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Occupant UV Exposure Measurements for Upper-Room Ultraviolet Germicidal Irradiation

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Abstract

The threshold limit value (TLV) guideline for ultraviolet (UV) radiation specifies that irradiance measurements to ensure occupant safety be taken over an angle of 80° at the sensor. The purpose of this study was to evaluate the effect of an 80° field of view (FOV) tube on lower room UV-C irradiation measurements.

Measurements were made in an experimental chamber at a height of 1.73 m with and without an FOV tube. The FOV tube reduced the lower room irradiance readings by 18-34%, a statistically significant reduction compared to the bare sensor.

An 80° FOV tube should be used for lower room irradiance measurements to comply with the TLV guideline. The resulting lower readings would allow more UV-C radiation in the upper room without compromising occupant safety. More UV-C radiation in the upper room could increase efficacy of UVGI systems for reducing transmission of airborne infectious diseases.

In addition, recommendations are made to standardize lower room irradiance measurement techniques.

Keywords

ultraviolet germicidal irradiation; threshold limit value; occupant safety measurements

1. Introduction

Ultraviolet germicidal irradiation (UVGI) has been shown to be effective in inactivating airborne microorganisms that cause diseases such as tuberculosis, smallpox, and influenza [1-3]. In particular, upper-room UVGI, which irradiates a horizontal layer of space in the upper part of an occupied room, is considered more effective than using UVGI in ducts because it has the potential to irradiate a larger volume of air in the same period of time [4].

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The application of upper-room UVGI generally involves specially designed fixtures mounted on a wall or suspended from the ceiling at a height greater than 2.1 m. Adequate air mixing, ideally provided with a ceiling fan, ensures that contaminated air moves from the lower into the upper room to be disinfected and then back down into the breathing zone. The fixtures contain low-pressure mercury lamps that emit UV-C radiation mostly at a wavelength of 253.7 nm, which is highly germicidal, yet minimally dangerous for human exposure compared to other UV radiation because of its shallow penetration depth [5]. Overexposure to 253.7 nm UV can lead to transitory photokeratitis and erythema, but is unlike UV exposure to wavelengths greater than 280 nm, which can cause skin cancers and permanent eye damage [4].

The American Conference of Governmental Industrial Hygienists (ACGIH) established a threshold limit value (TLV)—the dose to which a worker can be exposed eight hours a day, 40 hours per week for a working lifetime without adverse health effects—as a guideline for avoiding skin and eye injuries. Although the TLV for UV radiation varies with wavelength, the TLV for 254 nm can be applied for most upper-room UVGI fixtures because low-pressure mercury lamps emit mostly at this wavelength. The International Commission on Non-Ionizing Radiation Protection (ICNIRP), in collaboration with the World Health Organization (WHO), has adopted these same guidelines [5]. The TLV is expressed as a dose, in J/cm^2, the product of irradiance (in W/cm^2) and time (in seconds). For 254 nm, the dose limit is 6.0 mJ/cm^2. Thus, a worker can be exposed to an irradiance of 60 mW/cm^2 for 0.1 second or to 0.2 μW/cm^2 for eight hours. According to the ACGIH handbook on TLVs, the TLV values apply only to rays that hit inside an 80° cone from the face of the sensor. Specifically, the TLV states, "the sources may subtend an angle less than 80 degrees at the detector… for those sources that subtend a greater angle need to be measured over an angle of 80 degrees" [6]. Therefore, the readings taken with a bare sensor may overestimate irradiance when used for evaluating compliance with the TLV. The bare sensor needs to be modified to have an acceptance angle of 80° from the face of the sensor in order to accurately evaluate occupant exposure or dose in accordance with the TLV guideline. This can be accomplished by attaching an 80° field of view (FOV) tube to the sensor.

The goal of the present study was to evaluate the effect of using an 80° FOV tube on a UV-C sensor for lower room irradiance measurements. In addition, recommendations are given to standardize lower room measurement methods for upper-room UVGI applications.

2. Methods

In order to limit the rays hitting the sensor, an 80° field of view (FOV) tube can be positioned over the sensor housing. An FOV tube was manufactured by Gigahertz-Optik (Newburyport, MA) for their model 3718-2 UV sensor. The tube was made with the acceptance angle of 80° measured from the center of the sensor (α in Figure 1). The sensor with and without a Gigahertz tube is pictured in Figure 2.

2.1 Experimental chamber

Lower room irradiance measurements were conducted in a test chamber that has a 3.0 m by 4.6 m floor and a 3.0 m high ceiling. The floor is covered with vinyl tiles, and the walls and ceiling are covered with a pebbled, hard-finish, white plastic wallboard. The reflectivity of this wallboard was measured to be less than 10% at 254 nm [7]. The floor of the chamber was divided into a grid, specified by five columns, labeled 1-5, and seven rows, labeled A-G (Figure 3). Two Hygeaire Model LIND 24-EVO fixtures (Atlantic Ultraviolet, Hauppauge, NY), were mounted on the short walls (positions 2A and 4G) of the experimental chamber at a height of 2.6 m.

2.2 Irradiance measurements

Measurements were made using a Gigahertz-Optik model P-9710-1 optometer and a model UV 3718-2 flat UV sensor. The sensor was attached to a tripod such that the sensor's face was vertical, with its center at a height of 1.73 m to simulate a standing person looking straight ahead. For each measurement, the sensor was rotated horizontally 360°, with the face always kept vertical, to find the maximum irradiance.

Irradiance measurements were taken at 35 locations, separated from one another by 0.61 m, as indicated by circles in Figure 3. At each location, the maximum value was recorded for the bare sensor—the sensor without a FOV tube attached—and for the sensor with the FOV tube attached before the tripod was moved to the next location. After maximum irradiances at all 35 locations were measured, the procedure was repeated twice to assess measurement error.

3. Results

Using an 80° FOV tube reduced the lower room irradiance readings in every location (see Figure 4 and complete data in Appendix). A paired t-test showed a statistically significant reduction between the average values using the bare sensor and the sensor with the FOV tube (p = 7.25E-29).

The FOV tube reduced the lower room irradiance readings by 18-34%, depending on location, with an average reduction and standard deviation of 27.5% ± 3.85%. The average irradiance and standard deviation in the room were 0.082 ± 0.017 $\mu W/cm^2$ with the tube off and 0.060 ± 0.015 $\mu W/cm^2$ with the tube on. The largest reductions occurred near the center and side of the room (D1 at 34%; 2D, 3D, and 3C at 33%).

4. Discussion

The TLV handbook instructs that measurements be taken with an acceptance angle of 80° from the sensor because of humans' anatomical protection from overhead UV radiation sources. In the present study, using an 80° FOV tube reduced average irradiance readings by 18%-34%, depending on location. Thus, measuring lower room irradiance with a bare sensor overestimates UV exposure to lower room occupants, which is important because the safety of lower room occupants is a major consideration in the design of UVGI fixtures and the amount of UV-C radiation ultimately permitted in the room. Many designers of upper-room UVGI systems have adopted the practice of limiting the lower room irradiance at eye level to less than 0.2 $\mu W/cm^2$, which is the 8-hour time-weighted average (TWA) TLV based on the typical 8-hour workday [8]. To ensure this guideline is not exceeded, the UV-C output of fixtures is reduced; as a result, upper-room UVGI systems are extremely inefficient. If more UV-C radiation is permitted into the lower room, greater UV-C levels in the upper room would be possible as well, ultimately increasing efficacy of UVGI systems without compromising the safety of occupants. In this study, we concluded that up to 34% more 253.7 nm UV radiation could be added into the room with no adverse effects on lower room irradiance levels. However, these results are unique to our test chamber, and each space should be evaluated separately.

One of the major challenges encountered when designing the present study was the lack of a standardized method to measure lower room irradiance. The ACGIH, which issues the TLVs yearly, provides exposure limits but does not address how to perform the assessment. A standard method should be developed to provide clarity and allow comparisons to be made in future studies. The location of the sensor (i.e., height and orientation), the number and/or spacing of measurements taken, and the method for measuring 80° at the sensor should be specified. Each of these specifications is discussed in this section.

Other studies where lower room measurements were taken specify that these measurements should be taken at “eye-level,” defined as a height of 1.50 m by Miller et al. [9], 1.68 m by Nardell et al. [10], 1.73 m by First et al. [8], and 1.75 m in a NIOSH report summarizing results from several studies to give recommendations for UVGI systems [11]. In the present study, a height of 1.73 m was selected because it corresponds to the 95th percentile for male eye height in the USA [8]. For spaces that are consistently occupied by the same people (e.g. schools, offices), the height of the tallest occupant could be used to determine the height of lower room measurements. Although the heights used in previous studies are only slightly different, “eye-level” should be specified in the standard for lower room irradiance measurements to ensure consistency and replicability.

Orientation of the sensor face is not mentioned in any previous study, although First et al. used personal monitoring devices mounted on the chest, which suggest that the sensor face was close to perpendicular to the floor, as in our study [8]. Because the eyes are most vulnerable and also anatomically protected against UV radiation exposure from overhead sources by their deep-set position, horizontal measurements should be the norm when testing lower room irradiance for adherence to the TLV guideline. In settings such as hospital rooms, where patients may be laying down and looking up, vertical or line-of-sight measurements (i.e., pointing the sensor at the fixture) could be taken at bed-level as well. In a room with more than one fixture, the sensor should be rotated horizontally to face each fixture to find the maximum value.

The number and spacing of measurements is difficult to specify because it will differ based on the size of the space, reflectance of surfaces, and the number of UVGI fixtures used. In this study, a grid was created for repeatability and to ensure coverage of the entire space, but the maximum irradiance in the lower room may have been missed. First et al. recommend surveying a space “to find points of maximum irradiance” [8], and the NIOSH report similarly recommends “several locations throughout the room or area should be selected to make the measurements” [11]. In real-life applications, the method of searching for points of potentially high irradiance may be more practical than the grid method used in our study.

These “hot spots” can usually be easily predicted based on the positioning of the UVGI fixture(s), but surfaces reflecting UV-C radiation must be considered. Irradiance should be allowed to exceed 0.2 μW/cm^2 as long as occupants are not spending hours per day in the “hot spot.” The best approach is to use a personal monitor to determine if an occupant's dose exceeds the TLV during their daily routine.

The issue of 12-14 hour exposures is addressed elsewhere [5]. Even if an occupant spends 24 hours in the space (e.g. hospitalized patients), it is reasonable to assume that the eye undergoes continuous cellular repair, particularly at night, and that the exposure clock can begin again the next day [5].

Finally, the standard for measuring lower room irradiance should specify that an 80° FOV tube be used for adherence to the TLV guideline. The best method is to use a personal monitor with an 80° FOV tube attached. Because the reduction in lower room irradiance caused by the FOV tube changed depending on location in our test chamber, applying a correction factor is not recommended, at least not until further studies are conducted.

The Gigahertz-Optik FOV tube was designed with the acceptance angle measured from the center of the sensor, as is standard for FOV tubes for other applications (Bob Angelo, personal communication, October 28, 2013). Because the sensor is larger than a point, the acceptance angle will decrease with distance from the center, resulting in an acceptance angle of 77° on the perimeter of the sensor (θ in Figure 1) used in the present study; for sensors with larger diameters, the error at the perimeter would increase. This FOV tube restricts more rays from reaching the sensor and does not strictly comply with the TLV guideline. If the FOV tube is limiting the rays hitting the sensor to less than 80°, it is theoretically possible for occupants to be overexposed to UV radiation. To adhere more strictly to the TLV, the tube should be made with a height h that creates an 80° acceptance angle at the perimeter of the active sensor surface, resulting in a slightly larger acceptance angle elsewhere on the sensor surface. Although this is our recommendation, measuring the acceptance angle from the perimeter of the sensor will likely not impact lower room measurements significantly, especially with small diameter sensors. It is out of the scope of this study to determine how the 80° recommendation for the TLV was developed and how it should be interpreted. The design of the FOV tube should be clarified in the standard method for evaluating lower room irradiance levels to ensure consistency among manufacturers.

UVGI has proven effective at inactivating infectious airborne microorganisms that cause disease, but upper-room UVGI fixtures are inefficient because designers reduce fixture outputs to adhere to the 8-hour TWA TLV in the lower room without using an 80° FOV tube as specified by the guideline. Using an 80° FOV tube will ensure that the TLV guideline is met appropriately. Furthermore, without compromising the safety of occupants in the lower room, more UV-C radiation could be allowed in the room, thus increasing the efficiency of upper-room UVGI fixtures. A standard method to measure lower room irradiance should be published to reduce confusion for operators aiming to maximize the efficiency of their UVGI systems.

Acknowledgments

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Appendix

Table 1

All lower room irradiance data showing three trials with and without the 80° FOV tube in each of the 35 locations in the test chamber

	Bare Sensor			**Sensor with FOV Tube**		
Trial	**1**	**2**	**3**	**1**	**2**	**3**
A1	0.083	0.076	0.078	0.062	0.055	0.058
B1	0.070	0.070	0.066	0.053	0.046	0.047
C1	0.067	0.062	0.061	0.048	0.044	0.044
D1	0.062	0.068	0.062	0.042	0.043	0.041
E1	0.070	0.073	0.070	0.052	0.052	0.051
F1	0.074	0.075	0.071	0.053	0.054	0.052
G1	0.080	0.085	0.073	0.060	0.063	0.056
A2	0.089	0.084	0.085	0.066	0.063	0.062
B2	0.080	0.080	0.068	0.059	0.048	0.049
C2	0.071	0.068	0.066	0.050	0.046	0.045
D2	0.078	0.074	0.073	0.052	0.048	0.051
E2	0.086	0.080	0.081	0.065	0.059	0.058
F2	0.099	0.091	0.090	0.080	0.066	0.067
G2	0.104	0.101	0.102	0.079	0.075	0.078
A3	0.122	0.121	0.121	0.093	0.092	0.092
B3	0.090	0.090	0.096	0.064	0.064	0.061
C3	0.085	0.081	0.080	0.059	0.053	0.054
D3	0.082	0.079	0.079	0.054	0.053	0.053
E3	0.092	0.090	0.089	0.066	0.058	0.059
F3	0.139	0.130	0.132	0.117	0.106	0.106
G3	0.119	0.115	0.124	0.092	0.086	0.101
A4	0.103	0.101	0.096	0.078	0.073	0.070
B4	0.081	0.081	0.077	0.062	0.057	0.055
C4	0.080	0.075	0.079	0.059	0.055	0.057
D4	0.077	0.068	0.071	0.051	0.047	0.048
E4	0.076	0.074	0.075	0.053	0.052	0.053
F4	0.078	0.080	0.081	0.061	0.060	0.062
G4	0.097	0.098	0.100	0.075	0.070	0.079

	Bare Sensor			**Sensor with FOV Tube**		
Trial	**1**	**2**	**3**	**1**	**2**	**3**
A5	0.073	0.072	0.071	0.058	0.053	0.052
B5	0.066	0.066	0.063	0.047	0.043	0.045
C5	0.065	0.061	0.061	0.049	0.044	0.045
D5	0.067	0.060	0.064	0.048	0.041	0.045
E5	0.064	0.060	0.063	0.049	0.042	0.045
F5	0.070	0.073	0.070	0.056	0.054	0.053
G5	0.084	0.086	0.080	0.065	0.068	0.060

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Highlights

An 80° field of view tube should be used on flat UV-C sensors for safety measurements

The FOV tube reduced lower room irradiance readings by 18-34%

Lower readings allow more UV-C radiation without compromising occupant safety

Recommendations are made to standardize lower room irradiance measurement techniques

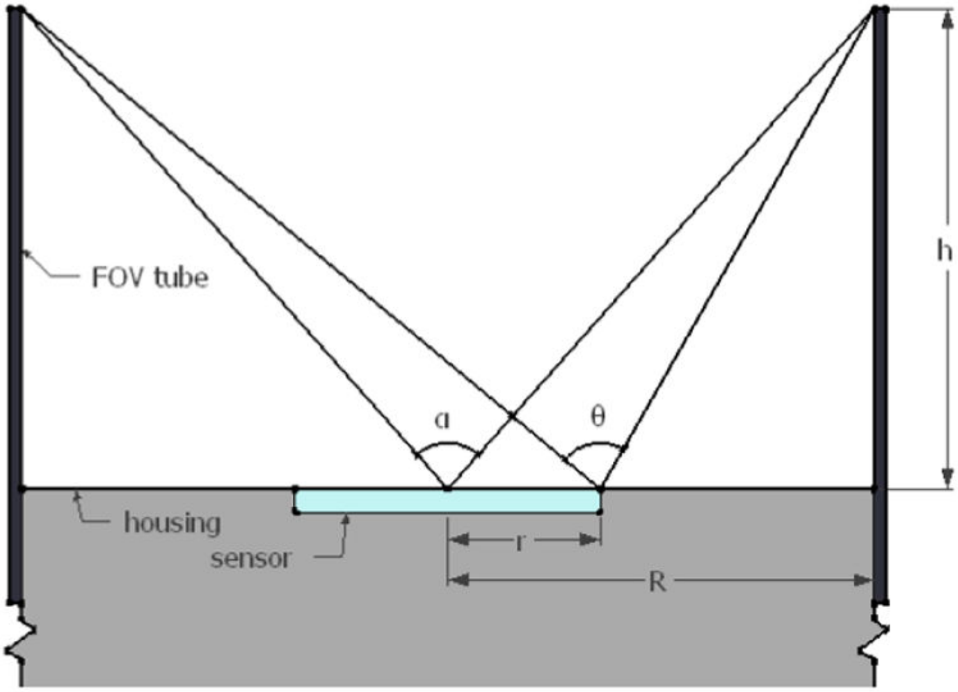

Figure 1. Section of sensor with FOV tube, where r is the radius of the sensor, R is the radius of the housing, h is the height of the tube, and θ and α are the acceptance angles from the perimeter of the sensor and the center of the sensor, respectively

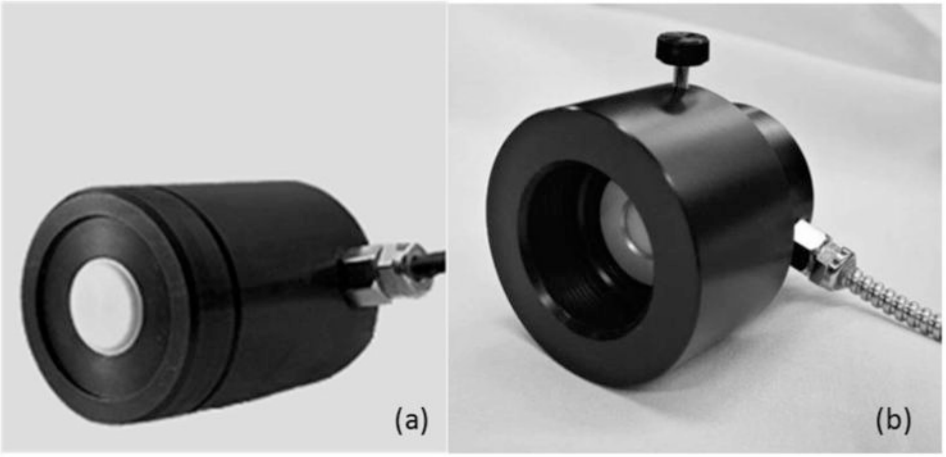

Figure 2. (a) A bare UV 3718-2 flat UV sensor and (b) the same sensor with an 80° FOV tube

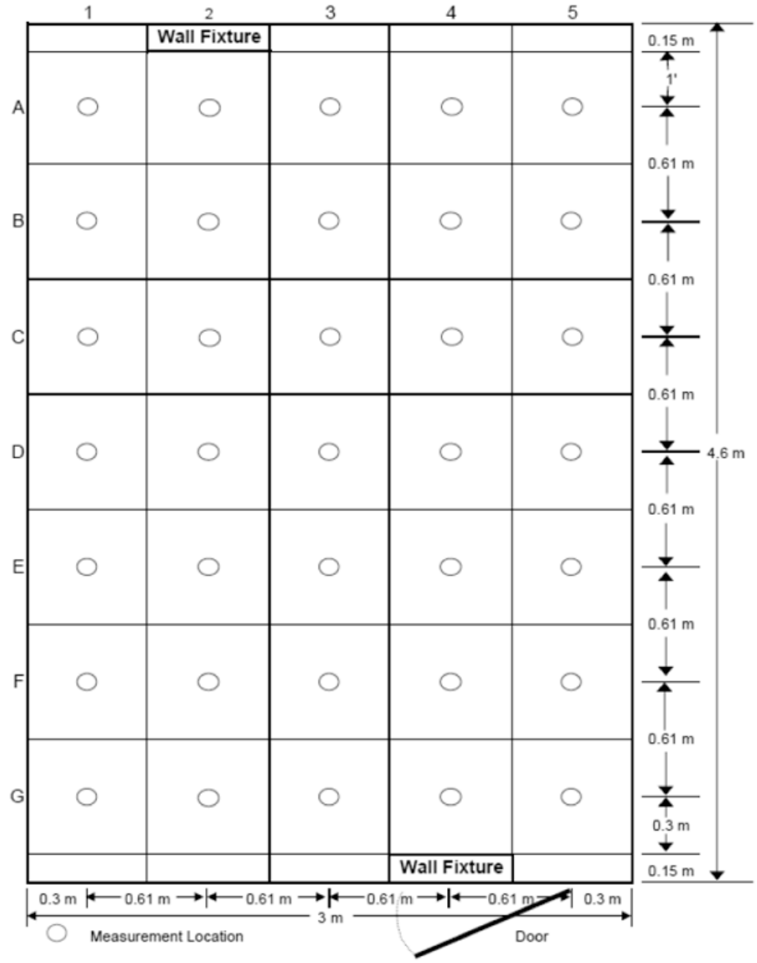

Figure 3. Plan view of experimental chamber setup, with two UVGI fixtures and chamber grid specifying measurement locations

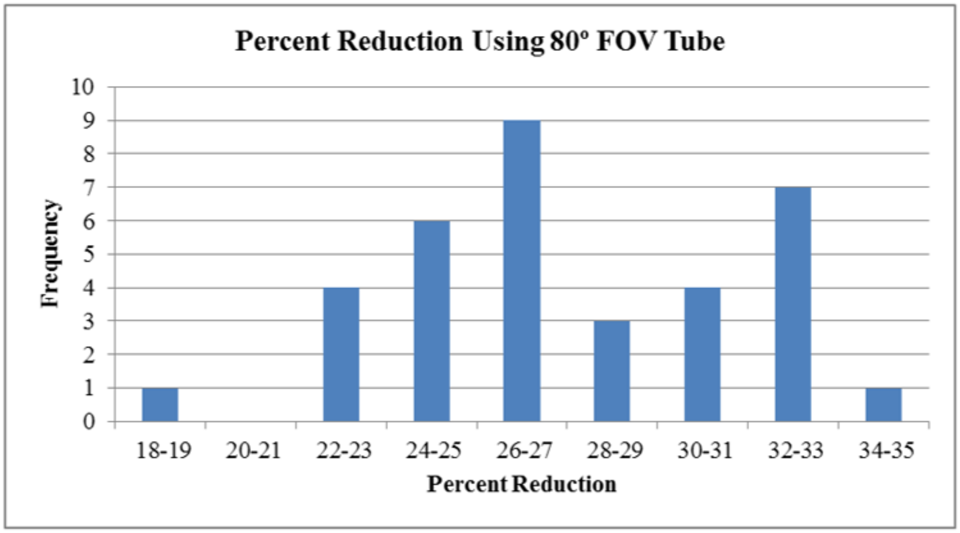

Figure 4. A histogram showing the percent reduction in irradiance using the FOV tube compared to the bare sensor.