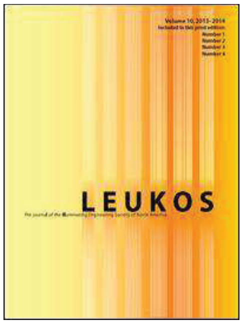

LEUKOS
The journal of the Illuminating Engineering Society of North America

ISSN: 1550-2724 (Print) 1550-2716 (Online) Journal homepage: http://www.tandfonline.com/loi/ulks20

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To cite this article: Stephen N. Rudnick & Edward A. Nardell (2017) A Simple Method for Evaluating the Performance of Louvered Fixtures Designed for Upper-Room Ultraviolet Germicidal Irradiation, LEUKOS, 13:2, 91-105, DOI: 10.1080/15502724.2016.1218774

To link to this article: https://doi.org/10.1080/15502724.2016.1218774

LEUKOS, 13:91–105, 2017

ISSN: 1550-2724 print / 1550-2716 online
DOI: 10.1080/15502724.2016.1218774

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A Simple Method for Evaluating the Performance of Louvered Fixtures Designed for Upper-Room Ultraviolet Germicidal Irradiation

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ABSTRACT The primary objective of the present work was to develop and validate a simple method for measuring the ultraviolet (UV) emission rate of louvered UV fixtures designed for upper-room ultraviolet germicidal irradiation (UVGI). A secondary objective was to compare the emission rates and energy usage of a few commercially available fixtures and explain the reasons for the differences observed. The ultraviolet emission rate of fixtures designed for upper-room UVGI is clearly an important metric for specifying the UV dosing requirements for a particular application—that is, determining how many UV fixtures should be installed in a given room. UV emission rate is also important for evaluating how efficiently the fixture utilizes the required electrical power input. The ratio of the UV emission rate to the electrical input is a useful parameter for ranking or improving fixtures. In this article, we describe "UV sensor traverse" and its validation. UV sensor traverse is a simple method for measuring UV emission rate by traversing the louvered face of a fixture with a UV sensor. Using this method, we show that a commercially available fixture with a cylindrical parabolic reflector with a tubular lamp has about 84% of the UV radiation exiting the fixture emitted from the back of the lamp, compared to only 21% for a fixture with a flat reflector and compact lamps. The energy-use efficiency of the former fixture is about five times greater than that of the latter fixture. In the fixture with the parabolic reflector, UV rays are redirected by the reflector so that they tend to be parallel to the louvers, allowing significantly more of the UV radiation emitted from the back of the lamp to exit the fixture than a fixture with a flat reflector, which simply alters the direction of the UV rays. To conserve energy and minimize the number of louvered UV fixtures required, well-designed parabolic reflectors are essential.

KEYWORDS air disinfection, upper-room GUV, upper-room UVGI, UV dosing, UV emission rate, UV sensor traverse

Received 20 March 2016; revised 25 July 2016; accepted 27 July 2016.

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1. INTRODUCTION

Airborne transmission of infectious disease is an important public health problem, particularly in resource-limited countries. Tuberculosis (TB), a disease spread essentially only by airborne transmission, ranks alongside HIV as the leading cause of death from infectious disease worldwide [World Health Organization 2015]. The common cold [Dick and others 1987], influenza [Tang and others 2009; Tellier 2006], SARS [Olsen and others 2003], measles [Ehresmann and others 1995], smallpox [Wehrle and others 1970], and anthrax [Weis and others 2002] are examples of other infectious diseases that are believed to be at least partly spread by the airborne route.

1.1. Upper-Room Ultraviolet Germicidal Irradiation

According to a National Institute of Occupational Safety and Health [NIOSH 2009] government report entitled *Engineering Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation Guidelines for Healthcare Settings*, upper-room ultraviolet germicidal irradiation (UVGI) has been shown in many experimental room studies to be very effective in reducing the airborne concentration of infectious agents. Subsequent to this report, by exposing guinea pigs to air removed from TB wards with and without upper-room UVGI turned on, Escombe and others [2009] and Mphahlele and others [2015] showed that upper-room UVGI was at least 70% to 80% effective for reducing airborne transmission of TB.

Effective and safe usage of upper-room UVGI requires that air in the upper portion of a room is irradiated adequately while ultraviolet (UV) radiation in the occupied lower portion of the room is kept below levels that are harmful to people. Due to these competing objectives, the UV radiation exiting a fixture and entering a room usually passes through deep, closely spaced, nearly horizontal louvers—at least for rooms that have ceiling heights of less than about 3.0 m (10 ft) [Riley and Nardell 1997]. The louvers create a slightly rising, nearly horizontally collimated UV beam above the heads of room occupants.

The UV dose received by infectious airborne particles, which determines the efficacy of an upper-room UVGI installation, depends primarily on two factors: (1) quantity of UV radiation supplied to the upper room and (2) air mixing—particularly air circulation between the upper and lower room. Either one of these can be the controlling factor [Rudnick and First 2007].

The location of fixtures in a room is also of fundamental importance. As a general rule, the mean UV ray length should be made as long as possible [Rudnick and First 2007]. Clearly, if UV radiation exits the fixture and immediately impinges on a UV-absorbing surface, such as a painted wall, the likelihood of the UV radiation inactivating pathogens will be greatly reduced.

The distribution of UV radiation in the upper room can also play an important role, particularly when room air is not well mixed. However, in the theoretical limit when the air in a room is truly well mixed, the spatial distribution of UV radiation would not be expected to be important. To ensure good mixing, NIOSH [2009] recommends the use of a ceiling fan, either blowing downward in the summer or upward at other times. Without a fan, the degree of mixing varies significantly because of buoyancy effects due to temperature gradients, air motion caused by mechanical ventilation and occupant motion, and pressure differences due to wind. However, in experimental tests conducted by McDevitt and others [2008], the efficacy of upper-room UVGI did not depend on buoyancy effects when a ceiling fan was used—that is, the ceiling fan appeared to overpower the effect of natural convection. In another study, improvement in efficacy could not be detected when the fan's turnover rate—defined as the quotient of a fan's air flow rate to room volume—was increased above about 65/h [Rudnick and others 2015], suggesting that at this rate and higher, adequate mixing was provided. A companion study using computational fluid dynamics came to the same conclusion [Pichurov and others 2015]. However, an air turnover rate of 65/h may lead to air velocities in the lower room that exceed the American Society of Heating, Refrigeration, and Air-Conditioning Engineers' Standard 55, "Thermal Environmental Conditions for Human Occupancy" [American Society of Heating, Refrigeration, and Air-Conditioning Engineers 2014].

1.2. Dosing Requirements for Upper-Room UVGI

The rule of thumb most commonly used for installation of upper-room UVGI for control of airborne transmission of tuberculosis, which was based on studies done by Richard Riley in his office at John Hopkins University [Riley and others 1976], is 30 W per 200 ft^2 of floor area (1.61 W per m^2), where W refers to watts of electrical power input to the lamps [Macher 1993; Riley and others 1976; Riley and Nardell 1989].

More recently, NIOSH [2009] published dosing guidelines for upper-room UVGI that were based on experimental studies that they funded at the University of Colorado [Miller and others 2002]. For effective killing or inactivation of airborne mycobacteria using louvered fixtures, NIOSH recommended either 1.87 W per m^2 of floor area or 6 W per m^3 of irradiated-zone volume, where W refers to watts of UV emission rate of the lamps, not the fixtures.

The emission rate of UV lamps is roughly 30% of the lamp's electrical input [First and others 1999]. Thus, if Riley's rule of thumb is restated on the basis of the UV emission rate of the lamps, it becomes 0.48 W/m^2, which is only one quarter of the NIOSH guideline of 1.87 W/m^2. This discrepancy is not surprising because Riley used open pendant fixtures without louvers, which emitted UV radiation vertically upward [Riley and others 1976]. Riley's office had high ceilings that made the use of open fixtures possible without overexposing room occupants to excessive UV radiation. Nevertheless, it has been common practice to also use Riley's rule of thumb for the installation of louvered UV fixtures.

Both NIOSH's guidelines and Riley's rule of thumb ignore the effect of fixture design on the fraction of a lamp's UV emission rate distributed to the upper room. Based on gonioradiometric measurements, the percentage of the lamp's UV emission rate that was emitted by three commonly used commercial louvered UV fixtures from two manufacturers varied from 1.2% to 5.6%, a factor of nearly five [Rudnick and others 2012].

Clearly, a better dosing guideline is the UV emission rate of the fixtures [Rudnick 2001], although the mean fluence rate in the room, which is difficult and time consuming to measure, is arguably an even better parameter as a dosing guideline. The mean room fluence rate ($\bar{F}$) can be calculated from a fixture's UV emission rate (P_F) [Rudnick and First 2007]:

$$\bar{F} = \frac{P_F \bar{d}}{V}, \tag{1}$$

where $\bar{d}$ is the mean ray length—that is, the distance, on average, from where the UV rays exit the fixture to where they strike a surface—and V is room volume.

In a recent study, Mphahlele and others [2015] exposed guinea pigs to air removed from TB wards. Based on (1) and the data collected in their study, they recommended 15–20 mW of UV emission rate from the fixtures per cubic meter of room volume with the additional requirement that fixtures should be positioned to achieve maximum ray length in the upper room.

For comparison purposes, NIOSH's dosing guideline [NIOSH 2009], which is discussed earlier in this section, can be revised because the UV emission rates of the same fixture models used in the University of Colorado study on which the guideline was based were measured in a previous study [Rudnick and others 2012). Based on these emission rates, the revised NIOSH dosing guideline becomes 13 mW of UV emission rate from the fixtures per cubic meter of room volume, which is closer to the 15–20 mW/m^3 recommended by Mphahlele and others [2015] than would have been expected.

1.3. Measurement of UV Emission Rate of Louvered Fixtures

A simple method for measuring the UV emission rate of louvered fixtures designed for upper-room UVGI based on a well-defined protocol is needed. The major objective of the present work was to develop and validate such a method, to use it to compare the emission rates and energy usage of a few commercially available fixtures, and to explain the reasons for the differences observed. This method could be used as a basis for manufacturers to improve their fixtures and for users to compare different models and brands of commercially available UV fixtures. As stated in Section 1.2, dosing guidelines can also be specified in terms of watts per square meters of floor area or watts per cubic meter of irradiated-zone volume or total room volume where watts refers to the UV emission rate of the fixture. Intuitively, watts per cubic meter of room volume would appear to be the better choice, at least if air mixing in the room is adequate, because room volume is related to the quantity of air that needs to be disinfected, all else being the same. Using the volume of the irradiated zone is probably a poor choice because it is a difficult parameter to quantify accurately due to the size and divergence of the UV beam, which are both specific to a particular fixture. Sophisticated methods are available for measuring UV emission rate, but they require relatively expensive equipment and expertise when used. An integrating sphere that is large enough to hold a UV fixture can be used to measure the fixture's emission rate [Kaufman and Christensen 1972]. Gonioradiometry can also be used to measure emission rate [Rudnick and others 2012; Zhang and others 2012]. However, although integrating spheres and gonioradiometry are available in commercial lighting laboratories for measuring visible light, these services are not presently available for the measurement of the UV emission rate of fixtures designed for upper-room UVGI. In this article, UV sensor traverse, a simple method for measuring emission rate of louvered fixtures designed for upper-room UVGI, is described. This method is analogous to determining air flow rate in a duct based on measuring air velocities using pitot-static tube traverses [Burgess and others 2004]. In this article, emission rates measured using UV sensor traverse are compared to those obtained using gonioradiometry and an integrating sphere.

2. MATERIALS AND METHODS

2.1. Instrumentation

We used a model P9710-1 optometer, which is programmable, and a model UV-3718-2 UV detector (Gigahertz-Optik GmbH, Türkenfeld, Germany) to measure and record UV irradiances at the louvered face of UV fixtures. According to the manufacturer, the UV detector has a relative calibration uncertainty of ±6.5% and its low-end resolution is 60 μW/m^2 (6 nW/cm^2); the optometer has an accuracy of ±0.2%. This optometer and detector system was factory calibrated but not within a year prior to the start of this study. However, after this study was completed, the device was compared with an identical calibrated device that was brand new. The error, defined as the difference in the readings between the new and old devices divided by the reading for the new device, was small: based on the means of seven pairs of measurements at approximately 2.5 W/m^2 (250 μW/cm^2) and 15 pairs of measurements at approximately 6 μW/m^2 (600 μW/cm^2), the errors were 1.2% and 0.14%, respectively.

As shown in Fig. 1, the cylindrical detector housing has a 37-mm diameter with a small segment of the cylindrical surface removed, leaving a flat rectangular surface. Only the slightly recessed, 11-mm-diameter center portion of the detector's face, which is also shown in Fig. 1 and hereafter referred to as the UV "sensing window," responds to UV radiation. The detector was designed for narrow-band UV sources emitting 254-nm UV radiation and was calibrated with a 254-nm UV source. It has a cosine-corrected field of view. The angular cosine corrections, which were supplied by the manufacturer, are compared with the cosine of the incidence angle in Fig. 2. This figure suggests that the detector may underestimate the irradiance at higher angles. However, up to about 50°, the error is <10%.

Electrical properties of the UV fixtures were measured using a Kill A Watt EZ Power Monitor (P3 International Corp., New York, NY, USA). Parameters measured included electrical power usage, power factor, voltage, and current.

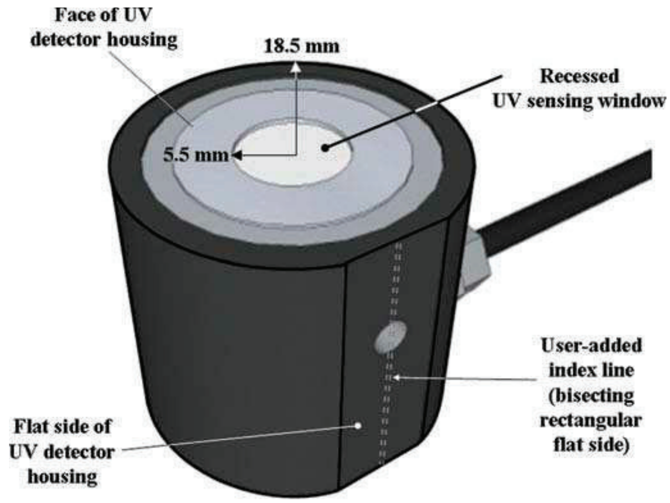

Fig. 1 A UV detector was used to measure irradiance at exit of fixtures.

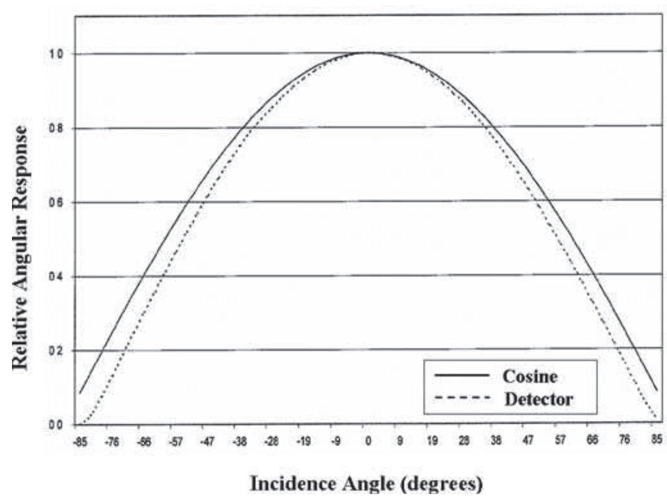

Fig. 2 Cosine correction curve is shown for the UV detector in Fig. 1.

2.2. UVGI Fixtures Evaluated

For the purpose of developing and validating a method for measuring UV emission rate of louvered fixtures designed for upper-room UVGI, we chose to evaluate the following three models of commercially available UV louvered fixtures:

1. Hygeaire wall fixture (model LIND24-EVO, Atlantic Ultraviolet, Hauppage, NY, USA)
2. Lumalier corner fixture (model CM-218, Lumalier Corp., Memphis, TN, USA)

3. Lumalier pendant fixture (model PM-418,[1] Lumalier Corp., Memphis, TN)

They were chosen because they are fixtures commonly purchased in the United States and their UV emission rates had been determined previously by Acuity Brands Lighting (Atlanta, GA, USA) using gonioradiometry [Rudnick and others 2012]. The lamps and reflectors in these fixtures were cleaned with ethyl alcohol prior to taking measurements.

A Hygeaire wall fixture, which is shown in Fig. 3, contains one 25-W Ster-L-Ray linear tubular lamp (model 05-1348-R, Atlantic Ultraviolet) that according to the manufacturer has an UV emission rate of 8.5 W; thus, 34% of the electrical input to the lamp is emitted as UV radiation. Hygeaire fixtures use electronic variable-output ballasts, which we always set to maximum UV output. The front of this fixture, which is shown in Fig. 3, includes a 102 mm × 610 mm louvered face—that is, the front edges of the fixture's 12 flat-black nearly horizontal louvers and the 6.35-mm openings on each side of these louvers through which UV radiation exits the fixture. The louvers are 76.2 mm deep. A cylindrical parabolic aluminum reflector is positioned behind the tubular lamp whose axis is at the focal line of the reflector. Its purpose is twofold: to (1) reverse the direction of the UV rays emitted from the back of the lamp so that they have an opportunity to exit the fixture and (2) modify the angle of these reflected UV rays so that they are nearly parallel to the louvers and, thus, likely to pass between the louvers and exit the fixture. The eight Hygeaire wall fixtures whose UV emission rates were measured in the present study had been used previously, two in research studies in our experimental chamber for a relatively brief time period and six for a large epidemiological study done in homeless shelters to determine whether upper-room UVGI could reduce airborne transmission of tuberculosis [Brickner and others 2000]. During the latter study, new lamps were installed annually. However, the history of these specific fixtures is not well documented.

A Lumalier corner fixture, which is shown in Fig. 4, contains two 18-W compact lamps (model TUV PL-L18W, Philips Lighting, Andover, MA, USA), each of which emits 5.5 W of UV radiation according to the manufacturer; thus, 31% of the electrical input to the lamp is emitted as UV radiation. A flat aluminum reflector is located behind the lamps. Its purpose is to reverse the direction of the UV rays emitted from the back of the lamp so that they have an opportunity to exit the fixture. The fixture has 32 flat-black nearly horizontal louvers with 6.35-mm air openings on each side of these louvers through which UV radiation exits the fixture. These louvers are 135 mm deep in the center of the fixture and taper to a depth of 75 mm at the edges of the fixture. As shown in Fig. 4, the entire vertical face of the fixture, which has a curved 387-mm-long front and a height of 242 mm, is louvered. The three Lumalier corner fixtures whose UV emission rates were measured in the present study had been previously used for a relatively brief time period in research studies in our experimental chamber.

The Lumalier pendant fixture, which is shown in Fig. 5, is cylindrically shaped and emits a nearly horizontally omni-directional UV beam. The fixture contains four 18-W compact lamps (model TUV PL-L18W, Philips Lighting), each of which has a UV emission rate of 5.5 W

Fig. 3 Hygeaire UV wall fixture.

Fig. 4 Lumalier UV corner fixture.

[1]Although Lumalier no longer manufactures the 72-W pendant fixture described here, this fixture had the same model number as the 72-W pendant fixture that Lumalier presently sells; however, the two fixtures have somewhat different exterior dimensions.

Fig. 5 Lumalier UV pendant fixture.

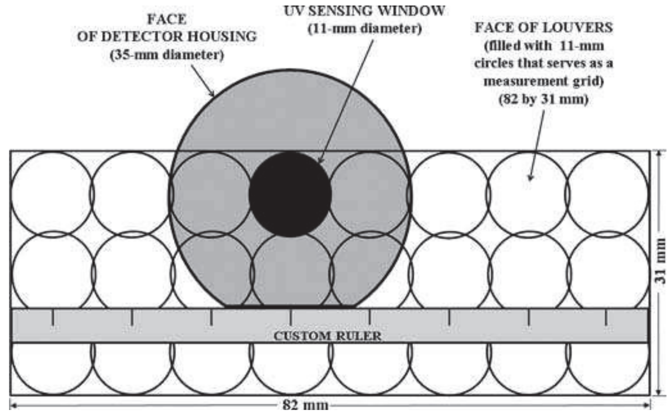

Fig. 6 Louvered face of hypothetical fixture is used to describe measurement procedure.

according to the manufacturer. This fixture, which does not contain reflectors, has 17 flat-black, nearly horizontal louvers with 6.35-mm air space on each side of a louver through which the UV radiation exits the fixture. The louvered surface of the fixture, shown in Fig. 5, has a 1.44-m circumference and a height of 230 mm and essentially covers the entire vertical cylindrical surface of the fixture. The Lumalier pendant fixture whose UV emission rate was measured in the present study was made by Lumalier specifically for a previous study [Rudnick and others 2012]; at that time, our objective was to use a pendant fixture that was the same model as the one used in the University of Colorado study [Miller and others 2002], which was the basis for NIOSH's guidelines discussed in Section 1.2, and that fixture was no longer manufactured. This fixture had been used only briefly [Rudnick and others 2012; Zhang and others 2012].

2.3. Measurement of UV Irradiance at the Fixture's Louvered Face

For a fixture designed for upper-room UVGI, the "louvered face" was defined as the front edges of the fixture's closely spaced, nearly horizontal louvers and the surrounding openings through which UV radiation exits the fixture and enters the upper room. The louvers are usually at a small angle to the horizontal ($\approx 4°$), so that when the UV beam exits the fixture, it rises slightly upward if the top of the fixture is level. This gradual rise helps to protect lower room occupants.

Figure 6 is a schematic diagram of the louvered face of a hypothetical fixture with the face of the UV detector (gray area), including its UV sensing window (black area), superimposed. The louvered face shown in this figure is relatively small (82×31 mm) compared to the louvered faces of commercially available upper-room UVGI fixtures. To provide a grid for irradiance measurements, we visualized the fixture's louvered face filled with circles whose radii are equal to the radius of the UV sensing window (5.5 mm) of the detector shown in Fig. 1. The circles are positioned so they have minimum overlap without being separated from each other. The circles on the perimeter of the louvered face just touch its border. For the louvered face shown in Fig. 6, there could be 7.45 circles (82/11) per horizontal row; however, in order to eliminate edge effects and have adjacent circles slightly overlapping each other, the number of circles in a horizontal row is rounded up to eight. Therefore, in each row, there are eight circles with their centers separated by 10.25 mm (82/8). Similarly, in the vertical direction, there are three circles per column whose centers are 10.33 mm apart (31/3). Thus, the louvered face contains 24 slightly overlapping circles.

The measurement procedure, which can be used for the louvered face of almost any commercially available upper-room UVGI fixture, was designed so that positioning the UV detector and measurement of irradiance for a specific location on the louvered face is relatively simple, rapid, and precise. For illustrative purposes, the hypothetical louvered face shown in Fig. 6 was used as a basis for explaining the measurement procedure described below:

1. **Note:** Eye and skin protection must be worn.
2. As shown in Fig. 1, a marker was used to draw an index line that bisects the flat rectangular surface of the detector's housing.[2]

[2]If the detector does not have a flat rectangular surface, then a vertical index line can be placed anywhere on the cylindrical surface of the detector housing.

3. A custom ruler was made whose length is the same as the width of the hypothetical louvered face shown in Fig. 6 (82 mm). The ruler's width and thickness can have any convenient dimensions. However, the thickness should be sufficient to allow the UV detector to slide along the ruler's edge. For louvered faces that are flat like the Hygeaire wall fixture, the custom ruler can be made from any material having a straight edge. If the louvered face is curved like the Lumalier fixtures, the custom ruler must be made from a flexible material, such as plastic, so that it can bend. For the present application, a bendable aluminum strip was used. For curved louvers, the sensor, which is flat, can theoretically be "rocked" slightly from side to side. However, based on geometric calculations, the maximum distance that the sensor can be rocked one way or the other for the Lumalier pendant and corner fixtures is 66 and 61 μm, respectively, which are about the diameter of a human hair and so small that that the technicians did not notice any rocking.
4. Marks that correspond to the centers of the eight circles contained in a row—that is, every 10.25 mm (82/8) for the louvered face shown in Fig. 6—are made on the ruler.
5. The ruler is taped to the fixture's face such that when the flat rectangular side of the detector's housing is resting on the edge of the ruler with its index line aligned with the first mark on the ruler and the face of the detector housing in physical contact with the edges of the louvers, the UV sensing window of the detector will be coincident with the first circle in the top row. The "enter" button on the optometer is pressed, thereby entering the measured irradiance into memory.[3] The detector is then slid horizontally such that the index line on the detector aligns with the second ruler mark. The enter button on the optometer is again pressed. This procedure is continued for each of the eight marks on the ruler. Because the detector's sensing window is slightly recessed, it does not make physical contact with the edges of the louvers, which might scratch the sensing window.
6. The ruler is then moved down 10.33 mm and taped so that the sensing window of the detector is coincident with the first circle in the second row of circles. Irradiance measurements are entered for all of the circles in the second row. This procedure is repeated for the remaining rows of circles.
7. In order to be able to estimate experimental error, the procedure described above is repeated at least three times.

Measurement of all specified irradiances for a particular UV fixture required time for setup that varied depending on the fixture. The measurement of UV emission rate for additional fixtures having the same model number was done fairly quickly. It took about 20 to 30 min depending on the size of the fixture's louvered face.

2.4. Evaluating Influence of Aluminum Reflector on Fixture's UV Emission Rate

To evaluate the influence of the aluminum reflectors in the Hygeaire wall and Lumalier corner fixtures, we covered the reflectors with black construction paper during one series of measurements in order to significantly reduce reflected UV radiation exiting the front of the fixture. Because the construction paper is flat black, it would be expected to reflect UV radiation poorly and diffusely; conversely, the aluminum reflector will tend to reflect UV radiation efficiently and specularly. Thus, when the black construction paper covered the reflectors, a significant portion of the reflected UV radiation exiting the fixture would be expected to be eliminated.

Initially, we had considered measuring the effect of the reflectors on UV emission rate more directly by making one set of measurements with the back half of the lamps covered with a UV-opaque material and another set of measurements with the front half of the lamp covered. We decided against this plan because the covering material would likely change the operating temperature and emission rate of the lamp [Bolton and Cotton 2008].

2.5. Minimization and Evaluation of Measurement Variability

The following parameters may affect the measured value of emission rates of UV fixtures: (1) room temperature, (2) burn-in time, (3) warm-up time, (4) intra-technician variability, and (5) inter-technician variability.

[3] It is worth noting that for some UV meters, such as a model number IL1400A light meter with a model SEL240 detector (International Light Technologies, Peabody, MA, USA) that we initially attempted to use, the UV irradiance at the face of the louvers will exceed the maximum irradiance that the instrument is capable of measuring. In addition, if the optometer does not data log, it is recommended that one person move the UV detector while another person reads the optometer and records the measured irradiance in order to minimize errors.

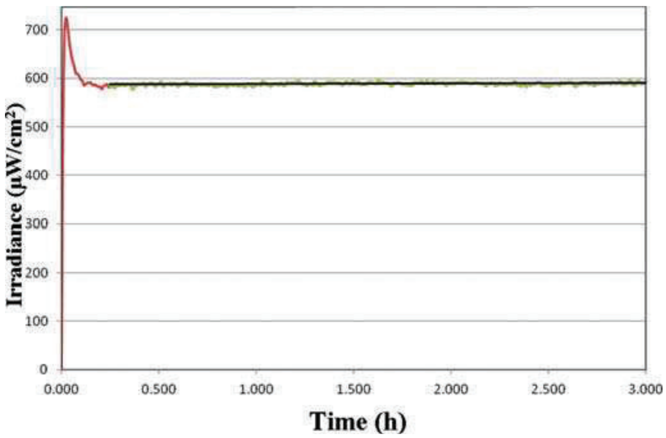

Fig. 7 Plot of thermal stabilization of Hygeaire UV wall fixture.

1. Because room temperature is known to significantly influence the UV emission rate of low-pressure mercury vapor lamps [Bolton and Cotton 2008], we recorded temperature using a HOBO temperature sensor (Onset Computer Corporation, Onset, MA, USA) while irradiance measurements were being made. The temperature ranged from 20.6°C to 22.1°C with a mean and standard deviation of 21.2°C and 0.3°C, respectively.
2. Because new fixtures tend to have higher UV emission rate for an initial relatively brief time period, all UV fixtures had been operated for at least 100 h prior to making measurements.
3. The emission rate of UV lamps is also known to vary as the fixture approaches thermal equilibrium. To determine the length of time required for the fixture's emission rate to stabilize, we positioned the Gigahertz-Optik UV-3718-2 UV detector 0.3 m away from the geometric center of the louvered face of the model LIND24-EVO Hygeaire wall fixture and recorded irradiance every 30 s for 3 h. As shown in Fig. 7, it took about 10 min for the irradiance to become constant. In order to be sure that thermal equilibrium had been reached, we waited at least 30 min after the fixtures had been turned on to take irradiance measurements.
4. To estimate experimental error, the technician repeated all measurements at least three times under the same operating conditions.
5. Three technicians who had never met each other measured the UV emission rates of a few of the same fixtures. Measurements were made by technician 1 in 2007, technician 2 in 2011, and technician 3 in 2013.

2.6. Calculation of Fixture's UV Emission Rate and Energy-Use Efficiency

The measured mean irradiance ($\bar{E}$) corresponding to all of the circles filling the louvered face of the fixture can be calculated from (2):

$$\bar{E} = \frac{1}{n}\sum_{i=1}^{n} E_i, \tag{2}$$

where n is the number of circles filling the fixture's louvered face and E_i is the UV irradiance for the ith circle. If we assume that the irradiance reading for each circle is representative of the section of the louvered face where it is located, a fixture's UV emission rate (P_F), the primary measure of an upper-room UV fixture's potential effectiveness, can be estimated from (3):

$$P_F = \bar{E}A, \tag{3}$$

where A is the rectangular area that encloses the louvers and all of the openings where UV radiation exits the fixture. For example, in Fig. 6, $A = 82\ \text{mm} \times 31\ \text{mm} = 2540\ \text{mm}^2$. Equation (3) can be easily modified to accommodate multiple rectangular areas, shapes other than rectangles, and areas free of louvers.

Because both the unsampled and double-sampled areas of the louvered face, which are shown in Fig. 6, are relatively small, and both are uniformly distributed over the louvered face, they would not be expected to have a significant impact on the calculated UV emission rate of the fixture.

Energy-use efficiency (η_e), a measure of the non-wasteful usage of electricity and defined as the fraction of electrical energy input that exits the fixture as UV radiation, is calculated from (4):

$$\eta_e = \frac{\bar{P}_F}{\bar{P}_E}, \tag{4}$$

where $\bar{P}_F$ is the fixture's mean UV emission rate in watts for a specified time period and $\bar{P}_E$ is the fixture's mean electrical power input in watts for the same specified time period. As discussed in Section 2.5, UV emission rate of the fixture and electrical power input to the fixture were both assumed to be constant after 30 min of operation. Energy-use efficiency accounts for energy losses due to fixture design and electrical components (for example, lamps and ballasts). For low-pressure mercury lamps, the energy-use efficiency will not exceed roughly 30%, which is approximately the percentage of electrical power input emitted by the lamp as UV radiation [First and others 1999]. However, in the future when UV LEDs will likely replace low-pressure mercury lamps, this percentage may become much higher.

An alternative metric to energy-use efficiency is fixture efficiency (η_f), which for visible light is generally referred to as luminaire optical efficiency:

$$\eta_f = \frac{\bar{P}_F}{\bar{P}_L}, \tag{5}$$

where $\bar{P}_F$ is the fixture's mean UV emission rate for a specified time period and $\bar{P}_L$ is the lamp's mean UV emission rate for the same specified time period. Although the lamps' nominal UV emission rate was specified by the manufacturers, we did not measure it in this study. Therefore, we did not calculate fixture efficiency.

3. RESULTS

3.1. UV Emission Rates

For each of eight different Hygeaire wall fixtures, which all have the same model number, we determined UV emission rates based on (2) and (3) at least three times. The means of these measurements are shown in Fig. 8 along with error bars corresponding to 95% confidence limits. If fixture H is excluded, emission rates varied from 0.432 to 0.496 W. For reasons that are unclear, the emission rate of Fixture H, which was confirmed by a series of three additional measurements, was considerably higher (0.559 W). The mean and coefficient of variation for the emission rates of the eight fixtures taken together were 0.477 W and 8.1%, respectively.

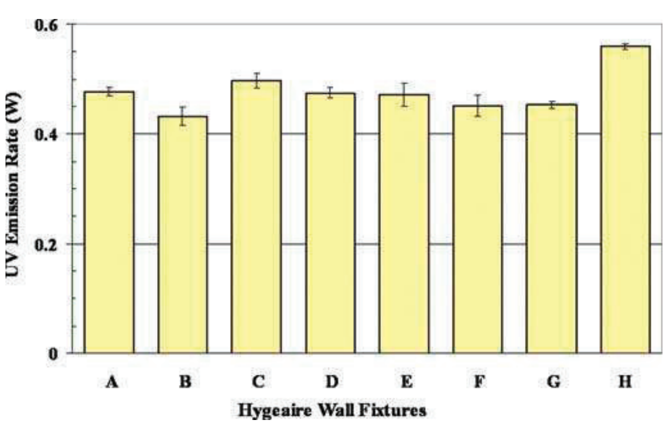

Fig. 8 **Mean UV emission rates for each of eight Hygeaire UV wall fixtures. Error bars correspond to 95% confidence intervals based on three independent measurements (except for fixture H, for which six measurements were made).**

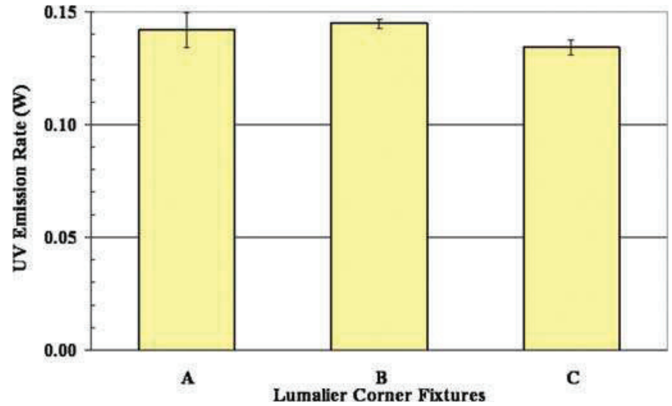

Fig. 9 **Mean UV emission rates for each of three Lumalier UV corner fixtures. Error bars correspond to 95% confidence intervals based on three independent measurements.**

Similarly, for each of three different Lumalier corner fixtures, which all have the same model number, mean UV emission rates and 95% confidence limits are shown in Fig. 9. The mean and coefficient of variation for the emission rates of the three fixtures taken together were 0.140 W and 3.9%, respectively.

For the single Lumalier pendant fixture, the mean and 95% confidence interval for the UV emission rate were 0.523 and 0.028 W, respectively.

3.2. Energy-Use Efficiency

Energy-use efficiency, which is defined by and calculated from (4), is shown in Fig. 10 for eight Hygeaire wall fixtures. Their efficiency varied from 1.73% to 2.23%. The

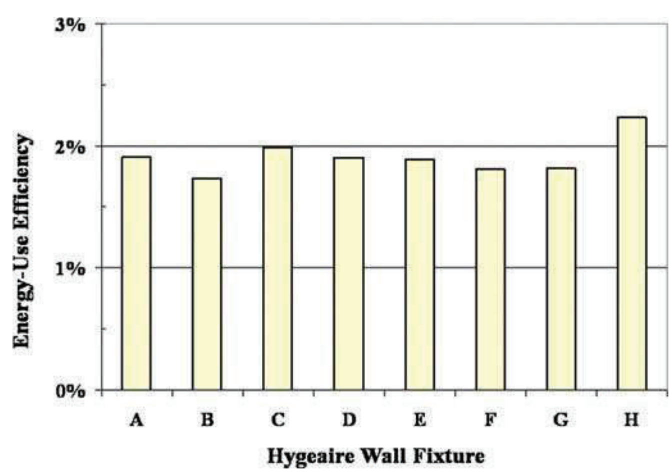

Fig. 10 **Mean UV energy-use efficiency of each of eight Hygeaire UV wall fixtures.**

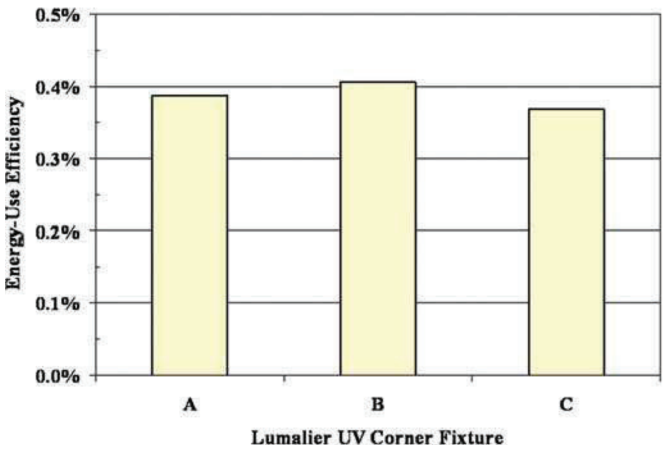

Fig. 11 Mean UV energy-use efficiency of each of three Lumalier UV corner fixtures.

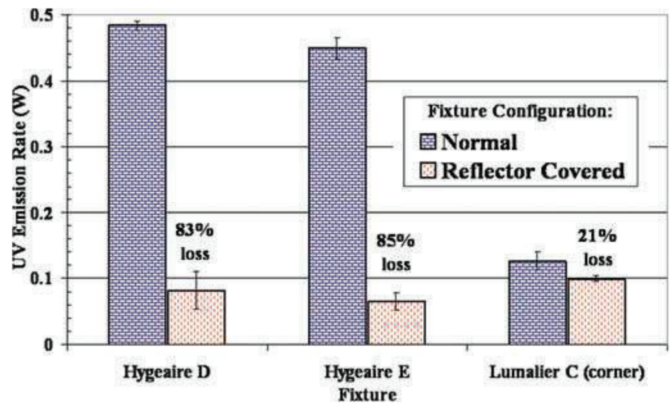

Fig. 12 UV emission rates for three fixtures with and without reflectors covered. Error bars correspond to 95% confidence intervals based on three independent measurements.

mean efficiency and coefficient of variation for the eight Hygeaire wall fixtures were 1.91% and 0.15%, respectively.

Figure 11 shows the energy-use efficiency for three Lumalier corner fixtures. Their efficiency varied from 0.37% to 0.41%. The mean efficiency and coefficient of variation for the three Lumalier corner fixtures were 0.39% and 0.018%, respectively.

The mean efficiency of the eight Hygeaire wall fixtures was about five times greater than that of the three Lumalier corner fixtures. The mean efficiency of the single Lumalier pendant fixture was 0.73%, nearly double that of the three Lumalier corner fixtures.

3.3. Influence of Aluminum Reflectors on UV Emission Rate

Figure 12 shows the UV emission rates of fixtures with and without the reflector covered with black construction paper, which would be expected to absorb most of the UV radiation that strikes it. When the reflector was covered, the fixtures' UV emission rates were reduced by an average of 84% for two Hygeaire wall fixtures and 21% for a Lumalier corner fixture. Thus, when the reflector is not covered, the percentage of exiting UV radiation that is emitted from the back of the lamp and then via the reflector exits the fixture is slightly more than 84% for the Hygeaire wall fixture and slightly more than 21% for the Lumalier corner fixture. In contrast, slightly less than 16% of the UV radiation exiting the Hygeaire wall fixture is emitted from the front of the lamp, whereas slightly less than 79% of the UV radiation exiting the Lumalier corner fixture is emitted from the front of the lamp.

3.4. Variation between Technicians

Figure 13 is a plot showing UV emission rate measurements taken by three different technicians on two specific Hygeaire wall fixtures (D and E) and a single Lumalier corner fixture (C) over a 6-year period. These fixtures got minimal or no usage during these 6 years. Error bars correspond to 95% confidence intervals based on three replicated measurements by technicians 2 and 3 and five by technician 1. Based on Fig. 13, agreement between the three technicians appears to be reasonably good. Nevertheless, a Students *t*-test indicates that measurements on Hygeaire wall fixture D by technicians 2 and 3 are statistically different at the 95% confidence level ($P = 0.042$), as are the measurements on Hygeaire wall fixture E by technicians 1 and 2 ($P = 0.046$). A one-way analysis of variance and Tukey's multiple comparison tests showed that measurements on the Lumalier corner fixture C by

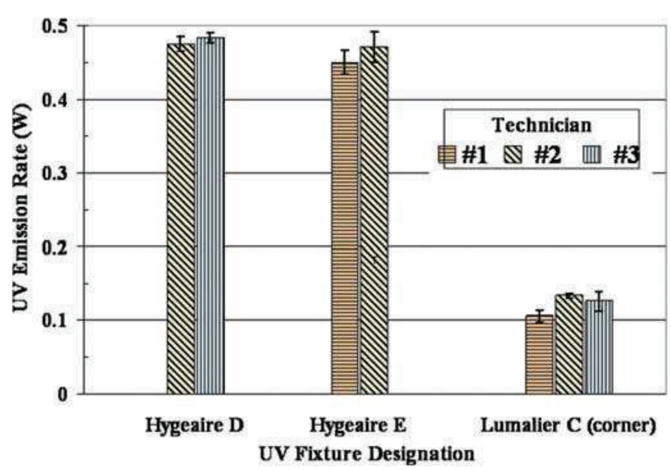

Fig. 13 UV emission rates measured by three technicians for three specific UV fixtures. Error bars correspond to 95% confidence intervals based on three or five independent measurements.

TABLE 1 UV emission rates by gonioradiometry and UV sensor traverse are compared

	Measurement method		% Error
	Gonioradiometry	UV sensor traverse	$\left(\frac{\text{Difference}}{\text{Mean}}\right)$
Hygeaire wall fixture E	0.473 W	0.471 W	0.42%
Lumalier corner fixture D	0.128 W	0.134 W	4.6%
Lumalier pendant fixture	0.591 W	0.523 W	12%

technician 1 were significantly different at the 95% confidence level than the measurements by both technicians 2 and 3. Measurements by technicians 2 and 3 on this fixture were not statistically significant different from each other.

3.5. Validation of UV Sensor Traverse Method

In a previous study [Rudnick and others 2012], gonioradiometry was used to measure the UV emission rate of Hygeaire wall fixture E, Lumalier corner fixture D, and the Lumalier pendant fixture. These three fixtures were also used in the present study. Table 1 compares the emission rates of these fixtures measured by gonioradiometry in this previous study with those measured by the UV sensor traverse method in the present study.

As can be seen from Table 1, agreement between the two methods was reasonably good. Depending on the fixture, the percentage error for each of the very different fixtures varied from 0.42% to 12%.

4. DISCUSSION

4.1. Influence of Fixture Design on UV Emission Rate

A comparison of Figs. 8 and 9 suggests that the Hygeaire wall fixture is preferable to a Lumalier corner fixture because the former emits about three and half times more UV radiation into a room while using less electricity. In addition, fewer UV fixtures are required for a specific application when a fixture's emission rate is high, so the first cost may be less.

Energy-use efficiency, which is the fraction of electrical energy input that exits the fixture as UV radiation, is arguably a more important parameter than UV emission rate. The higher the efficiency the lower will be the operational cost and generation of greenhouse gases. In addition, high efficiency is important where electrical power is scarce, particularly in resource-limited countries. The efficiencies of the Hygeaire wall fixture (1.91%), the Lumalier pendant fixture (0.73%), and the Lumalier corner fixture (0.39%) were all surprisingly low. The primary reason for these low efficiencies is the necessity to keep the UV irradiance in the lower, occupied portion of a room at a safe level. Nonetheless, there is clearly room for improvement.

The efficiency of the Hygeaire wall fixture was about five times greater than that of the Lumalier corner fixture and about two and half times greater than that of the Lumalier pendant fixture. A likely explanation for these differences is that the Hygeaire wall fixture has a linear lamp with a parabolic aluminum reflector, the Lumalier corner fixture has compact lamps with a flat aluminum reflector, and the Lumalier pendant fixture has compact lamps with no reflectors.

Ironically, despite the Hygeaire wall fixture's efficiency being five times that of the Lumalier corner fixture and its UV emission rate being three and half times that of the Lumalier corner fixture, to some people, the Lumalier corner fixture may appear to be superior to the Hygeaire wall fixture. This misconception is due to the rule of thumb for installation of fixtures for upper-room UVGI that has been commonly used for determining the number of fixtures required, as discussed in Section 1.2: provide 30 W/200 ft^2 (18.6 m^2) of floor area where watts refers to electrical power input to the lamps [Macher 1993; Riley and others 1976; Riley and Nardell 1989]. The Hygeaire wall and Lumalier corner fixtures require 25 and 36 W, respectively. Thus, based on this rule of thumb, 44% [(36 − 25)/25] more Hygeaire wall fixtures would be needed for a specific room than would be needed for the Lumalier corner fixture. This rule of thumb results in a "double whammy" when Lumalier corner fixtures are used rather than Hygeaire wall fixtures: (1) because more electricity is used to operate the Lumalier corner fixture, fewer fixtures will be installed and (2) because the Lumalier corner fixture's efficiency is lower, significantly less UV radiation per watt of electrical power input to the fixture is emitted into the room.

4.2. Variation in UV Emission Rate from Identical Fixtures

As shown in Fig. 8, for the same model Hygeaire wall fixture, the UV emission rate varied considerably for the eight fixtures evaluated; the range of emission rates was 27% of the mean. However, if fixture H is eliminated, this range is reduced to 13% of the mean. At least some of the variation is due to the length of time specific fixtures had been used previously. Nevertheless, the UV emission rate measured for fixture H was puzzling because it was significantly higher than the emission rate of the other seven Hygeaire wall fixtures. Switching lamps and ballasts did not change its emission rate. For confirmation, the initial series of three measurements on fixture H were repeated. However, all of the resulting six measurements were in excellent agreement with each other, suggesting that the higher emission rate for fixture H is real. The reason it was so high may be because the shape of the reflector and/or its location relative to the lamp are fortuitously nearly perfect. This explanation suggests that more precise manufacturing methods may result in an increase in emission rate of these fixtures.

4.3. Influence of Reflector and Lamp Geometry on UV Emission Rate and Energy-Use Efficiency

As discussed in Section 3.3, covering the reflectors in the Hygeaire wall and Lumalier corner fixtures resulted in the following two observations:

1. Slightly more than 84% of the UV radiation exiting the Hygeaire wall fixture is emitted from the back of the lamp and then exits the fixture via the reflector; the remainder of the exiting UV radiation is emitted directly from the front of the lamp.
2. In contrast, slightly more than 21% of the UV radiation exiting the Lumalier corner fixture is emitted from the back of the lamp and then exits the fixture via the reflector; the remainder of the exiting UV radiation is emitted directly from the front of the lamp.

As shown in the Appendix, 0.106 W of the UV radiation exiting Lumalier corner fixture C is emitted directly from the front of the lamps, whereas only 0.0281 W of the exiting UV radiation is emitted from the back of the lamps and via the reflector exits the fixture. Also from the Appendix, 0.0757 W of the UV radiation on average exiting Hygeaire wall fixtures D and E is emitted directly from the front of the lamp, whereas 0.397 W of the exiting UV radiation is emitted from the back of the lamp and leaves the fixture via the reflector. Thus, in marked contrast to Lumalier corner fixture C, which has about one fourth as much UV radiation exiting the fixture from the back of the lamps as from the front, Hygeaire wall fixtures D and E on average have about five times as much UV radiation exiting the fixture from the back of the lamp than from the front. This remarkable difference in the UV radiation emitted from the back of the lamp and then exiting the fixture strongly suggests that the reflector/lamp combination in Lumalier corner fixtures is very much inferior to that of Hygeaire wall fixtures.

Lumalier corner fixture C, which has two 18-W compact lamps, required 36.4 W of electricity, whereas Hygeaire wall fixtures D and E, which each has a single 25-W tubular lamp, on average required 26.0 W of electricity. If like Lumalier corner fixture C the Hygeaire wall fixtures D and E used 36.4 W instead of 26.0 W of electrical input, all else remaining the same, its energy-use efficiency would remain essentially the same based on (4). The exiting UV radiation it emitted directly from the front of the lamp would be 0.106 W ($0.0757 \times 36.4/26.0$), which is the same as the emission rate from the front of the lamps in the Lumalier corner fixture. However, the exiting UV radiation emitted from the back of the lamp in Hygeaire wall fixtures D and E would be on average 0.556 W ($0.397 \times 36.4/26.0$), which is about 20 times greater than the 0.028 W emitted from the back of the lamps in Lumalier corner fixture C. This factor of 20 and the fact that the exiting UV radiation emitted directly from the front of the lamp(s) is the same in both fixtures explains why the flat reflector and compact lamps in Lumalier corner fixtures are very much inferior to the parabolic reflector and tubular lamp in Hygeaire wall fixtures. The reflector in Hygeaire wall fixtures redirect UV rays so that they tend to be parallel to the louvers, allowing considerably more of the reflected UV radiation to exit the fixture than with the flat reflector in Lumalier wall fixtures, which tends to simply reverse the direction of the UV rays.

Because the Lumalier pendant fixture has no reflectors, compact lamps would likely perform as well in this fixture as other types of lamps, such as linear or circular tubular lamps. Essentially all of the UV radiation exiting this fixture comes directly from the lamps. Thus, the UV radiation is not horizontally collimated, so its energy-use efficiency (0.73%) is considerably less than that of the Hygeaire wall fixture (1.9%). However, because the UV radiation exits the Lumalier pendant fixture without interacting with a flat reflector, there are no losses due to this interaction, and its efficiency (0.73%) is thus greater than the Lumalier corner fixture (0.39%).

The energy usage of all three of these fixtures is very much less efficient than for the UV lamps contained in these fixtures, which, as mentioned in Section 1.2, is roughly 30%. Thus, significant improvement in the Hygeaire wall fixture and the Lumalier corner and pendant fixtures are theoretically possible. In order to conserve energy and to minimize the number of louvered UV fixtures required for a specific application, optimally designed parabolic reflectors are essential.

4.4. Additional Validation of UV Sensor Traverse Method

Measurements by other laboratories using the UV sensor traverse method provided further confirmation. The emission rate of an Ekran 0,4-0,6 upper-room UVGI fixture (Spetstekhnika-Vladimir, Ltd., Vladimir, Russia), which has been used extensively in Russian health care facilities, was determined using an integrating sphere and the sensor traverse method. This fixture is quite different from the fixtures used in the present study. It has three 940-mm-long louvers that are spaced 9 mm apart and a 940-mm-long opening with a width that can be adjusted from 22 to 92 mm. When the width was set at its maximum, the UV emission rate was measured to be 0.411 W using the UV sensor traverse method (personal communication, Grigory Volchenkov, MD, Vladimir Regional TB Control Center, Vladimir, Russia. Measurements using the UV sensor traverse method were made in his lab). and 0.407 W using an integrated sphere (Measurements using an integrated sphere were made in the laboratory of Prof. Wilhem Leuschner, Department of Electrical, Electronic & Computer Engineering, University of Pretoria, South Africa). Because the 92-mm-wide opening is considerably larger than the UV detector, the UV sensor traverse method described in Section 2.3 required minor modification.

Additional indirect confirmation of the UV sensor traverse method was obtained by comparison of our results with that of Mphahlele and others [2015]. After a more than 100-h burn-in period on a new Hygeaire wall fixture that was the same model as those tested in the present study, measurements with an integrating sphere gave an UV emission rate of 0.49 W. For the eight Hygeaire wall fixtures evaluated in the present study, the mean emission rate was 0.48 W.

4.5. Number of Fixtures Needed for Specific Applications

Measurements of the emission rates of fixtures using UV sensor traverse can be used to determine UV dosing requirements for a particular application—that is, the number of fixtures needed for a specific room. As an example, the NIOSH dosing recommendation for effective killing or inactivation of airborne mycobacteria, which was discussed in Section 1.2, is 6 W of lamp UV emission rate per cubic meter of irradiated-zone volume [NIOSH 2009]. As discussed in Section 1.2, the emission rate of UV lamps in a fixture and the emission rate of the UV fixture itself are not necessarily well correlated. In addition, because the UV beam diverges, the volume of the irradiated zone increases as the distance from the fixture increases and, thus, this volume can be difficult to measure. Fortunately, two of the fixtures whose UV emission rates were measured in the present study—Lumalier model CM-218 corner and model PM-418 pendant fixtures—were the same models that were used in the University of Colorado study on which the NIOSH dosing recommendations were based. Thus, the NIOSH recommendation can be restated in a more useful form—in terms of fixture UV emission rate per room volume. This modified NIOSH recommendation is 13 mW of fixture UV emission rate per cubic meter of room volume.

5. CONCLUSIONS

UV sensor traverse, a simple method for measuring UV emission rate of louvered fixtures designed for upper-room UVGI, was validated by comparison with measurements from gonioradiometry done by a well-known lighting manufacturer and measurements using an integrating sphere by a university lighting laboratory. Both gonioradiometry and integrating spheres utilize expensive instrumentation and equipment that require expertise and experience to be used properly. Integrating spheres are available in commercial lighting laboratories for visible light, but they are not suitable for measuring UV emission rates because of the low reflectance of the coating material. Commercial lighting laboratories in the United States do not presently use integrating spheres for sources below 350 nm (personal communication with lighting consultant Roff Bergman, who does accreditation audits for the National Voluntary Laboratory Accreditation Program, which is administered by the National Institute of Standards and Technology). Similarly, gonioradiometers are available in commercial lighting laboratories for visible light, but the labs are reluctant to invest in reconfiguring them for evaluating upper-room UVGI fixtures, which is at the present time a niche market. In addition, there is presently no standard method for performing gonioradiometry on UV fixtures designed for upper-room UVGI (0ersonal communication with Richard Vincent, Icahn School of Medicine at Mount Sinai New York, Community Medicine and TB UV Studies, chair of the National Commission on Illumination Committee TC 6-52 [Proper Measurement of Passive UV Air Disinfection Sources], which is drafting "CIE Guide for the Measurement of Upper Air Ultraviolet Germicidal Irradiation Luminaries Using Low Pressure Germicidal [Short Wavelength] UV-C Lamps," which will provide a standard method for UV gonioradiometry).

To perform UV sensor traverse, all that is needed is a UV meter, which most people involved with upper-room UVGI, such as fixture manufacturers, installers, researchers, and consultants, already own. UV sensor traverse is a valuable tool for improving fixture design and manufacturing methods. For example, based on measurements made using this method, we showed that for a louvered fixture designed for upper-room UVGI, a tubular lamp with well-designed parabolic reflector will significantly outperform a compact lamp with a flat reflector or with no reflector at all.

UV sensor traverse is also useful for determining UV dosing requirements for a particular application—that is, the number of fixtures needed for a specific application. The commonly used rule of thumb requiring 30 W of electrical power input to the lamps per 200 ft^2 of floor area (1.61 W per m^2) is misguided and rewards fixtures for consuming more electrical power regardless of how much UV radiation they produce. The rule of thumb would more logically be based on the UV emission rate of the fixture per room volume.

Energy-use efficiency, which is the fraction of electrical energy input to the fixture that exits it as UV radiation, can be determined easily using UV sensor traverse and an electrical power meter. This efficiency is a useful index for ranking fixtures for energy conservation purposes, which is particularly important because upper-room UVGI is generally never shut off.

FUNDING

This work was supported by the Fogarty International Center of the National Institutes of Health (Award No. D43TW009379) and the National Institute for Occupational Safety and Health (Award No. 2R01OH009050).

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APPENDIX: THE CAUSE OF THE SIGNIFICANTLY LOWER ENERGY-USE EFFICIENCY FOR THE LUMALIER CORNER FIXTURE THAN FOR THE HYGEAIRE WALL FIXTURE

For the following calculations, we assumed that if a reflector is covered with black construction paper, no reflected UV radiation exits the fixture from the back of the lamp. (In reality, although the black construction paper will reflect UV radiation poorly and diffusely, a small percentage of the UV radiation exiting the fixture will nevertheless be emitted from the back of lamp.)

From Fig. 9, the UV emission rate of Lumalier wall fixture C is 0.134 W. From Fig. 12, about 21% of this UV radiation is emitted from the back of the lamp, strikes the reflector, and finally exits the fixture. Consequently, about 79% or 0.106 W (0.79 × 0.134) of the exiting UV radiation is emitted directly from the front of the lamp and only 0.028 W (0.21 × 0.134) of the exiting UV radiation is emitted from the back of the lamps.

Similarly, from Fig. 8, the mean UV emission rate of Hygeaire wall fixtures D and E is 0.473 W. From Fig. 12, on average about 84% of the UV radiation exiting Hygeaire wall fixtures D and E is emitted from the back of the lamp and via the reflector exits the fixture. Consequently, about 16% or 0.0757 W (0.16 × 0.473) of the exiting UV radiation is emitted directly from the front of the lamp and 0.397 W (0.84 × 0.473) of the exiting UV radiation is emitted from the back of the lamp.

Lumalier wall fixture C, which has two 18-W compact lamps, required 36.4 W of electricity, whereas both Hygeaire wall fixtures D and E, which each have a single 25-W tubular lamp, required 25.6 and 26.4 W of electricity, respectively. If the lamp in Hygeaire wall fixtures D and E required 36.4 W of electricity, the same as the Lumalier wall fixture C, instead of a mean of 26.0 W [(25.6 + 26.4)/2], the exiting UV radiation emitted directly from the front of the lamp would be 0.106 W (0.0757 × 36.4/26.0), which is the same as the direct emission rate from the front of the lamps in the Lumalier corner fixture. However, the exiting UV radiation emitted from the back of the lamp in the Hygeaire wall fixture would be 0.556 W (0.397 × 36.4/26.0), about 20 times greater than the 0.0281 W emitted from the back of the lamp in the Lumalier corner fixture.

The difference in overall emission rate between these fixtures is due to the difference in the amount of reflected UV radiation exiting the fixtures, which is the result of having a parabolic reflector and tubular lamp in the Hygeaire wall fixture and a flat reflector and compact lamps in the Lumalier corner fixture. If the reflector and lamp combination in the Lumalier corner fixture was as good as in the Hygeaire wall fixture, both fixtures would have essentially the same UV emission rate (after normalizing for the difference in electrical input) and the same energy-use efficiency.