 (4). The TLV® for laser radiations in the past decades was simplified to a single value without an action spectrum at wavelengths less that 302 nm—at a single radiant exposure—3 mJ cm^{-2}. The ACGIH® Notice of Intended Change (NIC) in 2020 raised the limit considerably at 193 nm and increased the laser TLV® above the 3 mJ cm^{-2} for decreasing wavelengths shorter than 260 nm (4). This change for lasers became normative in the 2021 ACGIH® TLV®s (4).

Until recently, there has been little interest in revisiting the UV-C UV limits, since the only workers routinely exposed to UV-C wavelengths were arc welders and some scientists working with open arcs and specialized arc lamps, so the TLV®s were applied for risk assessments in those work areas. Although it was certainly known that some of the TLV®s in the UV-C band were very conservative, there were no serious efforts to suggest any changes, since welding filters and PPE easily reduced exposures far below the TLV® anyway. With a renewed interest in germicidal UV-C applications, questions arose as to whether the TLV®s were not overly conservative in this spectral band (10). This was of special interest to those working with upper-air ultraviolet germicidal irradiation (UVGI), where a frequent question was whether some scattered UV-C into occupied areas should really be of concern (10,11). With the development of shorter-wavelength UVGI sources, such as the KrBr and KrCl excimer lamps emitting at 207 and 222 nm respectively, there was even more interest, since there was hope that full-room irradiation would be safe to humans at levels that would still be effective in inactivating microbes (12,13) and several biological threshold research studies were published—particularly regarding the 222 nm wavelength (14–17). The preliminary studies began to suggest that thresholds were considerably higher than some published in the past using arc monochromators with 10–20 nm spectral bands for exposure. The earlier threshold studies for eye and skin effects had large uncertainties because of their rather large spectral bandwidths—leading to uncertainties as to the wavelength dependence, and some thresholds apparently had stray (out-of-band) radiation (18). By using monochromatic radiation such as 222 and 254 nm, the uncertainties were greatly reduced—at least for those two key UVGI wavelengths.

SPECTRAL WEIGHTING OF A BROADBAND SOURCE

Applying the current UV limits to a specific lamp spectral power distribution requires spectral weighting against the envelope action spectrum $S(\lambda)$ as shown in Fig. 2. The specific UV-C wavelengths of 254 nm (low-pressure mercury lamp) and 222 nm that are employed in UVGI applications are the primary emission lines of those lamps, and the exposure guidelines and lamp safety standards have current daily limits for these specific wavelengths of 6 mJ cm^{-2} (for $S(\lambda) = 0.5$) at 254 nm and 23 mJ cm^{-2} (for $S(\lambda) = 0.013$) at 222 nm. However, these two lamp examples also emit some energy at other wavelengths, and these must be weighted (4) with Eq. (1):

$$E_{\text{eff}} = \sum_{180}^{400} E_\lambda \cdot S(\lambda) \cdot \Delta\lambda \leq 3\text{mJ} \cdot \text{cm}^{-2} \tag{1}$$

where:

E_{eff} = effective irradiance relative to a monochromatic source at 270 nm [W cm^{-2}].

E_λ = spectral irradiance at a center wavelength [W cm^{-2}-nm^{-1}].

$S(\lambda)$ = relative spectral effectiveness at the center wavelength [unitless].

$\Delta\lambda$ = bandwidth around the center wavelength [nm].

And the above effective irradiance E_{eff} must be integrated over time by time-weighted averaging (TWA) to remain below the daily exposure limit $H_{\text{eff-TLV}}$ = 3 mJ cm^{-2} (30 J cm^{-2}):

$$H_{\text{eff}-\text{TLV}} = E_{\text{eff}} \cdot t \leq 3\ \text{mJ} \cdot \text{cm}^{-2} = 30\,\text{J} \cdot \text{m}^{-2} \tag{2}$$

The TWA concept is all too frequently ignored, and the lowest irradiance recommended by ACGIH and ICNIRP of E_{eff} = 0.1 μW·cm^{-2} is applied even if relatively brief exposures can be expected. This is a simple solution to avoid a time-and-motion study or even an estimate of reasonably foreseeable worst-case exposure duration. As another side to the same question, the question has arisen about whether the E_{eff} should even be lower for longer shift times, such as 10 or 12 h. The current reasoning is that the 8 h limiting irradiance should still be acceptable for the longer shifts because of dose-reciprocity failure beyond ~4–5 h. That is, a higher dose is required for longer durations for the same effect, and there is sufficient safety margin to readily accommodate these longer exposure durations. Dose additivity beyond a day can be ignored because of cellular repair (e.g. overnight) and the safety margin for exposures at or below the TLV. The constant replacement of epidermal cells and corneal epithelial cells and the location of germinative cells were carefully taken into account in the development of these limits. The fortunate evidence is that the protection of these critically important cells is far better in the UV-C than in the UV-B.

It should be noted that the contributions to the biologically effective irradiance E_{eff} in Eq. (1) outside the principle 254 nm line of the mercury lamp are quite small since about 90% of the emitted energy is in the 254 line. Furthermore, the low-pressure mercury lamp is one of the most efficient lamps existing with a "wall-plug" efficiency approaching 50%, where the "wall-plug" efficiency is the radiant power output divided by the electrical power input to the lamp. However, for significant over-exposures, the much weaker 297 nm, 303 nm and 313 nm Hg emission lines would actually contribute to most of the biologically effective dose when weighted by the nonmelanoma skin cancer (NMSC) action spectrum (Fig. 2). The 222 nm KrCl lamp frequently is supplied with a special filter that blocks longer-wavelength emissions in order to significantly increase its photobiological safety—particularly with respect to photocarcinogenesis (19). Consistent with the fact that the KrCl 222 nm

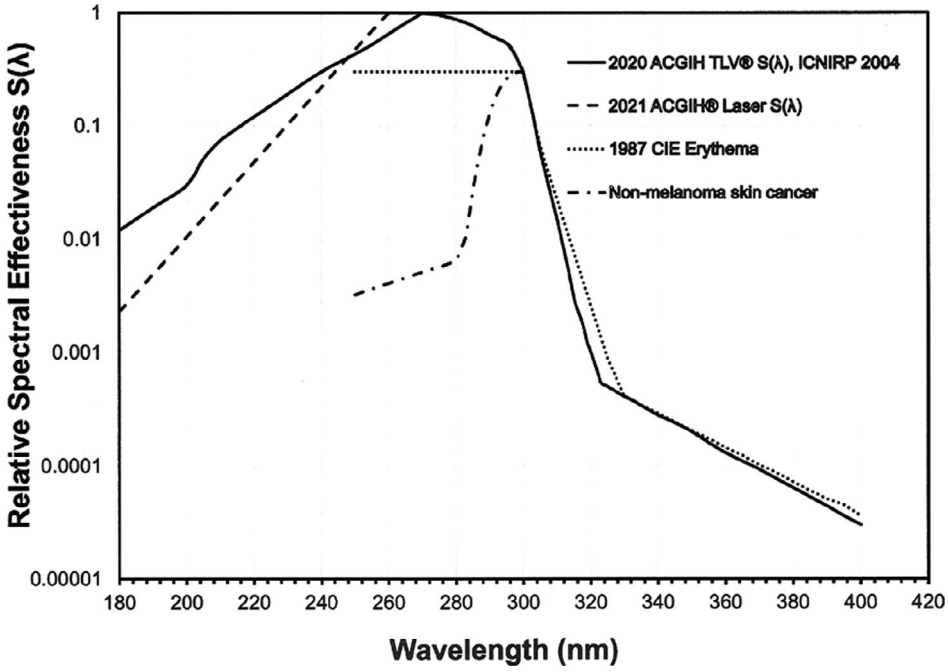

Figure 2. The 2020 ACGIH® Relative Spectral Effectiveness function $S(\lambda)$ (solid line) for the UVR. For wavelengths from 180 to 400 nm, $S(\lambda)$ has not changed in decades. The 1987 CIE erythema action spectrum in the UV (dotted line) is from 250 to 400 nm approximates the ACGIH®$S(\lambda)$ function. The CIE erythema action spectrum was specified only for wavelengths from 250 to 400 nm. The CIE nonmelanoma skin cancer (NMSC) action spectrum is shown for UV wavelength greater than 250 nm (dash-dot-dash line). The action spectrum for both erythema and NMSC decrease rapidly for wavelengths in the UV-C less than 300 nm. The relative spectral effectiveness of the ACGIH® laser TLV® adopted in 2021 is shown as a dashed line for comparison.

emission line is clearly safer than the 254 nm Hg line, the recent biological effects research (12–17) demonstrates that the current limit at 222 nm is overly conservative, which led to this review. Furthermore, throughout the UV-C spectral band, the thresholds of detectable skin damage are significantly higher than detectable corneal surface epithelial damage because of the strong preabsorption by the stratum corneum (19). It is the strong UV-C absorption by the stratum corneum as well as the superficial epidermis that explains the substantial reduction of skin-cancer risk for UV-C irradiation compared to UV-B (19–21). This led us to examine the known threshold data for the eye and skin separately.

REVIEW OF UV-C LABORATORY THRESHOLD DATA

Although current limits for the eye are much lower than for the skin in the UV-A spectral region, the limits are identical in the UV-B spectral region. The detectable biological thresholds for both eye and skin are very similar between 300 and 315 nm and rapidly change with wavelength—showing a ten-fold change with a wavelength change of only 7 nm—which is why monochromator-derived threshold data have an apparent shift to longer wavelengths in this spectral region compared to action spectra derived from laser or other highly monochromatic sources, (e.g. low-pressure mercury lamp lines) as explained by Chaney (18). Although this apparent wavelength shift of the action spectrum was carefully analyzed and corrected for when deriving the UV-B exposure limits, it could not be as carefully addressed in the shorter UV-C spectral band because of the very limited data below 250 nm, where only10 nm bandwidth (at half-maximum) exposures were made (22,23). A review of the recent studies of skin and eye effects at wavelengths below 250 nm clearly illustrates the distortion of the earlier action spectra for photokeratitis. There were very few if any efforts to measure dermal effects below 254 nm; and UV-C studies were largely limited to 254 nm mutagenic effects on isolated bacteria and human cells *in vitro* (24,25). Although the cellular studies indicate thresholds for DNA damage, these thresholds require adjustment based upon *in vivo* preabsorption in living skin (21,22,24–27). The limited data led to the initially overly conservative human exposure limits for all wavelengths below 250 nm (2).

The recent interest in the potential use of UV-C at 207 or 222 nm to deactivate the COVID-19 virus stimulated several groups to investigate threshold effects at these wavelengths on the eye (28,15) and skin (13–15,19–22,29) with comparisons with the photic effects of 254 nm. Most of these studies were done in small animal models (mice, rats, rabbits) with endpoints to identify interaction mechanisms and the locus of the threshold effect to identify carcinogenic potential by utilizing the cyclobutene pyrimidine dimer (CPD) marker. Exposure of the forearm of Type II human skin (29) to UV-C at 222 nm supported assertions that a larger cumulative dose was required to produce an observable cutaneous effect. In this case study, a cumulative dose of 1500 mJ cm^{-2} (diamonds in Fig. 3) at 222 nm did not produce an observable effect. Exposure at 6000 mJ cm^{-2} (diamonds) resulted in a faint yellowish color appearance to the exposed skin that was apparent almost immediately. The color change was quantified by making spectral reflectance

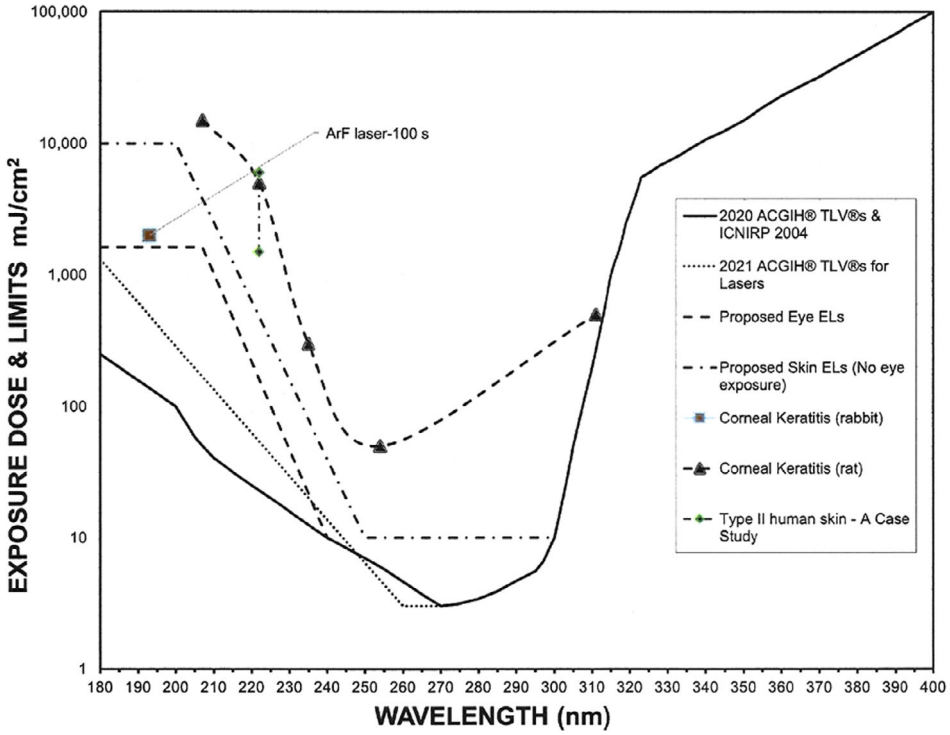

Figure 3. Recent biological effects discussed above are plotted with the 2020 ACGIH® TLV®s (4) and ICNIRP (8) (solid line) and the 2021 ACGIH® TLV®s for Lasers (dotted lined). The proposed exposure limits for the eye (dashed line) and skin (dot-dash-dot). Selected corneal and skin threshold are plotted for assessment of their relationship to the proposed exposure limit for the eye and skin.

measurements in accordance with a1976 CIE Lab color space protocol. The color change was apparent almost immediately after the exposure but only persisted for several hours. Tape stripping of the yellowish area, which removes the cutaneous stratum corneum, reduced the skin coloring suggesting that the effect was confined to the stratum cornea and the uppermost layer of the epidermis (those cells soon to die and form the stratum corneum). These investigators carefully measured the spectral emission and applied additional filters to minimize emissions of the longer-wavelength (e.g. 254 nm) UV-C such that the cutaneous effects were limited to the 222 nm exposure. Results of this case study are consistent with those published earlier (13–16,19). This 222 nm exposure was also consistent with results from two genotypes of hairless mice highly susceptible to carcinogenesis where an exposure dose of 5.0 kJ m^{-2} (500 mJ cm^{-2}) produced very faint staining with CPD and only in the uppermost cells of the epidermis (14,15). Repeated exposure over a 10 day period at 4.5 kJ m^{-2} showed no CPD-positive cells in the dorsal skin of the hairless mouse. No inflammatory skin response was observed at 222 nm for exposures of 10 kJ m^{-2}.

Threshold doses to produce a corneal keratitis in a rat eye model (28), were determined for wavelengths 207, 222, 235, 254 and 311 nm. Twenty-four hours after exposure, the rat corneas were evaluated by analysis of the mire image (the specular reflection of a ring light from the cornea) and by slit-lamp observation of corneal staining with topical sodium fluorescein. The minimal threshold dose (MTD) was determined from an analysis of both endpoints and are plotted in Fig. 3 (triangles). These MTDs for 207 nm and 222 nm were 15 000 and 5000 mJ cm^{-2}, respectively. These MTDs are well-above the current exposure limits and the MTD obtained at 254 nm (50 mJ cm^{-2}). Histological assessment of the cornea using the CPDs, the marker for DNA damage and indicative of potential carcinogenesis, was analyzed for each wavelength and as a function of total exposure dose. The depth of observed CPDs varied with wavelength. For the 207 and 222 nm exposures, the CPD marker was only observed in the upper cells of the corneal epithelium (soon to be sloughed off in the normal corneal epithelial life cycle). However, the observed CPDs for the 254 and 313 nm exposures at 254 nm were in all layers of the cornea including the corneal endothelium. These observations are indicative of the relative absorption in the target tissue as a function of wavelength. The experimental data from both skin and eye exposure studies support a substantial increase in the exposure limits at wavelengths less than 250 nm.

DELAYED EFFECTS

In setting any human exposure guideline for UV-C radiation, preventing delayed effects is of paramount concern. The photocarcinogenicity of sunlight and most significantly of UV-B has been well-demonstrated in both animal and epidemiological studies (4,5,8,24). Most *in vitro* cellular studies of DNA damage, mutagenesis and DNA repair have employed the low-pressure Hg lamp and most concentrated on the emission line at 254 nm, even though UV-C does not exist in terrestrial sunlight (4,5,8,25). Thus, to extrapolate data from laboratory studies of cell cultures and the limited animal studies to human skin (26,27), the actual penetration of UV-C into the basal (germinative) layer of the epidermis (26) had to be applied. Acute damage to the superficial layers of the epidermis would not be

expected to play a role in delayed effects since these cells would die within some days. When these calculations are performed, the result is as shown in Fig. 2 for the international standard action spectrum for nonmelanoma skin cancer (NMSC) (21). Note that the NMSC action spectrum drops rapidly below ~280–290 nm and falls nearly two orders of magnitude lower than the action spectrum $S(\lambda)$. What this means is that individuals working in the vicinities of welding arcs or germicidal UV-C lamps will experience a mild erythema at exposures well above the current $S(\lambda)$-based exposure limits and the relative photocarcinogenic dose would need to be at least 1–2 orders of magnitude higher to be equivalent to exposure to UV-B in sunlight. Another way to look at this is that because erythema and photokeratitis occur at very low doses, workers do not require reminders to take precautions after their first accidental over-exposure and wear the protective gloves, aprons, welding helmets, etc. Because of this, epidemiological studies cannot be expected to report individuals demonstrably exposed to any significant levels of UV-C. Irritation appears indirectly to motivate compliance. Thus, a routine daily exposure below the current exposure limits to UV-B has been argued to be an insignificant risk in the UV-B, but an even far lower risk for UV-C (4,5,8,21) as shown in Fig. 2. This initially comes as somewhat of a surprise to biologists who are well aware of the greater energy of UV-C photons compared to UV-B and who have studied DNA damage and cellular mutagenesis from 254 nm. Yet, in practice, outdoor workers are routinely exposed to solar UV above the UV-B exposure guidelines. The current exposure guidelines (4,5,8) can be exceeded in midday midsummer within less than ten minutes. Thus, by drawing comparisons for those exposed to scattered UV-C below the limits from overhead UVGI installations, the risk is comparable to only a few minutes outdoors in sunlight during late spring or early summer. The greatest concerns generally expressed about the open application (Upper-room) UVGI have been the perceived risk of skin cancer, but properly installed UVGI fixtures in the upper-room surely have benefits of infection control far above these over-stated perceived risks (11), and room occupants are not exposed above the human exposure guidelines.

An expert committee of scientists and physicians who had studied solar and ultraviolet photocarcinogenicity met at the International Agency for Research on Cancer (an Agency of the WHO—the World Health Organization) in Lyon, France, in 1992, and concluded that sunlight was carcinogenic in humans (Group 1), and: "Ultraviolet C radiation is probably carcinogenic to humans (Group 2A)." A later IARC group particularly concerned about risks of photocarcinogenicity from tanning beds met in 2009; and, although the focus of their review appeared to be the risks of UV-A and UV-B from tanning beds, this group recommended updating all ultraviolet radiation (along with sunlight) to Group 1 (24, 30). One cannot argue against the potential for ultraviolet radiation—particularly UV-B—to pose a significant skin-cancer risk; however, for UV-C exposure below the recommended limits, there is a far lesser risk (but not zero). The comparison with how little sunlight exposure duration compares to a daily exposure to the UV-C limit is helpful for risk communication to those concerned.

Exposure of the human eye has been well-studied in the UV-B and UV-A (3–5,8,23,32–35), and these longer UV wavelength bands have been shown by laboratory and epidemiological studies to contribute to age-related eye diseases of the anterior segment of the eye, such as pterygium, droplet keratopathies and cortical cataract (34,35). However, in the UV-C, all energy is absorbed in the corneal epithelium; hence, cataract cannot result from chronic UV-C exposure since the energy does not transmit even deeply into the cornea (36,37). Actually, very few studies have been conducted at wavelengths below 254 nm until recently (9,17,23,32). Acute photokeratitis occurs at the lowest radiant exposures—as low as 4–6 $mJ \cdot cm^{-2}$ at 270 nm (23,32). Although the surface epithelial (wing) cells of the cornea do not have a substantial preabsorbing shield (such as the stratum corneum of the skin), it has only the tear layer, and the typical lifetime of the surface cells is about 48 h. So, the "sacrificial" surface cells act as a protective shield for underlying corneal epithelium. Solar ultraviolet radiation, very dry air, dust, air pollution and wind all contribute to the steady turnover of the surface cells. The germinative cells in the corneal limbus are shielded by at least three cell layers that heavily attenuate UV-C (38). The most recent studies of Kaidzu (28,17) clearly show very high exposures are required to detect corneal effects at shorter wavelengths below 260 nm. It is important to keep in mind that the one study of photokeratitis in humans (23) had to employ very wide (10 nm FWHM) monochromator bands because of the small throughput, and stray-light (out-of-pass-band) spectral radiant energy and this led to large uncertainties. For that reason, the first author of this paper exposed himself to exposure doses well-above the current limit (~23 $mJ \cdot cm^{-2}$) at 222 nm without being able to detect a photokeratitis change at levels below 160 $mJ \cdot cm^{-2}$, the highest dose attempted. He did note that at high irradiance levels, there was a sensation of dryness that could be detected as low as ~10 $\mu W \cdot cm^{-2}$ and at much higher irradiances, tears were produced. Therefore, some discomfort would apparently limit individuals from actually exceeding the daily exposure limit if the dose were delivered in a very short duration. This is unlike the experience with photokeratitis at much longer wavelengths where there are no signs or symptoms for at least 6–12 h.

CONCLUSION

Based on the fact that the UV envelope action spectrum always was based on the lowest acute effect that produced damage—and this was photokeratitis, the current TLV is clearly substantially overly conservative at wavelengths less than ~250 nm and the $S(\lambda)$ values could be reduced. Furthermore, although it was of no consequence in the past that all of the UV-C exposure limits were far more conservative than necessary, consideration should be given to having separate, higher exposure limits throughout the UV-C, because it is now consequential because of the potential impact of UVGI as an intervention in controlling COVID-19. Indeed, an exposure limit of 10 $mJ\ cm^{-2}$ for wavelengths between 250 and 300 nm could be justified. Still, much higher limits at wavelengths less than 250 are clearly justified as well (13–16). It should be noted that melanin pigmentation no longer plays a significant absorbing role at those wavelengths, so that discerning skin phototypes is not important. Photosensitization also should not be a concern in the UV-C because of the very shallow penetration depth into the epidermis.

A few of these studies are plotted in Fig. 3 along with current and proposed exposure limits suggested by the data. Human exposure limits are proposed for both the eye and skin for exposure in the 180–270 nm spectral range. The proposed

skin exposure limits are intended for conditions where the eye is not exposed (either protected or shielded from exposure).

RECOMMENDATIONS

Figure 4 provides a proposed adjustment of the exposure limits for UV-C wavelengths below 250 nm. For situations where the eyes are not exposed, a revised spectral weighting function, which we would propose to refer to as $S'(\lambda)$, could be applied as shown in Fig. 5. Noting that the proper measurement of UV exposure is through a limited field-of-view (FOV) of 80°, and for ocular exposure the detector would be aimed in the direction of gaze(s), the eyes can be exposed to overhead scattered UV-C from germicidal lamps without the same effect as directly exposed skin as routinely happens in outdoor sunlight (300). Eventually, it would be helpful if the lamp-product safety

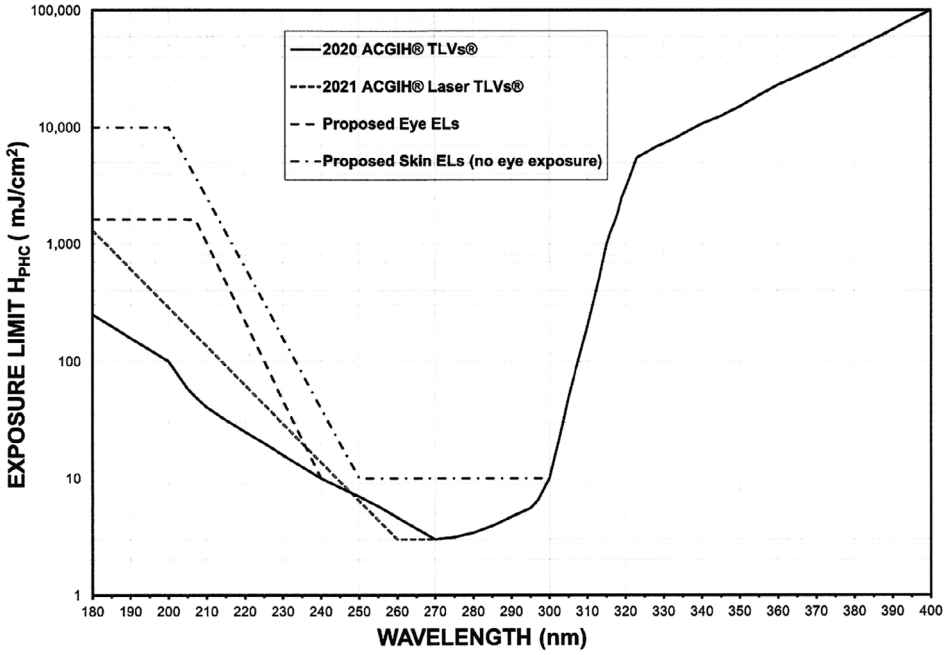

Figure 4. The proposed exposure limits for the UV-C are shown along with the 2020 ACGIH® TLV®s (solid line) and the 2021 ACGIH® Laser TLV®s (small-dashed line). Proposed exposure limits are defined for the eye (large-dashed line) and the skin (dot-dash-dot line). The skin exposure limits apply when the eye is not exposed by protection or other exclusion conditions. For comparison, see Table 1.

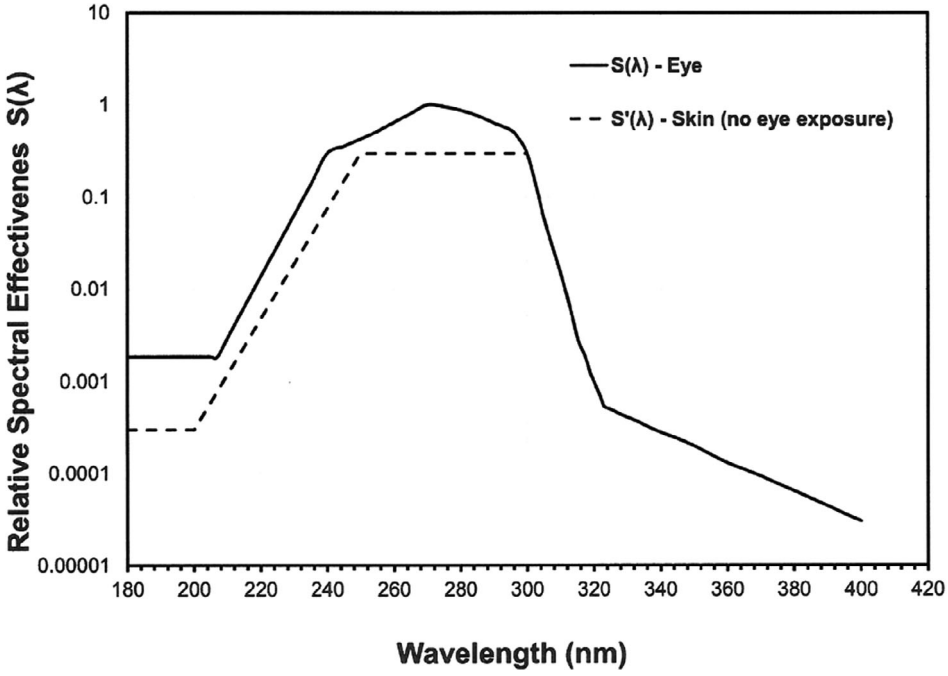

Figure 5. Proposed UV hazard functions. The spectral effectiveness of the eye, $S(\lambda)$, and the skin, $S'(\lambda)$, differ for wavelengths from 180 to 300 nm. The two hazard functions are identical from 300 to 400 nm.

Table 1. The current and proposed exposure limits (ELs) for ultraviolet radiation are tabulated for selected wavelengths and exposure conditions.

Wavelength	2020 ACGIH® TLV®	2021 ACGIH® TLV®—Laser	Proposed ELs for Eye Exposures	Proposed ELs for Skin Exposures (no eye exposure)
λ nm	$H_{Incident}$ mJ cm^{-2}	$H_{Incident}$ mJ cm^{-2}	$H_{Incident}$ mJ cm^{-2}	$H_{Incident}$ mJ cm^{-2}
180	250	1310	1626	10 000
200	100	286.5	1626	10 000
207	51.4	168.3	1626	3802
210	40.00	134.0	1023	2512
222	23.00	53.84	160.7	479
230	16.00	29.32	46.8	158
235	13.00	20.05	21.6	79.4
240	10.00	13.71	10.0	39.8
250	7.00	6.41	7.00	10.0
254	6.00	4.73	6.00	10.0
260	4.60	3.00	4.60	10.0
270	3.00	3.00	3.00	10.0
280	3.40	3.40	3.40	10.0
300	10.0	10.0	10.0	10.0
310	200	200	200	200
320	2.90E + 03	2.90E + 03	2.90E + 03	2.90E + 03
340	1.10E + 04	1.10E + 04	1.10E + 04	1.10E + 04
360	2.30E + 04	2.30E + 04	2.30E + 04	2.30E + 04
380	4.70E + 04	4.70E + 04	4.70E + 04	4.70E + 04
400	1.00E + 05	1.00E + 05	1.00E + 05	1.00E + 05

The ELs are expressed in terms of the Incident Radiant Exposure ($H_{Incident\ or\ total\ dose)\ in\ mJ\ cm^{-2}}$ (1 mJ cm^{-2} = 10 J m^{-2}). The 2020 ACGIH® TLV®s are the current ELs. The UV-C ELs for lasers have been updated in the 2021 ACGIH® TLV®s. The shaded cells indicate conditions where no changes are proposed. Changes proposed in the UV-C are for two conditions: (1) where both the eye and skin are potentially exposed, and (2) where only the skin is exposed with no eye exposure. These ELs for UV-C are plotted in Fig. 4.

standards (39) would reflect more realistic values for UVGI applications. Table 1 compares the current and the recommended revised exposure limits.

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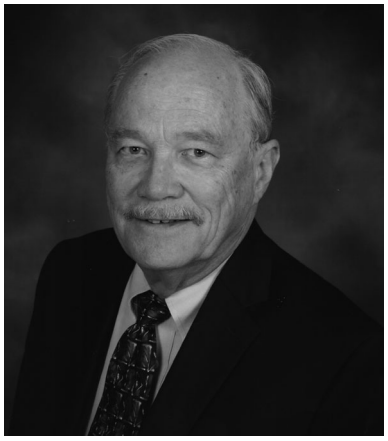

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