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Invited Review

Balancing the Risk of Eye Irritation from UV-C with Infection from Bioaerosols†

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ABSTRACT

The very aspect (phototoxicity) that makes short-wavelength ultraviolet (UV) radiation an effective germicidal agent also is responsible for the unwanted side effects of erythema (reddening of the skin) and photokeratitis ("welder's flash" or "snow-blindness"). Overexposure to this short-wavelength UV radiation can produce these unwanted side effects from a very mild irritation of the skin and eyes to a rather painful case of photokeratitis. These effects are fortunately transient, as only superficial cells of the eye—the corneal epithelium—and the most superficial layer of the skin—the superficial epidermis—are significantly affected. Normal turnover of these cells soon erase the signs and symptoms of these effects. Radiant energy in the UV-C band has very shallow penetration depths which account for the very superficial nature of any injury to the skin and eyes from excessive exposure, minimum risk of delayed effects and at the same time the strong absorption by bioaerosols. Guidelines for human exposure to UV-C must be applied intelligently so as not to limit germicidal efficacy in upper-room ultraviolet germicidal irradiation.

INTRODUCTION

The very phototoxicity that makes short-wave ultraviolet (UV) radiation an effective germicidal agent also is responsible for the unwanted side effects of erythema (reddening of the skin) and photokeratitis ("welder's flash" or "snow-blindness") (1). Overexposure to this short-wavelength UV radiation can produce these unwanted side effects from a very mild irritation of the skin and eyes to a rather painful case of photokeratitis. These effects are fortunately transient, as only superficial cells of the eye—the corneal epithelium—and the most superficial layer of the skin—the superficial epidermis—are significantly affected by the characteristic 254 nm ultraviolet emission of UV germicidal irradiation (UVGI) lamps. Normal turnover of these cells soon erases the signs and symptoms of these effects. The photobiological spectral region employed in germicidal applications is referred to as UV-C by the International Commission on Illumination (Commission International de L'Eclairage, Vienna, Austria, referred to simply as "the CIE"), which includes wavelengths between 100 and 280 nm (2–4). Radiant energy in the CIE band has very shallow penetration depths which account for the very superficial and transient nature of any injury to the skin and eyes from excessive exposure, and at the same time the strong absorption by bioaerosols.

As photon energy increases with decreasing wavelength, UV-C photons have higher photon energies than longer wavelength (UV-B or UV-A) photons. The higher photon energies coupled with the very high absorption by most biological molecules, such as proteins and collagen account for both efficacy and long-term safety. As the outer (dead tissue) layer of the skin—the *stratum corneum*—is highly absorbing in the UV-C, only very small traces of incident UV-C penetrates to the germinative (basal) layer of the epidermis. CIE report 187 on cancer risks from germicidal lamps has explored in depth the question of the potential for skin cancer (skin carcinogenesis) from ultraviolet C radiation (photocarcinogenesis) (5). This report clearly demonstrates that the risk is exceedingly small.

DESCRIBING PHOTOBIOLOGICAL EFFECTS

In assessing both benefits and risks of exposure to ultraviolet radiation, several concepts must be well understood. Dosimetric quantities must be properly specified and the action spectrum—the relative photobiological effectiveness as a function of wavelength—must be known. In this regard, several CIE publications are important.

Photobiological dosimetric quantities

The CIE has defined several radiometric quantities that are important for risk assessment. In describing nonphotometric, *i.e.* nonvisual effects, the CIE defines exposures in terms of "radiometric" terminology, and these are used in phototoxicology and safety (6). Photometric terms are different and are used in architecture and lighting science only for visible light (*e.g.* candelas, cd; lumens, lm; and lumens-per-square meter, lux). To describe the optical emission, one employs radiant power (in watts, W) to describe a continuous-wave (CW) source, or radiant energy (in joules, J; where: 1 sJ = 1 W-s). To describe concentration of

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power upon a surface, the proper term is irradiance, E (in W/m^2 or W/cm^2) and this is sometimes used as the exposure dose rate. After an exposure period of t seconds (s), the radiometric concentration of energy upon a surface is the radiant exposure, H (in J/m^2 or J/cm^2) and this is an exposure dose. However, what is frequently unclear to many is that for dosimetry within a medium (either in room air or internal tissue, the concept of a true photobiological dose is different. However to clarify this meaning, it is important to remember the fundamental concept in photobiology—the Bunsen-Roscoe Law (4) of photochemistry, or the reciprocity of exposure dose rate E and time t:

$$E \times t = H = \text{“the exposure dose”} \quad (1)$$

Normally all optical radiation, including UV is absorbed on a surface; and the power divided by exposed surface area is the irradiance, E, or “the dose-rate”—however, in tissue or in air, the true photobiological exposure rate is *fluence rate* in power per unit area (*e.g.* in W cm^{-2}) and the final exposure dose is *fluence* in energy per unit area (*e.g.* in J cm^{-2}) as shown in Fig. 1. In the case of 254 nm UV-C radiation, the penetration and absorption is so superficial that irradiance and radiant exposure are perfectly adequate to describe skin or corneal exposures.

Photon energy

All light is composed of photons of energy, “the Quantum Theory.” The energy of a single photon varies with wavelength. Photon energy increases with decreasing wavelength; and, in photochemistry: one photon interacts with one absorbing molecule, which is very different from thermal effects, where bulk absorption is important. Photobiologists always describe an action spectrum because of the great importance of wavelength for any effect (this is not very important for thermal effects) (1). In photochemistry and photobiology, the action spectrum is critical. It describes the relative effectiveness of different wavelengths to produce the defined response or endpoint. Generally, the full width at half maximum, where the relative response reaches 50% of maximum is less than 100 nm, and there is a sharp cutoff due to low photon energy at the longer wavelength end of the action spectrum. For the photochemical action spectra of interest to this discussion, it is generally acknowledged that the target molecules are proteins and DNA (5). Thus, the action spectrum for germicidal (UVGI) effectiveness and the action spectrum for killing superficial corneal cells are very close to the absorption spectrum of DNA. The action spectra for adverse effects upon the cornea are also similar to that for DNA damage. Hence, the need to consider benefits *versus* risks of UVGI.

Photobiological spectral bands

In the early 1930s, the CIE Committee on Photobiology created the concept of the CIE photobiological spectral bands and named the bands (3). These remain as international standards for shorthand notation:

1 UV-A 315 nm to 380–400 nm.
2 UV-B 280–315 nm.
3 UV-C 100–280 nm (Germicidal).
4 Visible 360–380 nm to 780 nm (overlap intended).
5 IR-A 780 nm to 1400 nm (0.78–3.0 μm).
6 IR-B 1400–3000 nm (1.4–3.0 μm).
7 IR-C 3000–106 nm (3.0–1 mm).

GUIDELINES FOR HUMAN EXPOSURE TO UV-C

A number of national and international groups have recommended human exposure limits (ELs) for laser exposure and for noncoherent optical radiation [*i.e.* ultraviolet (UV), light and infrared (IR) radiant energy] (1,7–14). The earliest group to recommend the modern system of ELs is well known in the field of occupational health—the American Conference of Governmental

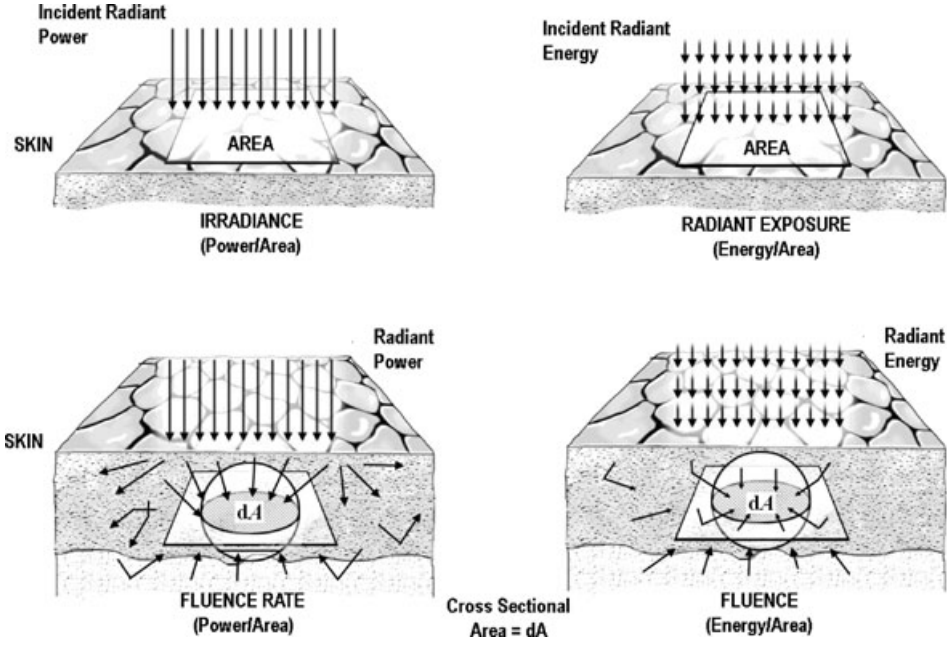


Figure 1. Radiometric and dosimetric concepts in photobiology (adapted from Sliney, 2005) (6).

Hygienists (ACGIH) (7,8). The ACGIH refers to its ELs as "Threshold Limit Values," or TLVs, and these are issued yearly, so there is an opportunity for a yearly revision (7). On the international scene, there are currently limits for optical radiation exposure as well as for the special case of laser irradiation. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) publishes "Guidelines on Limits of Exposure to Ultraviolet Radiation of Wavelengths between 180 and 400 nm (incoherent optical radiation)," which most recently was updated in 2004 (9). ICNIRP guidelines are developed through collaboration with the World Health Organization (WHO) by jointly publishing criteria documents, which provide the scientific base for the ELs (10). The ICNIRP guidelines for exposure to lasers and noncoherent optical radiation also became the bases for the European Union Directive on Optical Radiation, and these limits are basically those also recommended by ACGIH for UV-C radiation.

It should be noted here that the US Federal Regulation that applies to light sources as electronic products currently only has standards for laser products (21CFR1040) (11), and was issued by the US Food and Drug Administration (FDA), Center for Devices and Radiological Health (CDRH). However, some special germicidal medical products if construed as medical devices must also meet the FDA requirements for medical devices. The Illuminating Engineering Society of North America (IESNA) has employed the above limits in lamps safety guidelines that have become standards of the American National Standards Institute (ANSI) (12–14). These IESNA/ANSI recommended practices were the bases of international lamp safety standards of the CIE and the International Electrotechnical Commission (the IEC) (2).

Ultraviolet radiation exposure limits

The potential ultraviolet (UV) hazard from most conventional lamps is small as the small amount of emitted radiant energy below 315 nm is filtered by the glass envelope of most lamps. For that reason, germicidal lamps must have quartz or special, high, UV-transmission glass envelopes to be effective—hence the common term: "quartz lamp," applied to some germicidal lamps. Exposure limits are expressed as a radiant exposure H over a wide range of exposure times from milliseconds to hours. A spectral weighting function, $S(\lambda)$, must be applied to the spectral power to account for the varying efficiency of radiation in producing a hazard (*i.e.* the "action spectrum"). The resultant irradiance is designated as "effective irradiance." The $S(\lambda)$ function (as shown in Fig. 2) is used by ACGIH, ICNIRP, ISO, ANSI and other safety guidelines and standards. Also, these

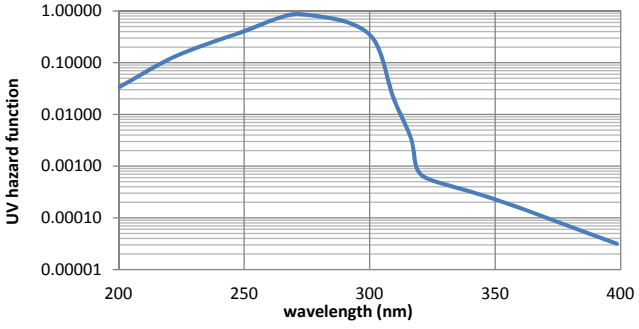


Figure 2. The $S(\lambda)$ UV hazard function applied by ACGIH, ICNIRP, ANSI, IEC and other organizations peaks at 270 nm and has a value of 0.5 at 254 nm.

references define the hazard EL in terms of effective dose H_S UV as 3.0 mJ cm^{-2} (0.003 J cm^{-2}). The general equation for evaluating a constant exposure of spectral irradiance E_λ (W cm^{-2} nm^{-1} or W m^{-2} nm^{-1}) and an exposure time t (s) based on this EL was originally intended for a full 8 h workday (1):

$$H_{S-UV} = E_{S-UV} \cdot t = \sum E_\lambda \cdot S(\lambda) \cdot t \cdot \Delta\lambda \leq 3.0 \text{ mJ} \cdot \text{cm}^{-2} (30 \text{ J} \cdot \text{cm}^{-2}) \text{ effective} \quad (2a)$$

The term "effective" refers then to the radiant exposure at 270 nm [the $S(\lambda)$ peak] that would cause the same effect as the measured, radiometric UV radiation. Only effective irradiance received through a circular, right-angle cone of 80° total angular extent and centered on a normal to the receiving element contributes to the EL. Note that essentially all the UV-C emission from the mercury, low-pressure discharge, germicidal lamp is at 254 nm. Thus, for UVGI considerations, $S(\lambda) = S(254 \text{ nm}) = 0.5$, and a summation over wavelengths is unnecessary. Standard UV irradiance meters measure irradiance E_{UV} without spectral weighting. Special UV safety meters exist which have a spectral response follow the UV-Hazard function $S(\lambda)$. Such meters are designed to measure an "effective irradiance $E_{S\text{-}UV}$," *i.e.* spectrally weighted against $S(\lambda)$ (15).

As an example, the maximum permitted constant irradiance exposure E_{UV} for a 2 h interval (7,200 s) would be determined from:

$$H_{S-UV} = \sum E_\lambda \cdot S(\lambda) \cdot t \cdot \Delta\lambda = E_{254} \cdot (0.5)(7,200 \text{ s}) \leq 3.0 \text{ mJ} \cdot \text{cm}^{-2} (30 \text{ J} \cdot \text{cm}^{-2}) \text{ effective} \quad (2b)$$

$$E_{254} \cdot (0.5) \leq 3.0 \text{ mJ} \cdot \text{cm}^{-2} / (7,200 \text{ s}) = 0.416 \mu\text{W} \cdot \text{cm}^{-2}) \text{ effective} \quad (2c)$$

As $S(\lambda)$ has a value of 0.5 at 254 nm, the true irradiance in 2*b* would be: 0.83 μW cm^{-2}, but $E_{S\text{-}UV}$ as measured directly by a UV safety meter would still be ~0.42 μW cm^{-2}. If however, one were concerned about continuously occupied zones, *e.g.* at seated level in an office or at a nurse's station, the criterion of 3 mJ cm^{-2} in one work day (~8 h) results in an averaged $E_{S\text{-}UV}$ of only 0.1 μW cm^{-2}. One may question the magnitude of the safety factor or reduction factor built into the ELs, but at 270 nm this factor is less than two-fold, based upon the corneal threshold studies of Pitts and Tredici (16). Right above some unlouvered fixtures, the irradiance at 254 nm could be as high as ~2 mW cm^{-2} and the effective irradiance $E_{S\text{-}UV}$ would be as follows:

$$H_{S-UV} = \sum E_\lambda \cdot S(\lambda) \cdot t \cdot \Delta\lambda \sim 1.0 \text{ mW} \cdot \text{cm}^{-2}) \text{ effective} \quad (2d)$$

And the safe exposure duration would then be only 3 s. There is another criterion that is primarily intended to protect against UV-A, and it is a limit upon the total UV radiation (unweighted) in the spectral region of 315–400 nm of 1 mW cm^{-2} averaged over 1 day (ACGIH), or 1 J cm^{-2} (ICNIRP), but this is generally never reached by germicidal lamps.

There is no reason for accessible UV-C radiation to exceed the ELs! One need only employ good fixtures that are properly installed. Improper installation is a root of most accidental exposures (17–25). Improper UV safety measurement in occupied

spaces has sometimes ignored the fact that an individual in the lower room is generally looking forward or downward. Thus, the 80° cone measurement criterion should be followed, as facial features and the upper lid normally exclude much of the ocular UVGI exposure that would be measured with a vertically oriented detector—or with a horizontally aimed detector without a 80° cone attachment. Proper measurement in occupied spaces therefore must assess downward-directed UV, but a relatively brief exposure/day (*e.g.* 15 min) contributing to eye exposure; whereas, the measurement directed horizontally would be compared with the limit for continuous exposure, or at least an appreciable fraction of time. Furthermore, there have been challenges to some installations where a very conservative risk assessment would presume continuous 8–12 h/day exposure of a standing person (22–29). What limit should apply for continuous ("CW") exposures exceeding 8 h?

Limiting exposures exceeding 8 hours

Neither the ACGIH nor the ICNIRP exposure guidelines explicitly address the situation where exposures are continuous for periods exceeding 8 h. Although one could apply the 3 mJ cm^{-2} daily EL to expected exposure durations exceeding 8 h, this would lower the daily CW limit below 0.1 μW cm^{-2} effective. This becomes an issue for long work-shifts, or hospital rooms employing upper-room UVGI. The lamp safety standards addressed the issue of 12–14 h exposures by eventually agreeing on two factors: (1) time-weighted (time-averaging) assumptions that individuals are almost never exposed to worst-case conditions, and (2) subcellular biological repair of damaged molecules, such as DNA, begin to alter reciprocity of irradiance and duration, such that a greater safety margin builds by 8 h, such that the 8 h irradiance limit (0.1 μW cm^{-2}-effective) can be reasonably applied to 12 h exposures (2,30). Although rare, situations may exist, as in tuberculosis wards, where a person may be exposed to low-level scattered UV-C for 24 h at bed level and seated level. As the level of scattered UV-C radiant energy is typically much lower than at the worst case (eye-level of tall, standing adult), this question has normally been set aside in safety assessments. Should there be two safety measurements for these conditions? For example, should there be a UV-C irradiance limitation specified at *e.g.* 1 m above the floor and 2 m above the floor, with very different time-weighted durations? However, it is worthwhile to note that both the ACGIH and ICNIRP guidelines assume a normal night period of cellular repair with the exposure clock beginning the nest day. The ICNIRP rationale also cites studies showing DNA repair 24 h after exposures, etc (9). Although the use of the 0.1 μW cm^{-2} for 12 h may be reasonable, is it really unreasonable that it should apply for 24-h/day exposures? As the real limiting exposure is the eye at 254 nm, the 24-h exposure really does not occur, as the eyelids will prevent exposure during sleeping. With regard to skin exposure, the EL at 254 nm wavelength has a much larger reduction factor (safety margin) from cellular damage levels than at UV-B wavelengths as noted below.

Concerns about UV-C photocarcinogenesis

Squamous cell photocarcinogenesis requires the germinative layer of the epidermis to be affected, as that has the long-term "memory" for the skin. The ACGIH and ICNIRP threshold limit is based upon no visible, acute effects, but also serves as a substantial risk reduction for long-term delayed effects. The real risk of UV photocarcinogenesis at 254 nm is extremely small, primarily because of the extremely shallow penetration of this wavelength radiation to the basal layer of the epithelium and strong attenuation of the stratum corneum and epidermis are accounted for in the action spectrum for squamous cell carcinogenesis based upon animal studies with the hairless mouse (*i.e.* corrections were made based upon the much greater attenuation in human skin) (5,17,31–33). The penetration to the basal layer of the epidermis becomes an insignificant value at 254 nm (5,31,33). The 3 mJ cm^{-2}-effective limit for 8 h continuous exposure to UV-C radiation at 254 nm is 6 mJ cm^{-2} (60 J m^{-2}) - radiometric, as was explained above (34). However, ICNIRP notes that this UV EL in the UV-B is where no unrepaired DNA can be detected 24-h postexposure. For UV-C, the photocarcinogenesis risk is much lower than in the UV-B because of the great difference in penetration depth (5,9,17). Note the 100-fold difference between the $S(\lambda)$ and UV-carcinogenic weighting factor at 254 for this reason, whereas the two functions become nearly matched for the wavelengths between 300 and 315 nm in Fig. 3. The UV-B lines of 297, 303 and 313 nm are all very weak emissions from the low-pressure mercury germicidal lamp and contribute much less than 10% to the effective UV hazard dose, thus one can conclude that the application of the 8-h, 0.1 μW cm^{-2}–effective (0.2 μW cm^{-2} at 254 nm) is conservative. It then remains to determine worst-case time-weighted average irradiance limitations as a function of height above the floor.

Both the ACGIH and ICNIRP emphasize that the human EL should not be exceeded for ocular exposure, as there is little margin of safety for ocular effects. However, the EL when applied to the skin is only a desirable goal. Indeed, it is extremely important that ACGIH has termed the limit as a "ceiling value" for the eye, but not for the skin. ICNIRP is more explicit and states: *This limit should be considered a desirable goal for skin exposure to minimize the long-term risk, but it must be recognized that this limit is difficult to achieve in sunlight and judgment must be used in its practical application* (2004) (9).

Ocular photobiological effects

The UV-C hazard to the skin is minimal because of the very high attenuation by the *stratum coneum* of the 254 nm UVGI lamp

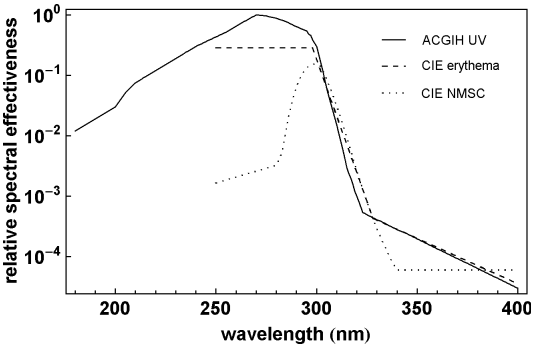


Figure 3. Comparison of photobiological risk of eye irritation (exposure limit weighting value of 0.5) and erythema (~0.3) compared with CIE nonmelanoma skin cancer (NMSC) at ~ 0.002. The curves were properly normalized to 300 nm to assure the same slope between ~300 and 320 nm.

emission (5,17). However, the corneal epithelium has no such protector. Therefore, a radiant exposure of only about 10 mJ cm^{-2} at 254 nm will produce photokeratitis and photoconjunctivitis (sometimes referred to as photokeratoconjuctivitis, "welders' flash," "arc eye," or "snowblindness") (18,34–36). The surface epithelial cells that are damaged from UV-C exposure are normally sloughed off over night—certainly within 48 h (1,9). Another problem associated with UV exposure of the eye is lenticular fluorescence as an acute interference with vision, but this is limited to UV-A. A more serious concern is the risk of long-term delayed effects such as UV cataract (lenticular opacities), pterygium (a neoplasia over the cornea in some outdoor workers) and droplet keratopathies (spheroidal degeneration of the cornea). Concerns without much epidemiological evidence relate to suggestions of UV-induced photoretinitis and retinal degeneration. UV-C is all absorbed in the cornea. Unfortunately, the determination of chronic exposure effects is difficult because of confounding factors. For example, epidemiological studies appear to conflict on the role of UV in producing cataract. The major problems of most environmental studies relate to poor ocular dosimetry (*e.g.* the presumed protective role of sunglasses compared with the actual effect of sunglasses to enhance localized ocular exposure, from the extreme periphery of one's field of view as noted by Coroneo, which may be significant (35,36). Certainly, there are more than one million cataract surgeries in the USA each year. The UV spectral absorption in ocular tissue indicates which wavelengths can produce a given effect. The action spectrum for cataract for acute-exposure cataract in laboratory animals is known to (295–325 nm) emphasize UV-B, and only *in vitro* biochemical laboratory studies suggest that UV-A could play a role. Although some animal studies suggest "UV-A cataract," the dosimetry was severely flawed and the small fraction of UV-B present easily explained the cataractogenesis. The controversy remains about UV-A, but there is no suggestion that UV-C could produce cataracts as no UV-C penetrates to the crystalline lens. It should be noted that the anatomy of the crystalline lens, with lens cell nuclei behind the iris near the equator led Coroneo to postulate that UV-B focused into the pupil from the temporal side of the eye was an etiological factor in cortical cataract (the Coroneo effect) (35).

EXPOSURES FROM UPPER-ROOM UVGI

Past safety experience

Knowledge for safe use of UVGI exists from decades of safety experience from germicidal UV-C irradiation of room air and surfaces (1). It is important to state what we know about safety. UVGI is hardly new and there is a wealth of safety experience. During the 1940s–1960s low-pressure, quartz mercury lamps were widely use for disinfection of both room air and contaminated surfaces. Tuberculosis wards, medical laboratories and even public spaces employed these UV-C lamps. Figure 4 shows some examples of earlier UVGI applications and fixtures from a 1948 UVGI sales brochure. With the development of antibiotics, new disinfectant cleaners and other control strategies, the application of UV-C became used rarely except for water purification, or in-duct irradiation. One reason that upper-room UVGI fell out of fashion was the installation of suspended ceilings connected with the introduction of air conditioning (HVAC) in older, high-ceiling buildings. With lower ceilings, the number of rooms and hallways that had ideal upper-room space for UVGI dwindled. Still another reason for discontinuance was the occasional eye injuries that occurred from bad installation or bad maintenance of UVGI fixtures. In operating rooms, the occasional eye injury from operating room staff failing to properly wear face protection or complaining about its discomfort led to the gradual abandonment of a useful UVGI application designed to reduce hospital-acquired infections. In a nutshell, UVGI became a "nuisance" to staff. A key lesson from past accidents that the author has investigated at installations employing UV-C for upper-room UVGI has been: UVGI fixtures must be installed and maintained by competent well-trained staff or the consequences may well be a painful eye injury of a tall person standing for a period or a beam being misdirected downward. We have also learned from many past measurements of UV below upper-room UVGI fixtures that hazardous conditions have always occurred when a tall person could see the bluish glow of the lamp tube itself. Indeed, this simple observation suggests special warning signs for tall individuals and for installation and maintenance staff.

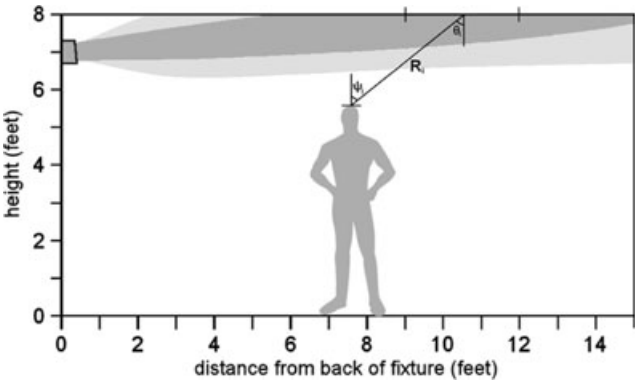
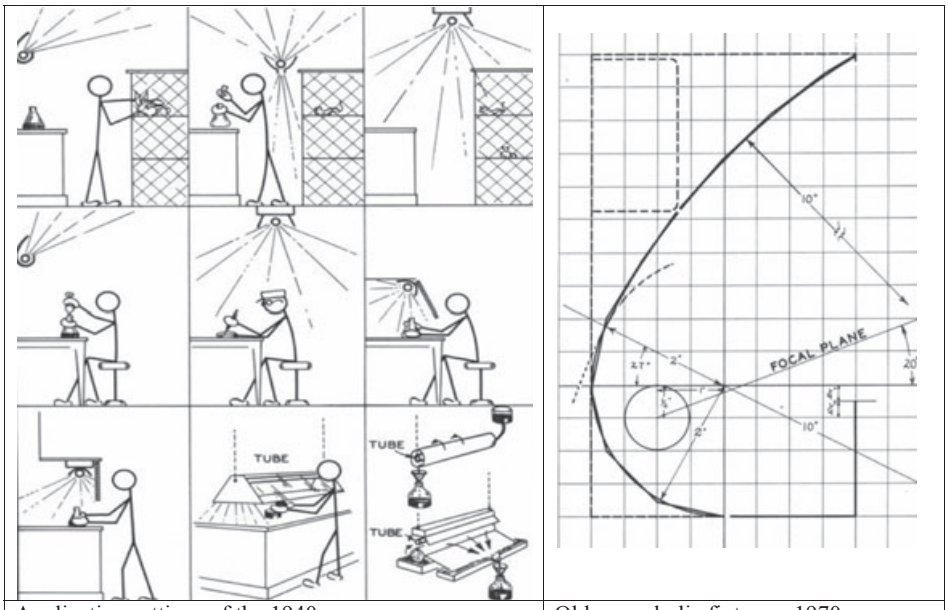


Figure 4. Instructional drawings redrawn from early UVGI publications. Engineers experienced in use of UVGI in the 1940s–1960s are no longer in the workforce to provide advice on safe installations. Parabolic reflectors (right) were prominent in UVGI fixture designs.

More recent attempts to employ highly louvered UVGI fixtures with high beam collimation should reduce the likelihood of unwanted UV-C down in occupied areas, but highly collimated louvers can also reduce the total emitted UV-C and potentially reduce germicidal efficacy (27,28,37). Figure 5 shows an example of a well-collimated fixture (37).

Skin effects are a mild reddening that peaks early compared with UV-B erythema—in about 5 hours—and normally results in a very pinkish erythema that can be quite itchy. This skin irritation is seldom the primary complaint. Instead, it is the eye irritation of UV-C that creates the greatest complaints from overexposure. The corneal sensitivity to photokeratitis is greatest at 270 nm in the UV-C (Fig. 2). By comparison, UV-B is more dangerous for initiating potential delayed effects (cataract, skin cancer, etc.) (5,31–36).

Location (distance) and time are critical. Design approaches have been developed to aid in the layout of UVGI upper-room installations (37). Their approach was applied by Reed and Wengraitis that is shown in estimating reflected UV-C levels at different room positions (Fig. 5) (38).



Application settings of the 1940s | Older parabolic fixture—1970s

Figure 5. Estimating UV-C exposure of the head from scattered radiation in an upper-room UVGI installation (adapted from a figure in Vasconez *et al.*) (37).

CONCLUSIONS

Geometry is everything! Proper design, installation and maintenance of UVGI fixtures for upper-room air disinfection should preclude unwanted irritations of skin and eye and virtually eliminate real risks of delayed effects such as cataract and skin cancer. Newer fixtures with well characterized reflectance from ceiling tiles can prevent potentially hazardous exposures in the lower room. The studies by Reed and Wengraitis at the US Army Public Health Command, Aberdeen Proving Ground showed that the reflected 254 nm irradiance (μW cm^{-2}) incident upon the top of the head or incident upon a vertical-plane facing wall can be maintained within reasonable limits if certain ceiling tiles are avoided (38). The greatest challenge is the definition of acceptable UV-C levels in occupied areas at standing position (generally a shorter term) and seated level (potentially 8–12 h). The problem is not the average person, but the unusually tall person who can see the emitting lamp tube, or the maintenance person who climbs into an upper-room unoccupied space. Clearly, training and good warning signs are needed. Application of UV-C germicidal irradiation requires a reasoned balance of benefits *versus* risk. Localized irradiation can be used with proper design of louvers and irradiators, and UV germicidal fixtures for upper-room disinfection should not have to be so restrictive that efficacy is severely affected. Parabolic reflectors that were common a few years ago, direct the ultraviolet radiation upward and above the eyes, but must be properly installed and maintained. Louvers can further protect the eyes in occupied space. To summarize:

1 Acute, accidental exposure within the UVGI treatment zone requires attention, as fixture misalignment has been the cause of UR-UVGI accidents in the past. A goal must be to employ methods (even proximity detector turn-off switches) to prevent the angry complaints against UVGI use.
2 The carcinogenic risk is vanishingly small for chronic exposure—particularly below the EL. The envelope action spectrum $S(\lambda)$ for safety evaluation greatly overstates the risk for UV-C skin exposure and is accurate—with minimal safety factor—for acute eye exposures (photokeratitis) (5).
3 Acute ocular injury from accidental exposure is the key cause of complaints, but when assessing the safety of the occupied zones (with appropriate time-based occupancy factors), it should be measured with only an 80° field-of-view instrument —and for the eye, with the detector aimed horizontally (36). Hence, downward UV-C is less hazardous than many in this symposium have assumed. If one has a UV safety meter with a detector having a full-field cosine response or any full-field collection angle, one can readily construct their own collecting cone that masks radiant energy at angles greater than 40° (*e.g.* a section of cylindrical tube can be employed for this purpose).

AUTHOR BIOGRAPHIES

David Sliney: Initially studied physics and radiological health, but obtained his Ph.D. in biophysics and medical physics from the University of London, Institute of Ophthalmology. He worked for US Army Medical Department for many years until retiring in 2007. He was President of the American Society for Photobiology during 2008–2009. His research interests focus on subjects related to vision, ultraviolet and intense light effects upon the eye, optical hazards from light, medical devices and lasers, laser–tissue interactions, photobiological/laser applications in medicine and surgery.

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