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Ultraviolet Spectral Reflectance of Ceiling Tiles, and Implications for the Safe Use of Upper-Room Ultraviolet Germicidal Irradiation

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ABSTRACT

Ultraviolet germicidal irradiation can be used to prevent airborne transmission of infectious diseases. A common application is to irradiate upper-room areas, by passing air from the lower room into the irradiated zone. Well-designed systems do not expose people directly; however, some UV radiation may be reflected off ceiling tiles and wall paints into the lower room. Lower room exposure should be limited to the American Conference of Governmental Industrial Hygienists threshold limit value of 6 mJ·cm^{-2} of 254 nm radiation per day. To limit the lower room exposure, the reflectance of upper-room surfaces must not be high. The reflective properties of wall paints have been studied, but less is known about the UV reflectance of ceiling tiles. Using a double monochromator spectroradiometer and an integrating sphere reflectance attachment, the UV spectral reflectance of 37 ceiling tiles was measured from 200 to 400 nm. The reflectances varied from 0.020 to 0.822 in this range, and from 0.035 to 0.459 at 254 nm, the main wavelength emitted by upper room low-pressure mercury germicidal lamps. These data were then used to estimate an 8 h exposure based on several simplified workplace scenarios. The implications for workplace safety are then discussed.

INTRODUCTION

Safety limits for exposure to ultraviolet (UV) radiation (200–400 nm) have been established by the American Conference of Governmental Industrial Hygienists (ACGIH; 1) and adopted by the American National Standards Institute (2). The ACGIH threshold limit value (TLV) for UV exposure is a cumulative, effective (spectrally weighted) dose of 3 mJ·cm^{-2} in an 8 h period. Common sources of UV radiation include arcs, gas and vapor discharges, fluorescent and incandescent sources and solar radiation. People may be directly exposed to these sources or to their reflections, *e.g.* off room surfaces or a snow-covered ground in the case of solar radiation. Occupational safety professionals should ensure that worker exposures do not exceed the TLV during an 8 h work day.

A UV radiation source of modern interest is ultraviolet germicidal irradiation (UVGI) lamps. Interest in this technology is being revived due to concerns over multidrug resistant (MDR) and extensively drug-resistant (XDR) tuberculosis, pandemic influenza, bioterrorism and other infectious threats (3,4). UVGI is used for disinfection purposes and can be used to disinfect air, surfaces and water. Low-pressure mercury discharge lamps are commonly used in UVGI applications and emit radiation in the UV-C range (UV-C: 180–280 nm), primarily at 254 nm. This radiation damages the DNA of microbes and inactivates their ability to replicate (5). Engineered to prevent airborne infections such as tuberculosis, a common application of UVGI is to irradiate an entire cross-section of the upper room, by passing lower room air through the irradiated zone (6–8). Using well designed, baffled lamps and installing them properly restricts high levels of radiation to a plane not accessible to occupants (9); however, some of this radiation can be reflected into the lower room and must be limited to safe levels.

The TLV for 254 nm radiation is an unweighted dose of 6 mJ·cm^{-2}. This relatively low limit reflects the fact 254 nm radiation can readily cause photokeratitis (10) to the eyes (‘‘welder’s flash’’). The minimal dose required to cause erythema (11) to the skin (‘‘sunburn’’) varies with each person, although 21 mJ·cm^{-2} has been accepted in some circles as a minimum erythema dose for persons with skin Type-II (*e.g.* fair-skinned Caucasians; 12). Photokeratitis and erythema from UV-C radiation can be quite painful, but the effects are temporary and usually resolve within 24–48 h. A radiation of 254 nm, like other types of UV radiation, has been identified as a possible contributor to the risk for non melanoma skin cancer (NMSC). However, the International Commission on Illumination (Commission International de l’Eclairage or CIE) does not consider UV-C exposures in the workplace to present the recognized risk for skin cancer. The CIE has developed a standardized action spectrum for NMSC, which has a maximum relative effectiveness of 1.0 at 299 nm; 254 nm radiation is far less effective, with a relative effectiveness value of 0.0119 (13). The greater penetration depth of longer wavelength solar UV radiation is another reason why chronic exposure to outdoor sunlight is the main source of skin cancer risk (14,15).

Computer models have been developed to predict the in-room distribution of radiation from UVGI systems (16,17). To estimate the radiation reflected into the lower room and restrict it to safe levels, the reflectance of materials in the upper room, *e.g.* ceiling tiles and wall paints, must be known. The reflectance of wall paints and other building materials have been addressed in previous studies; however, there is little if any data available with regarding to ceiling tile reflectance

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(18–20). The data that does exist on UV reflectance of materials often does not extend to or specifically apply to 254 nm, and reflectance data provided by manufacturers most often applies only to visible radiation. This study is an effort at closing some of the current knowledge gap and is intended to assist in furthering the science of UVGI.

The reflectance of a material, ρ, is defined as the ratio of the reflected radiant flux to the incident flux in the given conditions (for incident radiation of given spectral composition, polarization and geometrical distribution; 21). Reflectance may be specular, reflection in accordance with the laws of geometric optics, without diffusion (*i.e.* mirror like). Reflectance may also be diffuse, diffusion by reflection in which, on the macroscopic scale, there is no specular reflection. Most real-world materials will exhibit partly specular and diffuse reflection, or mixed reflection (*i.e.* have a reflectance comprised of both a diffuse and specular component).

In this study, measurements were made of the diffuse UV spectral reflectance of 37 ceiling tiles with and without the specular component included, and the specular component was inferred from the difference in these measurements. We then estimated the irradiances reflected into a sample room by the ceiling tiles and wall paints, and compared them to the ACGIH exposure limits (1). The full range of ultraviolet wavelengths from 200 to 400 nm was measured, because new designs of upper room UVGI fixtures may include sources based on light emitting diodes or other lamp technologies. This could lead to a wide range of possible emission wavelengths for UVGI lamps in future years.

MATERIALS AND METHODS

Instrumentation and experimental setup for reflectance measurement. The spectral reflectance was measured using the following equipment from Optronic Laboratories (Orlando, FL): a model 750-C double monochromator spectroradiometer (5 nm entrance slit and 3 mm exit aperture), with a model 750-C spectroradiometer controller, a model 740–70 integrating sphere reflectance measurement attachment, and a model 750-HSD-310 photomultiplier tube (PMT) detector head operated at 650 V. The light source used was a model 750-20D/UV automated UV-visible dual source attachment containing a 40 W deuterium arc lamp and a 150 W quartz tungsten halogen (QTH) lamp, with a model 45D deuterium lamp precision current source operated at 500 mA and a model 83A programmable direct current source operated at 5.0 A.

This system measures the reflectance factor R of a material. The reflectance factor of a material is defined as the ratio of the radiant flux reflected in the directions delimited by a given cone with apex at a point on the surface under test to that reflected in the same directions by a perfect reflecting diffuser (Lambertian) identically irradiated (22). The reflectance factor measurements reported in this study approach the true reflectance ρ of the material for the specified geometry and are referred to simply as reflectance. Reflectance was measured in 5 nm intervals from 200 to 400 nm and at the single wavelength of 254 nm. The geometric conditions of the reflectance measurement were conical–hemispherical, and the measurements were performed using the comparison method theory, to compensate for possible changes in the integrating sphere's efficiency. The incident beam irradiated the samples at 10° from normal with an irradiation cone of ±2.8° and a 6 mm beam diameter at the sample. The reflected radiation was measured over the entire hemisphere. The reflectance measurement attachment included a PTFE specular light trap plug, which was inserted into an integrating sphere aperture and used to include the specular component in the reflectance measurements. A specular light trap with a ±6° exclusion cone was inserted into the same aperture and used to exclude the specular component in other reflectance measurements. For the majority of measurements, the deuterium lamp was used from 200 to 305 nm, and the QTH lamp was used from 310 to 400 nm. The sample and sample aperture were covered with black foil to prevent light leakage.

The spectral reflectance including the specular component of each distinct model and item number ceiling tile was measured a total of 10 times. The specific area of ceiling tile being irradiated was changed before each new measurement to account for macroscopic, non homogeneous surface characteristics. The 10 measurements were then averaged at each wavelength, and the standard deviation (SD) of the reflectance was calculated. The spectral reflectance excluding the specular component of each model and item number ceiling tile was measured twice. These measurements were performed to give an estimate of the diffuse and specular components of the reflectance, and the SD was not calculated.

The ceiling tiles were provided by Armstrong (Lancaster, PA), CertainTeed (Valley Forge, PA) and USG Interiors (Chicago, IL). Table 1 lists the manufacturer, model, item number and ID letter (for identification in proceeding Tables and Figures) of the ceiling tiles used in this study. All tiles were white unless specifically noted in Table 1. More detailed tile characteristics may be found in the manufacturers' literature.

Uncertainty in reflectance measurements. The SD in the reflectances including the specular component, averaged over all wavelengths for all ceiling tiles, was ±0.020. Nearly, all reflectances including the specular component had a SD less than ±0.040 at all wavelengths. Four samples had SDs that was noticeably higher, and these ranged from ±0.049 to ±0.099. The typical accuracy and precision reported by the manufacturer were ±1% and ±0.25%, respectively.

Geometry of in-room exposure to UV radiation reflections. The following equations were used to approximate the lower room irradiances from upper-room UVGI reflections, and were derived from radiometric principles (23). The ceiling tiles and wall paints act as the source and the exposed room occupant is the receiver. Figure 1 diagrams the general exposure geometry used in the derivation.

From the definition of radiance, the flux received from a source is given by:

$$\Phi = \int_{As}\int_{A_r} L\frac{\mathrm{d}A_r\cos\theta\,\mathrm{d}A_s\cos\psi}{R^2} \tag{1}$$

where Φ is the flux of the source in W, L is the radiance of the source in $\mathrm{W{\cdot}cm^{-2}{\cdot}sr^{-1}}$, $\mathrm{d}A_r$ is an infinitesimal element of the receiver area, $\mathrm{d}A_s$ is an infinitesimal element of the source area, θ is the angle made by the direction of emerging flux with respect to the normal to the surface of the source, Ψ is the angle made by the direction of incident flux with respect to the normal to the surface of the receiver, and R is the distance between points on $\mathrm{d}A_r$ and $\mathrm{d}A_s$.

The irradiance incident upon the receiver, or flux per unit area, is found by dividing both sides of Eq. (1) by $\mathrm{d}A_r$, resulting in the simplified equation of:

$$E_r = \int_{A_s} L\frac{\cos\theta\cos\psi\,\mathrm{d}A_s}{R^2} \tag{2}$$

whereE_r is the irradiance incident upon a point on $\mathrm{d}A_r$ in $\mathrm{W{\cdot}cm^{-2}}$.

Treating the source as a Lambertian surface, it can be derived from radiometric principles that the irradiance incident upon the surface from the UVGI lamp, E_0, is diffusely reflected into the surrounding hemisphere with the following radiance:

$$L = \frac{\rho E_0}{\pi} \tag{3}$$

whereρ is the reflectance of the source.

Substituting Eq. (3) into Eq. (2), and approximating the integral as a sum of N finite elements, E_r is given by:

$$E_r \approx \frac{1}{\pi}\sum\nolimits_{i}^{N}\frac{\rho_i E_{0,i}\cos\theta_i\cos\psi_i\Delta A_{s,i}}{R_1^2} \tag{4}$$

If the entire source area has the same reflectance, ρ can be placed outside the summation. Similarly, if all finite areas are equal, ΔA_s can be placed outside the summation.

Table 1. Ceiling tile information*,†.

Mfr.	Item name	Item no.	Materials	Notable surface features	ID
ARMSTRONG	ARMATUFF	860	Wet-formed high density mineral fiber	Latex paint	R
	CERAMAGURAD	605	Ceramic and mineral fiber composite	Scrubbable plastic finish	KK
	CIRRUS	574	Wet-formed mineral fiber	Latex paint	HH
	CIRRUS (camel)	589	Wet-formed mineral fiber	Latex paint	S
	CIRRUS (platinum)	589	Wet-formed mineral fiber	Latex paint	X
	CLEAN ROOM MYLAR	1721	Wet-formed mineral fiber	Soil-resistant polyester film	G
	CLEAN ROOM VL	870	Wet-formed mineral fiber	Vinyl-faced membrane	K
	CORTEGA	769	Wet-formed mineral fiber	Latex paint	V
	CROSSGATE	2625	Wet-formed mineral fiber	Latex paint	AA
	DUNE	1772	Wet-formed mineral fiber	Latex paint	U
	ENDURA	639	Wet-formed high density mineral fiber	Vinyl latex paint	GG
	FINE FISSURED SCHOOL ZONE	1714	Wet-formed mineral fiber	Latex paint	FF
	FINE FISSURED (camel)	1729	Wet-formed mineral fiber	Latex paint	T
	FINE FISSURED (haze)	1729	Wet-formed mineral fiber	Latex paint	DD
	FINE FISSURED (tech black)	1729	Wet-formed mineral fiber	Latex paint	D
	FINE FISSURED (white)	1729	Wet-formed mineral fiber	Latex paint	Z
	FINE FISSURED OPEN PLAN	1754	Wet-formed mineral fiber	Latex paint	II
	GEORGIAN	1753	Wet-formed mineral fiber	Latex paint	CC
	GRAPHIS	8005	Wet-formed mineral fiber	Latex paint	J
	LATITUDES	588	Wet-formed mineral fiber	Latex paint	W
	LEDGES	8011	Wet-formed mineral fiber	Latex paint	P
	MESA	680	Wet-formed mineral fiber	Latex paint	E
	OPTIMA	3151	Fiberglass with acoustically transparent membrane	Acoustically transparent membrane and latex paint	B
	PAINTED NUBBY	3101	Fiberglass	Latex paint	EE
	PEBBLE	2989	Fiberglass	Latex paint	N
	RANDOM FISSURED	2910	Fiberglass	Scrubbable vinyl film facing	F
	SANSERA	573	Embossed wet-formed mineral fiber	Latex paint	Y
	SHASTA	2906	Fiberglass	Scrubbable vinyl film facing	H
	STRATUS	531	Wet-formed mineral fiber	Latex paint	JJ
	VL	871	Wet-formed mineral fiber	Vinyl-faced membrane	L
CERTAIN-TEED	ECOPHON GEDINA E	–	Fiberglass	Sound-resistant coating	BB
	FINE FISSURED HIGH NRC	454	Wet-felted mineral fiber	Latex paint	M
	SYMPHONY F	1340,2,4	Fiberglass	Laminate	C
	THEATRE BLACK F	1910,2	Fiberglass	Laminate	A
	VINYLROCK	1140,2-CRF-1	Gypsum	Scrubbable vinyl film facing	I
USG	ASTRO CLIMAPLUS	–	Mineral fiber	–	O
	BRIO CLIMAPLUS	–	Mineral fiber	–	Q

*All tiles are white unless noted in parentheses next to the model, or in the model name itself; †ID used to identify specific tiles in Figures, Tables, and text.

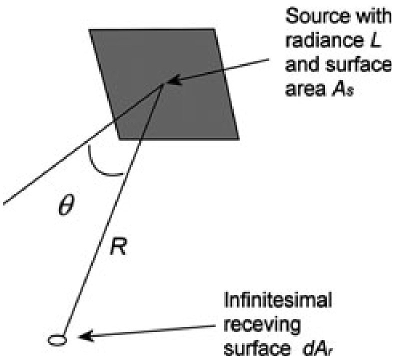

Figure 1. General exposure geometry for a source (upper-room surface) and receiver (person). Adapted with permission from McCluney (23).

The ACGIH exposure limits for UV radiation apply only to sources within ±40° of the normal to the receiver area (1), and thus Eq. (4) applies only to $\Psi_i \leq 40°$. Because Eq. (4) assumes finite elements, there was a possibility that part of a finite source area, $\Delta A_{s,i}$, could be located within $\Psi_i = 40°$, but be excluded from the calculation of E_r, an error that may become problematic with large $\Delta A_{s,i}$. Therefore, a "worst-case," conservative Ψ was calculated, so that if any part of $\Delta A_{s,i}$ was within $\Psi_i = 40°$, the entire finite source area and associated $E_{0,i}$ would be included in Eq. (4).

Exposure approximation example. Our estimated exposure is an approximation and is shown for illustrative purposes only; this should not be considered as a substitute for actual radiometric measurements. Our example calculated the reflected radiation from upper-room surfaces, originally emitted by a wall-mounted UVGI fixture in a 3.66×4.57 m^2 (12×15 ft^2) small office with a 2.44 m (8 ft) ceiling. We assumed that the UVGI fixture was located on the center of one wall at a lamp height of 2.13 m (7 ft). Our example also assumed that the UVGI fixture typically emits the UV beam at an upward angle of *ca* 3–5°; this is often the case, although some fixtures exist that are designed to irradiate in a flat plane. It should be noted that this is not an ideal installation. In an ideal installation, the room ceiling would likely be higher, and the UVGI fixture would be mounted and shimmed so that the UV beam does not strike the ceiling. The beam would only reach the opposite wall, thereby increasing the germicidal capability and reducing the exposure to room occupants. Only reflections off the ceiling tiles and the wall opposite the UVGI fixture

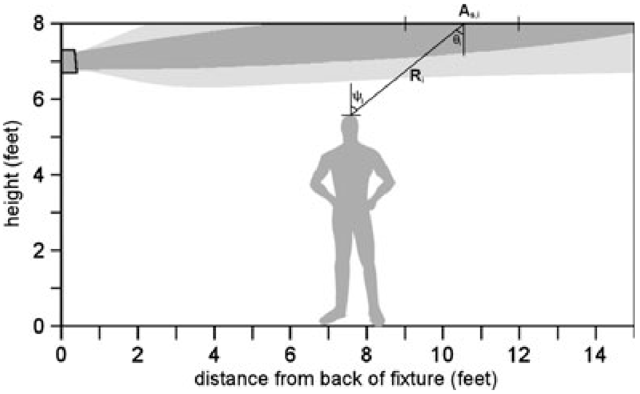

Figure 2. Model room exposure from a single source element with area, $A_{s,i}$, incident upon a horizontal receiver (top of head) at a source-receiver distance R_i. Total exposure found by summing contributions from all source elements. Adapted with permission from Vasconez *et al.* (26).

were considered for this calculation. The values used for the ceiling tile reflectances were based on those measured in this study and ranged from 0.05 to 0.50. For the reflectances of wall paint, we used 0.10 and 0.35, which were reported for water-based paints by the IES (19) and a variety of sources whose data were collected by Kowalski (21).

The exposures were calculated for several orientations: standing *vs* sitting, facing the UVGI fixture *vs* facing the opposite wall, and at several distances away from the fixture. The irradiance incident upon a horizontal plane (simulating the top of the head) and the irradiance incident upon a vertical plane parallel to the fixture wall (simulating the eyes and face) were calculated. The maximum standing and sitting heights were based on the 99th percentile anthropometric data for males and females wearing shoes with erect posture (24,25). Figure 2 diagrams the 2-D exposure geometry for a single finite source element, i, incident upon a horizontal receiving surface. The standing height (*i.e.* full stature) of 99th percentile males is 6 feet 4.5 inches (1.94 m) for males, and the standing height of 99th percentile females is 5 feet 11 inches (1.80 m). Figure 2 was adapted from Vasconez *et al.* (26). It is important to note that the human eye actually gazes slightly downward at 15° below the horizontal during normal tasks (27). This would direct the eyes away from the irradiance reflections, and decrease the risk still further. Hence, our example illustrates a higher risk than would be expected in a real situation.

Our irradiances were based on measurements of the emissions from a model LIND24-EVO Hygeaire upper-room UVGI fixture (Atlantic Ultraviolet, Hauppauge, NY) installed at the Laser/Optical Radiation Program Laboratories. The UVGI source was a G24T5L lamp, operating at 25 lamp watts and 8.5 W UV output. Portions of the vertical and horizontal cross-sections of the irradiance distribution as measured in that laboratory are shown in Fig. 3a,b. The laboratory where the UVGI lamp was installed did not have the same room dimensions as our 12′ × 15′ example room, nor was the UVGI lamp installed at a height of 7 feet. The Figures illustrate where the walls and ceiling would be relative to the UVGI lamp for our example. The irradiance was measured with a model X1-1 Optometer with a model UV3718 UV-C detector (Gigahertz-Optik, Newburyport, MA). Spatial constraints and the detector's angular response prevented us from performing irradiance measurements in the same location and geometry as the ceiling reflections (*i.e.* facing directly downward). Instead, measurements were taken pointing the detector toward the lamp, and the measured irradiance at each location i was multiplied by the tangent of 4° to calculate $E_{0,i}$ that would be incident upon the ceiling. Irradiances that would be incident upon the wall opposite the fixture were measured at the center of 0.418 m^2 (1.5 ft^2) rectangular grid-like sections at 4.57 m (15 ft) from the fixture. The total reflected irradiance incident upon the receiver was determined in each case by calculating Eq. (4) from each source (*i.e.* the ceiling tiles and wall paints), and summing them together.

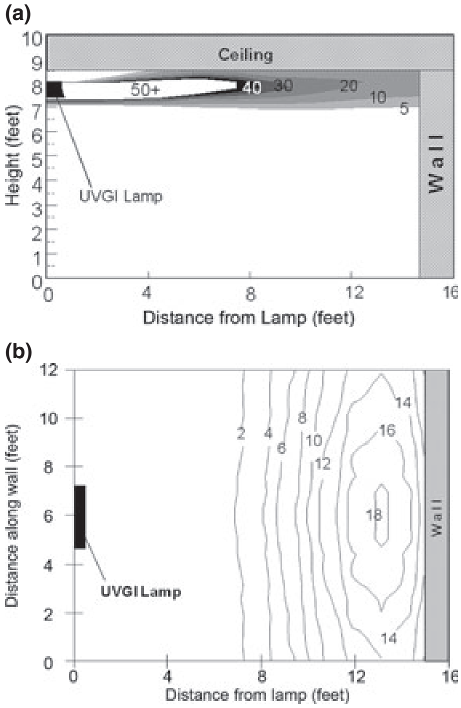

Figure 3. Vertical (a) and horizontal (b) irradiance distributions for the model room used to estimate the in-room exposure to UV reflections from ceiling tiles and wall paints. (b) Illustrates the

RESULTS

Ceiling tile reflectance measurements

Figure 4a,b plot the spectral reflectance of the ceiling tiles including the specular component from 200 to 400 nm. For illustrative purposes, Fig. 4a plots the reflectance of tiles with a reflectance less than 0.100 at 254 nm, and Fig. 4b plots those with a reflectance > 0.100 at 254 nm. Table 2 tabulates the 254 nm reflectance of the ceiling tiles including and excluding the specular component. As shown in the Table, the 254 nm reflectance varied from a low of 0.035, to a maximum of 0.459. It should also be noted that the measured specular reflectance only applies to the geometry employed by this system, *i.e.* specular reflection at 10°. The spectral reflectance excluding the specular component was not plotted, as these values were very similar to those including the specular component. Because the reflectance of the ceiling tiles did not exhibit an appreciable specular component, this justified the assumption of a Lambertian source in Eq. (3). The minimum and maximum specular reflectances were 0.022 (measured in the UV-C range) and 0.822 (measured in the UV-A range; UV-A: 315–400 nm). The reflectances measured across the full ultraviolet range (from 200 to 400 nm) are also available in a supplemental electronic file.

Estimate of reflected irradiance at various locations within a sample room

Tables 3a,b, 4a,b and 5a,b list the reflected irradiances calculated for the various conditions and reflectance values.

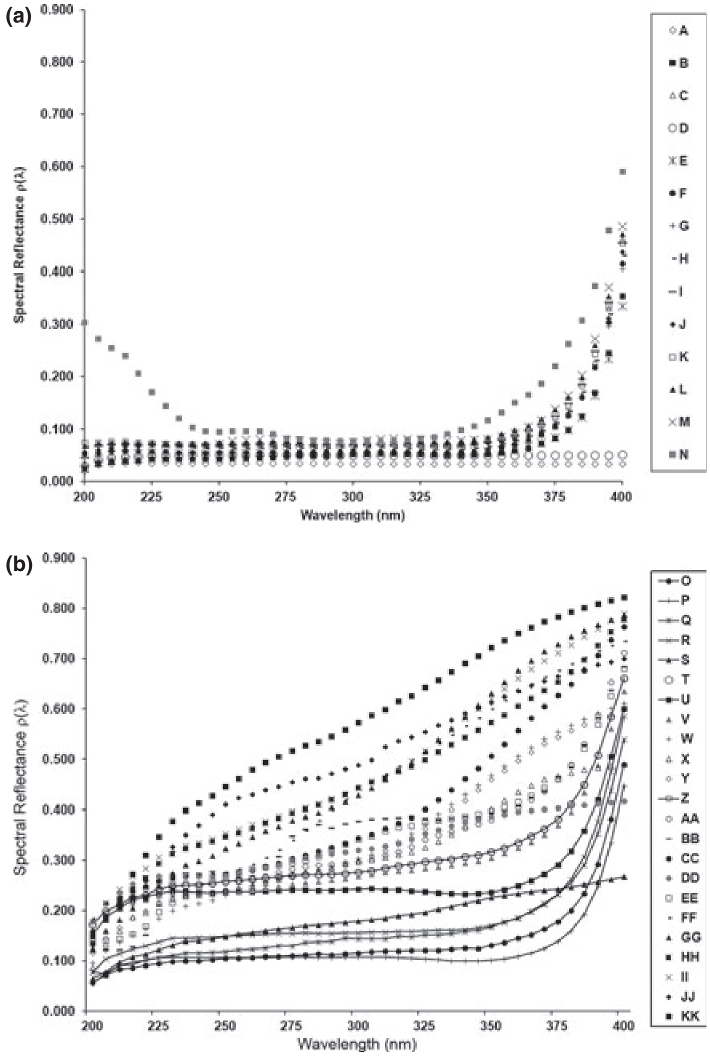

Figure 4. Spectral reflectance including the specular component of ceiling tiles with a 254 nm reflectance (a) less than 10% and (b) greater than 10%. Plots are base-10 logarithmic. See Table 1 for identification of the tiles.

Table 2. 254 nm Reflectance values of ceiling tiles.

ID	ρ, Incl specular	ρ, Excl specular	ID	ρ, Incl specular	ρ, Excl specular	ID	ρ, Incl specular	ρ, Excl specular
A	0.035 ± 0.001	0.034	N	0.096 ± 0.003	0.086	Z	0.260 ± 0.048	0.288
B	0.043 ± 0.002	0.041	O	0.106 ± 0.006	0.102	AA	0.260 ± 0.035	0.243
C	0.048 ± 0.001	0.047	P	0.107 ± 0.024	0.076	BB	0.273 ± 0.007	0.274
D	0.051 ± 0.001	0.050	Q	0.122 ± 0.007	0.131	CC	0.275 ± 0.016	0.280
E	0.052 ± 0.002	0.047	R	0.151 ± 0.008	0.150	DD	0.276 ± 0.013	0.283
F	0.055 ± 0.006	0.054	S	0.152 ± 0.009	0.164	EE	0.276 ± 0.026	0.290
G	0.060 ± 0.002	0.059	T	0.165 ± 0.021	0.169	FF	0.282 ± 0.029	0.306
H	0.064 ± 0.004	0.062	U	0.237 ± 0.011	0.227	GG	0.334 ± 0.024	0.333
I	0.070 ± 0.001	0.065	V	0.240 ± 0.033	0.270	HH	0.353 ± 0.031	0.363
J	0.071 ± 0.005	0.071	W	0.240 ± 0.063	0.220	II	0.362 ± 0.028	0.364
K	0.071 ± 0.001	0.069	X	0.244 ± 0.023	0.249	JJ	0.423 ± 0.103	0.410
L	0.074 ± 0.001	0.071	Y	0.245 ± 0.070	0.277	KK	0.459 ± 0.015	0.438
M	0.076 ± 0.003	0.067						

Bolded values would lead to a daily dose above the TLV, if one were to assume a very conservative constant 8 h exposure. The movements of room occupants play a very significant role in the exposure of room occupants to upper-room UVGI (28). Pertinent results from our study are summarized below:

Table 3. Reflected 254 nm irradiance (μW·cm^{-2}) incident upon a horizontal plane (standing/sitting). Potentially hazardous irradiances shown in bold.

ρ Ceiling tiles	ρ Wall paint	Distance from back of UVGI fixture 0.46 m (1.5 ft)	1.37 m (4.5 ft)	2.29 m (7.5 ft)	3.20 m (10.5 ft)	4.11 m (13.5 ft)
(a) Male, 99th percentile						
0.05	0.10	0.00/0.00	0.00/0.00	0.02/0.01	0.06/0.01	0.01/0.06
0.10		0.00/0.00	0.01/0.00	0.04/0.02	0.12/0.03	0.06/0.07
0.25		0.00/0.00	0.02/0.01	0.10/0.04	**0.30**/0.07	0.11/0.08
0.50		0.00/0.00	0.03/0.02	0.20/0.08	**0.61**/0.14	**0.23**/0.11
0.05	0.35	0.00/0.00	0.00/0.00	0.02/0.01	0.06/0.01	0.06/0.19
0.10		0.00/0.00	0.01/0.00	0.04/0.02	0.12/0.03	0.12/0.20
0.25		0.00/0.00	0.02/0.01	0.10/0.04	**0.30**/0.07	**0.30/0.24**
0.50		0.00/0.00	0.03/0.02	0.20/0.08	**0.61**/0.14	**0.60/0.30**
(b) Female, 99th percentile						
0.05	0.10	0.00/0.00	0.00/0.00	0.02/0.01	0.05/0.01	0.05/0.07
0.10		0.00/0.00	0.01/0.00	0.04/0.02	0.10/0.03	0.10/0.08
0.25		0.00/0.00	0.02/0.01	0.09/0.04	**0.25**/0.07	**0.24**/0.11
0.50		0.00/0.00	0.03/0.02	0.18/0.08	**0.49**/0.13	**0.48**/0.17
0.05	0.35	0.00/0.00	0.00/0.00	0.02/0.01	0.05/0.01	**0.31**/0.20
0.10		0.00/0.00	0.01/0.00	0.04/0.02	0.10/0.03	**0.36/0.21**
0.25		0.00/0.00	0.02/0.01	0.09/0.04	**0.25**/0.07	**0.50/0.25**
0.50		0.00/0.00	0.03/0.02	0.18/0.08	**0.49**/0.13	**0.74/0.30**

Table 4. Reflected 254 nm irradiance (μW·cm^{-2}) incident upon a vertical plane facing wall opposite fixture (standing/sitting). Potentially hazardous irradiances shown in bold.

ρ Ceiling tiles	ρ Wall paint	Distance from back of UVGI fixture 0.46 m (1.5 ft)	1.37 m (4.5 ft)	2.29 m (7.5 ft)	3.20 m (10.5 ft)	4.11 m (13.5 ft)
(a) Male, 99th percentile						
0.05	0.10	0.03/0.03	0.05/0.04	0.07/0.04	0.12/0.01	**0.23**/0.00
0.10		0.04/0.04	0.05/0.04	0.08/0.04	0.12/0.01	**0.24**/0.00
0.25		0.04/0.04	0.05/0.04	0.09/0.05	0.13/0.01	**0.27**/0.00
0.50		0.06/0.06	0.05/0.04	0.12/0.06	0.15/0.01	**0.32**/0.00
0.05	0.35	0.12/0.10	0.18/0.14	**0.23**/0.14	**0.40***/0.03	**0.78***/0.00
0.10		0.12/0.10	0.18/0.14	**0.23**/0.14	**0.40***/0.03	**0.79***/0.00
0.25		0.12/0.10	0.18/0.14	**0.23**/0.14	**0.41***/0.03	**0.82***/0.01
0.50		0.12/0.10	0.18/0.14	**0.24**/0.14	**0.43***/0.03	**0.87***/0.01
(b) Female, 99th percentile						
0.05	0.10	0.03/0.03	0.05/0.04	0.06/0.04	0.11/0.00	0.08/0.00
0.10		0.03/0.03	0.05/0.04	0.06/0.04	0.11/0.00	0.09/0.00
0.25		0.03/0.03	0.05/0.04	0.07/0.04	0.12/0.00	0.12/0.01
0.50		0.03/0.03	0.05/0.04	0.07/0.04	0.13/0.00	0.17/0.01
0.05	0.35	0.12/0.10	0.18/0.14	**0.22**/0.13	**0.36**/0.01	**0.26**/0.00
0.10		0.12/0.10	0.18/0.14	**0.22**/0.13	**0.36**/0.01	**0.27**/0.00
0.25		0.12/0.10	0.18/0.14	**0.22**/0.13	**0.37**/0.01	**0.30**/0.01
0.50		0.12/0.10	0.18/0.14	**0.23**/0.13	**0.39**/0.01	**0.35**/0.01

*If 15° downward gaze is included, these irradiances are reduced to 0.30–0.40 μW·cm^{-2}, and the other irradiances in bold are all reduced below 0.20 μW·cm^{-2}. If 15° downward gaze is included, all of the irradiances in bold are reduced below 0.20 μW cm^{-2}.

1. *Sitting persons*: As shown in Table 3a,b, the worst-case irradiances for sitting conditions were those incident on a horizontal plane, and these were calculated for wall paint reflectance = 0.35, and ceiling tile reflectance = 0.10–0.50. These irradiances ranged from 0.23 to 0.30 μW·cm^{-2}. At worst, this irradiance could only lead to an ocular dose in excess of the TLV if the exposed person looked up at the ceiling enough times for the exposure duration to exceed 5 h in a given work day (1), and would not pose an erythema risk for skin Type-II persons even after 12 h of continued exposure (5). This would not appear to pose a realistic risk for overexposures in workplace settings, although it seems possible that a hospital patient reclining in a bed for long periods could look at the ceiling long enough to receive an 8 h dose in excess of the TLV. This would pose some risk to the eyes, and possible skin risk for people with a sensitive skin type, or who may be taking photosensitizing antibiotics. This is qualitatively consistent with the results of a personal dosimeter study by First *et al.* (27), which included four hospital subjects who were either in bed or in a wheelchair. This study included some caveats that the personal dosimeters' exposure geometry cannot not perfectly replicate the exposure to the eye, and this could lead to overestimates in the measured doses. The maximum eye-level irradiances for

Table 5. Reflected 254 nm irradiance (μW·cm^{-2}) incident upon a vertical plane facing wall with fixture (standing/sitting). As shown, none of the calculated irradiances were potentially hazardous.

ρ Ceiling tiles	ρ Wall paint	Distance from back of UVGI fixture				
		0.46 m (1.5 ft)	1.37 m (4.5 ft)	2.29 m (7.5 ft)	3.20 m (10.5 ft)	4.11 m (13.5 ft)
(a) Male, 99th percentile						
0.05	0.10	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00
0.10		0.00/0.01	0.01/0.01	0.01/0.00	0.01/0.00	0.00/0.00
0.25		0.01/0.01	0.01/0.02	0.02/0.01	0.02/0.00	0.00/0.00
0.50		0.01/0.03	0.03/0.03	0.05/0.02	0.04/0.00	0.00/0.00
0.05	0.35	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00
0.10		0.00/0.01	0.01/0.01	0.01/0.04	0.01/0.00	0.00/0.00
0.25		0.01/0.01	0.01/0.02	0.02/0.01	0.02/0.00	0.00/0.00
0.50		0.01/0.03	0.03/0.03	0.05/0.02	0.04/0.00	0.00/0.00
(b) Female, 99th percentile						
0.05	0.10	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00
0.10		0.00/0.01	0.01/0.01	0.01/0.00	0.01/0.00	0.00/0.00
0.25		0.01/0.01	0.02/0.01	0.02/0.01	0.02/0.00	0.00/0.00
0.50		0.02/0.03	0.03/0.03	0.05/0.02	0.04/0.00	0.00/0.00
0.05	0.35	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00	0.00/0.00
0.10		0.00/0.01	0.01/0.01	0.01/0.04	0.01/0.00	0.00/0.00
0.25		0.01/0.01	0.01/0.02	0.02/0.01	0.02/0.00	0.00/0.00
0.50		0.01/0.03	0.03/0.03	0.05/0.02	0.04/0.00	0.00/0.00

those four subjects ranged from 0.27–0.79 μW·cm^{-2}, and the highest recorded daily dose for those four subjects was 1.25 mJ·cm^{-2}. This illustrated some reason for concern, although the daily doses in that study were still less than the 6 mJ·cm^{-2} TLV (1).

2. *Standing persons, irradiances incident upon horizontal plane*: For standing persons, some irradiances were potentially hazardous, but would not pose a hazard under realistic conditions. As shown in Table 3a,b, the potentially hazardous irradiances were determined for a variety of ceiling tile and wall paint reflectances, for persons facing the opposite wall from the UVGI fixture. The irradiances ranged from 0.23 to 0.74 μW·cm^{-2}. At worst, 0.74 μW·cm^{-2} would lead to an ocular dose in excess of the TLV after more than 2 h of exposure (1). This would not be likely unless the person looked repeatedly at the ceiling many times during the work day. This irradiance could only pose an erythema risk for skin Type-II persons after almost 8 h of exposure (5), and workers would be unlikely to stand in one location long enough during normal work activities for this to occur.
3. *Standing persons, irradiances incident upon vertical plane*: As shown in Tables 4a,b and 5a,b, the worst-case calculated irradiances from reflections ranged from 0.22 to 0.87 μW·cm^{-2}, for persons facing the opposite wall from the UVGI fixture. Whereas the tendency of room occupants to move during normal work activities would render low irradiances unlikely to pose a realistic UV hazard (*e.g.* persons standing near the wall and receiving 0.40 μW·cm^{-2} would require over 4 h of ocular exposure in a work day to exceed the TLV [1]), the highest irradiances would be a cause for some concern. For example, persons standing near the wall opposite the UVGI fixture would receive 0.87 μW·cm^{-2} reflected irradiance to the eyes and would require just under 2 h of ocular exposure to exceed the TLV (1). Whereas it seems unlikely that workers would stand for a sufficient amount of time at this location to accumulate a reflected dose that exceeds the TLV, this is the type of issue that would need to be addressed for safety reasons. In this example, the reflections could only pose an erythema risk for skin Type-II persons who stood near the wall for more than 6.5 h in a work day (5).
4. *Effect of downward gaze on reducing ocular hazard*: We noted in the Materials and Methods that, during normal tasks, the human eye tends to be directed at 15° below the horizontal (27). This would further reduce ocular exposure to UV radiation from in-room reflections. As shown in Table 4a,b, the worst-case calculated irradiances would then be decreased to 0.30–0.40 μW·cm^{-2}, for 99th percentile males, standing in close proximity to the wall, with $\rho = 0.35$.

5. *Skin cancer risk for this example*: These data are consistent with the CIE's position that exposure to outdoor sunlight is a much greater source of risk for NMSC than exposure to UVGI in the workplace. The worst case calculated irradiance in the above examples was 0.87 μW·cm^{-2}. If we multiply this irradiance by the CIE NMSC action spectrum's value for 254 nm, which is 0.0119, we obtain an NMSC-effective irradiance of 10.4 nW·cm^{-2}. This effective irradiance is more than 50 times less than the NMSC-weighted solar spectral irradiances that are typical for sunlight near the horizon, let alone for when the sun is higher in the sky (29).

DISCUSSION AND CONCLUSIONS

As mentioned in the Introduction, a properly designed and installed upper-room UVGI system should not directly expose the room occupants to UV emissions. Occupant exposure is then dependent on the amount of radiation reflected off upper-room surfaces like ceiling tiles and wall paints into the lower room. In this study, the measured 254 nm reflectances from ceiling tiles ranged from 0.035 to 0.459. These data may be used in computer aided design programs to help calculate the irradiance in a wide range of room dimensions and locations

(16,17). It should also be noted that UV reflectance is not a main quality of interest for ceiling tile manufacturers. Materials and manufacturing processes may change in the future to improve qualities, such as fire resistance, appearance, etc. It is possible that the tiles may be provided under the same description in the future, but the UV reflectances could be different.

Using our measurements, and the reflectance data for water-based paints obtained in other studies (18–20), we estimated the irradiance incident on horizontal and vertical surfaces for standing and sitting men and women whose heights were in the 99th percentile (24,25). The calculated irradiances could theoretically pose a hazard for persons who were sitting or reclining for long periods (*e.g.* hospital patients), especially if the person had a sensitive skin type or was taking photosensitizing antibiotics. However, none of the calculated irradiances appeared to pose a realistic hazard for normal workplace conditions, especially if a slight downward gaze is included to simulate the performance of normal tasks. This is qualitatively consistent with the results of a study of in-room exposures from upper room UVGI to 16 subjects at hospital, classroom and homeless shelter rooms (27). In that study, although some of the irradiances measured in that study would raise concerns for UV hazard, none of the measured 8-h doses exceeded the ACGIH UV hazard limit (1).

Our estimates are not a substitute for actual radiometric measurements, as wall surfaces may be composed of materials with significantly higher reflectance. For example, the reflectance of white plaster ranges from 0.4 to 0.6 (22). Such materials would need to be painted over with a paint or coating that reduces the 254 nm reflectance prior to the installation of a UVGI system. This study provides examples of the influence that the reflectance of ceiling tiles and paints can have on improving the safety of a UVGI installation. The IES has recommended that all upper-room surfaces that are likely to be irradiated have reflectances "as low as 5%" (20). This study is not only consistent with that statement but also suggests that higher reflectances than 5% could also be acceptable. Even if materials with relatively low UV reflectances are used, maintenance workers would still be required to follow standing operating procedures that include deactivating the UVGI source if it is necessary to perform any tasks in the UVGI source's emission plane. If the UVGI source cannot be deactivated, then personal protective equipment like face shields and clothes with tightly woven fabrics that cover the skin would be required (30).

Design and operation guidelines for the application of upper-room UVGI have been developed in other studies (31,32), although no application standard yet exists. These data on ceiling tiles may now be included as part of this discussion, if such a standard is developed. Design guidelines for upper-room UVGI with low-pressure mercury lamps should include not only a maximum reflectance of 0.10 for all upper-room surfaces but should also require that the facility pass an acceptance survey by a UV radiation safety officer, performed with a UV-C meter with diffusing optic with a calibration that includes the 254 nm wavelength. Any areas where more than 0.2 μW·cm^{-2} irradiance is measured for a horizontal or vertical surface should only be considered unsafe after a realistic assessment of the exposure duration for room occupants within those areas, as well as their movements during that period (9,30,31). It is very important to note that our sample calculations were based entirely on reflected UVGI. It is also not uncommon (in sufficiently large rooms) for there to be a direct line-of-sight to the UVGI lamp. The presence of a line-of-sight would depend on the spacing and depth of the louvers, the angle of the emitted beam, and the relative height between the exposed person and the fixture. In our example of a 12′ × 15′ room, this was not an issue. However, if the room dimensions were doubled in size, then a direct line-of-sight to the UVGI lamp would be possible for persons standing in the more distant areas of the room. First and Nardell *et al.* noted such risks in a discussion of UVGI lamps installed in a variety of settings (31), and suggested the use of baffles or sconces to block direct line-of-sight where necessary. This again shows the need to require that each facility with UVGI lamps pass an acceptance survey by a UV radiation safety officer, which has been noted in other studies (4,31).

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table S1. Total (diffuse & specular) reflectance.

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