A simple method for evaluating the performance of louvered fixtures designed for upper-room UVGI

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Abstract

The ultraviolet emission rate of fixtures designed for upper-room ultraviolet germicidal irradiation (UVGI) is clearly an important parameter 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 determining energy-use efficiency—the ratio of a fixture's UV emission rate to the required electrical power input—which is a parameter that can be used to rank and to improve fixtures. In this paper, we described and validated "UV sensor traverse," a simple method for measuring UV emission rate by traversing the louvered face of a fixture with a UV sensor. Using this method, we showed that a commercially available fixture having a cylindrical parabolic reflector with a tubular lamp has about 84% of the UV radiation exiting the fixture emitted from the back half of the lamp, compared with only 21% for a fixture having 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 cylindrical parabolic reflector, UV rays are redirected 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 changes the direction of the UV rays.

Keywords

air disinfection; upper-room UVGI; louvered UV fixture; UV sensor traverse; UV emission rate; UV dosing

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, is of worldwide concern because more adults die from it than any other infectious disease other than AIDS [1]. The common cold [2], influenza [3] and [4], SARS [5], measles [6], smallpox [7], and anthrax [8] 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

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According to a U.S. government report entitled “Engineering Control for Tuberculosis: Basic Upper-Room Ultraviolet Germicidal Irradiation (UVGI) Guidelines for Healthcare Setting,” upper-room UVGI has been shown in many experimental room studies to be very effective in reducing the airborne concentration of infectious agents [9]. Subsequent to this report, Escombe et al. [10] and Mphahlele et al. [11] showed that upper-room UVGI could be 70 to 80% effective for reducing airborne transmission of tuberculosis (TB) by exposing guinea pigs to air removed from TB-patient wards with and without the upper-room UVGI turned on.

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) [12]. 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 [13]. Where fixtures are located in a room is also of fundamental importance. As a general rule, the mean UV ray length should be made as long as possible [13]. Clearly, if UV radiation exits the fixture and immediately impinges on a UV absorbing surface, such as a painted wall, the likelihood for the UV radiation to inactivate pathogens will be greatly reduced.

The distribution of UV radiation in the upper room also plays an important role, particularly when air mixing is insufficient. However, in the theoretical limit, for a room in which the air is truly well mixed, the spatial distribution of UV radiation is not important. To ensure good mixing, the National Institute of Occupational Safety and Health [9] 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 and air motion caused by wind, mechanical ventilation, and occupant motion. In experimental tests conducted by McDevitt et al., 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 [14]. In another study, improvement in efficacy could not be detected when the fan’s turnover rate—defined as the quotient of a fan’s airflow rate to room volume—was increased above about 65/h [15], suggesting that at least above 65/h, adequate mixing was provided. A companion study using computational fluid dynamics came to the same conclusion [16]. However, an air turnover rate of 65/h may lead to air velocities in the lower room that exceed ANSI/ASHRAE Standard 55-2013, “Thermal Environmental Conditions for Human Occupancy” [17].

1.2. Dosing requirements for upper-room UVGI

The UV emission rate of a fixture—that is, the UV power output of the fixture—is the best, easily measured single-number parameter for characterizing the potential of louvered UV fixtures to inactivate airborne pathogens [18] although the mean fluence rate in the room, which is difficult to measure, is probably a better single-number parameter. Based on experimental studies that they funded at the University of Colorado [19], NIOSH [9] published dosing guidelines for upper-room UVGI. For effective killing or inactivation of airborne mycobacteria, they 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 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 [20], is 30 W per 200 ft^2 (1.61 W per m^2) of floor area where W refers to watts of *electrical power input to the UV lamps* [21], [22], and [23]. The emission rate of UV lamps is roughly 30% of the lamp's electrical input [24]. Thus, if Riley's rule of thumb is restated on the basis of the UV emission rate of the lamp, 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 [20]. 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 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 the lamps' UV emission rate distributed to the upper room. Based on gonioradiometric measurements, the percentage of the lamps' UV emission rate that was emitted by three different commercial louvered UV fixtures from two manufacturers varied from 1.2% to 5.6%, a factor of nearly five [25].

By exposing guinea pigs to air removed from TB-patient wards, Mphahlele et al. in a recently published paper recommended 15–20 mW/m^3 of room volume where W refers to the UV emission rate of the *fixtures* [11].

1.3. Measurement of UV emission rate of louvered fixtures

A simple method for measuring UV emission rate and energy-use efficiency of louvered fixtures designed for upper-room UVGI based on a well-defined protocol is needed. 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. 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, W/m^3 of room volume would appear to be a 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 divergence of the UV beam and it is specific to a particular fixture. Sophisticated methods are available for measuring UV emission rate, but they require 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 UV emission rate [26]. Gonioradiometry can also be used to measure UV emission rate [25] and [27]. However, although integrating spheres and gonioradiometry are available in commercial laboratories for measuring visible light, these services are not readily available for the measurement of the UV emission rate of fixtures designed for upper-room UVGI. In this paper, 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 measuring airflow rate in a duct based on the use of pitot-static tube traverses to measure mean air velocity [28]. In this paper, emission rates measured using UV sensor traverse are compared to those obtained using gonioradiometry and an integrating sphere.

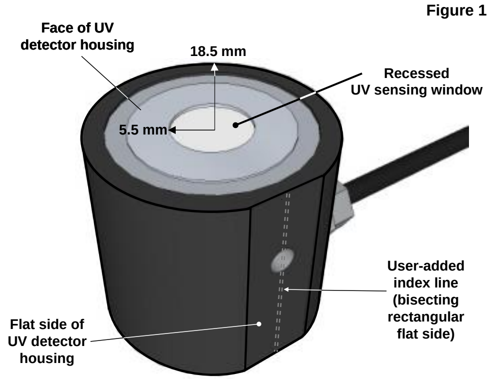
2. Materials and methods

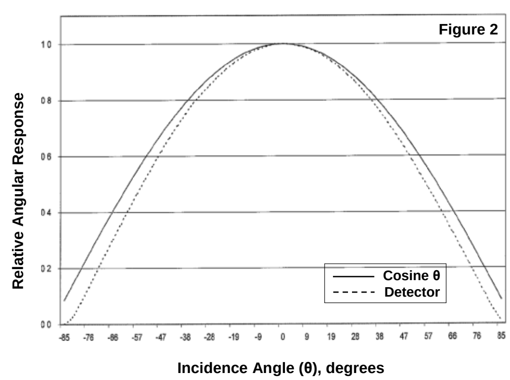
2.1. Instrumentation

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 irradiance at the louvered face of the UV fixture. According to the manufacturer, the UV detector has a relative calibration uncertainty of ±6.5% and its low-end resolution is 6 nW/cm^2; the optometer has an accuracy of ±0.2%. This optometer and detector system were 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 7 pairs of measurements at approximately 250 μW/cm^2 and 15 pairs of measurements at approximately 600 μW/cm^2, the errors were 1.2% and 0.14%, respectively.

As shown in Figure 1, the detector has an 18.5-mm radius cylindrical housing with a small segment of the cylindrical surface removed, leaving a flat rectangular surface. Only the 5.5-mm radius, slightly recessed center portion of the detector's face, which is also shown in Figure 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 Figure 2. This figure suggests that the detector may underestimate the irradiance at higher angles. However, up to about 50°, the error is <10%.

Figure 1





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

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)
2) Lumalier corner fixture (model CM-218, Lumalier Corp., Memphis, TN)
3) Lumalier pendant fixture (model PM-418,[2] Lumalier Corp., Memphis, TN)

They were chosen because they are fixtures commonly purchased in the USA and their UV emission rates had been determined previously by Acuity Brands Lighting (Atlanta, GA) using gonioradiometry [25]. The lamps and reflectors in these fixtures were cleaned with ethyl alcohol prior to taking measurements.

A Hygeaire wall fixture, which is shown in Figure 3, contains one 25-W Ster-L-Ray linear tubular lamp (model 05-1348-R, Atlantic Ultraviolet, Hauppage, NY), which according to the manufacturer has an UV emission rate of 8.5 W, and an electronic variable-output ballast, which we always set to maximum UV output. The front of this fixture, which is shown in Figure 3, includes a 102 mm by 610 mm "louvered face," which is defined as 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: 1) to reverse the direction of the UV rays emitted from the back half of the lamp so that they have an opportunity to exit the fixture and 2) to 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 for a relatively brief time period in research studies in our experimental chamber and six for a large epidemiological study done in homeless shelters to determine whether upper-room UVGI could reduce airborne transmission of tuberculosis [29]. During that latter study, new lamps were installed annually. However, the history of these specific fixtures is not well documented.

[2]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; the two fixtures have somewhat different exterior dimensions.

A Lumalier corner fixture, which is shown in Figure 4, contains two 18-W compact lamps (model TUV PL-L18W, Philips Lighting, Andover, MA), each of which emits 5.5 W of UV radiation according to the manufacturer. A flat aluminum reflector is located behind the lamps. Its purpose is to reverse the direction of the UV rays emitted from the back half of the lamp so that they have an opportunity to exit the fixture. The fixture has 32 flat-black nearly horizontal louvers with a 6.35-mm air space on each side of a louver through which the 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 Figure 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 Figure 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, Andover, MA), each of which has a UV emission rate of 5.5 W. 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 Figure 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 [25]; 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 [19], which was the basis for NIOSH's guidelines [9] discussed in Section 1.2, and that fixture was no longer manufactured. This fixture had been used only briefly ([25] and [27]).

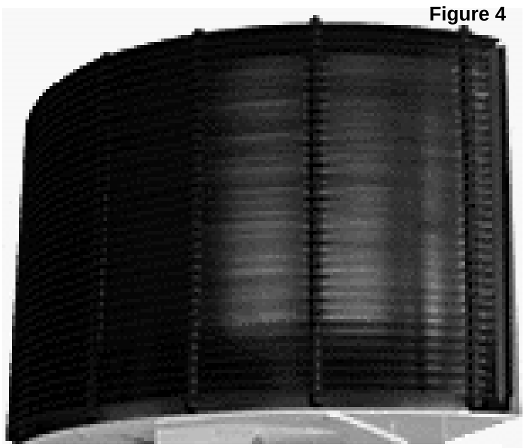


Figure 4


Figure 5

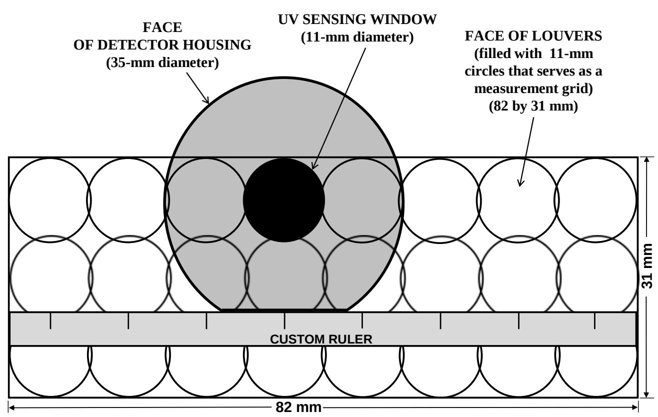
2.3. Measurement of UV irradiance at the fixture's louvered face

For a fixture designed for upper-room UVGI, the "louvered face" is defined as the front edges of the fixture's closely spaced, nearly horizontal louvers and the openings surrounding them through which UV radiation exits the fixture and enters the upper room. The louvers are usually at a small angle to the horizontal (≈ 4°), so that when the

UV beam exits the fixture, it rises slightly upward if the top of the fixture is level. This gradually 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, which is used below to describe the measurement procedure, is relatively small (82 by 31 mm) compared with 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 Figure 1. The circles are positioned so they have minimal overlap, without being separated from each other. For the louvered face shown in Figure 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 was rounded up to 8. Therefore, in each row, there are 8 circles with their centers separated by 10.25 mm (82/8). Similarly, in the vertical direction, there are 3 circles per column whose centers are 10.33 mm apart (31/3). Thus, the louvered face contains 24 slightly overlapping circles.

Figure 6



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

1) **<u>Note</u>:** eye and skin protection must be worn.
2) As shown in Figure 1, a marker was used to draw an index line that bisects the flat rectangular surface of the detector's housing.[3]

[3]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 is made whose length is equal to the width of the hypothetical louvered face shown in Figure 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 flexible aluminum strip was used.
4) Marks that correspond to the centers of the 8 circles contained in a row—that is, every 10.25 mm (82/8) for the louvered face shown in Figure 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 the memory.[4] The detector is 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 was repeated at least three times.

Measurement of all specified irradiances for a particular UV fixture requires setup time 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 minutes 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 set of measurements in order to significantly reduce reflected UV radiation exiting the front of

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[4]It is worth noting that for some UV meters, such as a model number IL1400A International Light meter with a model SEL240 detector (Newburyport, MA), which 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 readings.

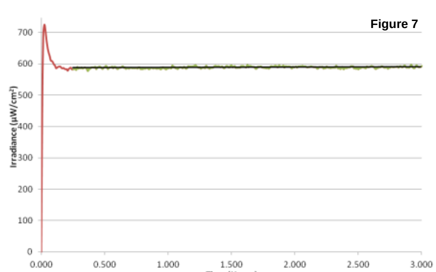
the fixture. Because the construction paper is flat black, it would be expected to reflect UV radiation poorly and diffusely; conversely, the aluminum reflector will tend to reflect UV radiation efficiently and specularly. Thus, a significant portion of the reflected UV radiation would be expected to 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 [30].

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-operator variability, and 5) inter-operator variability.

1) Because room temperature is known to significantly influence the UV emission rate of low-pressure mercury vapor lamps [30], we recorded temperature using a HOBO temperature sensor (Onset Computer Corporation, Onset, MA) while irradiance measurements were being made. The temperature ranged from 20.6 to 22.1°C with a mean and standard deviation of 21.2 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 hours 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 Figure 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, all measurements were repeated at least three times under the same operating conditions.
5) Three technicians who had never met each other measured the UV emission rates of fixtures designed for upper-room UVGI. Measurements were made by technician #1 in 2007, #2 in 2011, and #3 in 2013.



2.6. Calculation of fixture's UV emission rate and energy-use efficiency

The measured mean irradiance ($\overline{E}$) corresponding to all of the circles filling the louvered face of the fixture can be calculated from Equation 1:

$$\overline{E} = \frac{1}{n}\sum_{i=1}^{n} E_i \tag{1}$$

where n is the number of circles filling the fixture's louvered face and E_i is the UV irradiance for the i^{th} circle. If we assume that the irradiance reading for each circle is representative of the section of the louvered face where it is located, then a fixture's UV emission rate (P_f), the primary measure of an upper-room UV fixture's potential effectiveness, can be estimated from Equation 2:

$$P_f = \overline{E}A \tag{2}$$

where A is the area of the rectangular region that encloses the louvers and *all* of the openings where UV radiation exits the fixture. For example, in Figure 6, A = 82 mm x 31 mm = 2540 mm^2. Equation 2 can be easily modified to accommodate multiple rectangular regions or other shapes. In addition, these regions can be free of louvers.

Because both the unsampled and double-sampled areas of the louvered face, which are shown in Figure 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), a measure of the non-wasteful usage of electricity, is calculated from Equation 3:

$$\eta = \frac{P_f}{P_e} \tag{3}$$

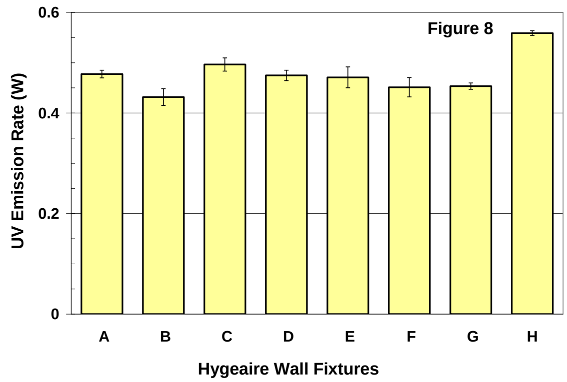
where P_e is the actual electrical power input to the UV fixture in watts. Energy-use efficiency accounts for energy losses due to fixture design, lamps, and electrical components (e.g., ballasts). For low-pressure mercury lamps, the energy-use efficiency cannot exceed about 30%, which is approximately the percentage of electrical power input emitted by the lamp as UV radiation [24]. However, in the future when UV LEDs will likely replace low-pressure mercury lamps, this percentage may become much higher.

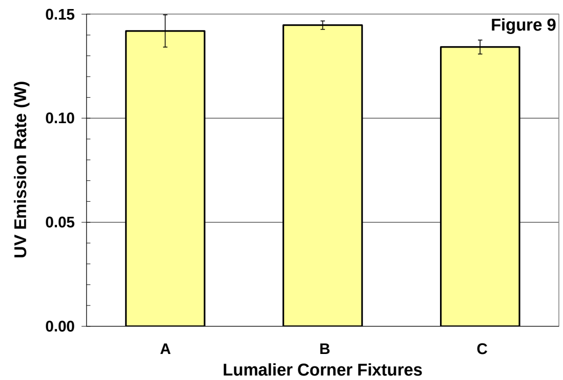
3. Results

3.1. UV emission rates

For each of eight different Hygeaire wall fixtures, which all have the same model number, we measured UV emission rates at least three times. The means of these measurements are shown in Figure 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.

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 Figure 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.





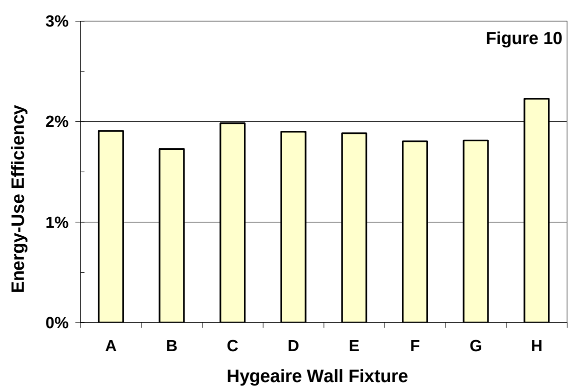
For the single Lumalier pendant fixture, the mean and 95% confidence interval for the UV emission rate were 0.523 W and 0.028 W, respectively.

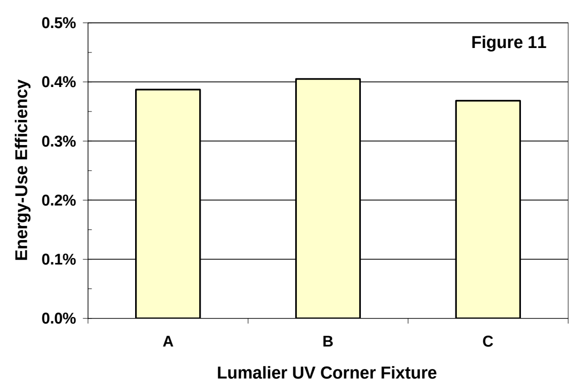
3.2. Energy-use efficiency

Energy-use efficiency, which is defined by Equation 3, is shown in Figure 10 for eight Hygeaire wall fixtures. Their efficiency varied from 1.73% to 2.23%. The 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.



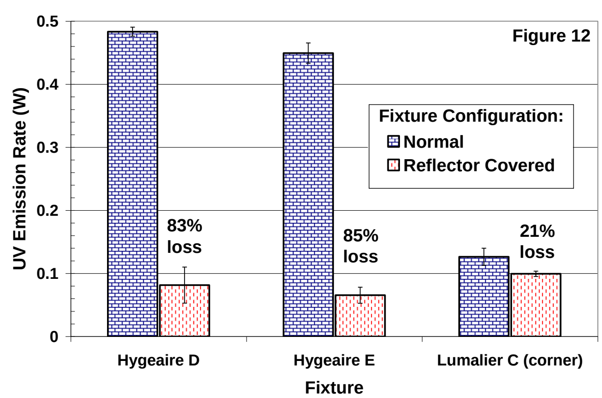


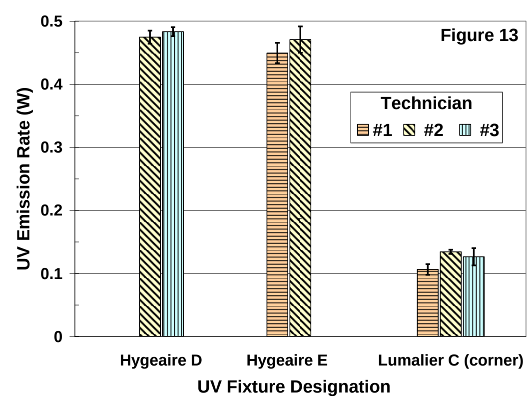
3.3. Influence of aluminum reflectors on UV emission rate

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 is covered, the fixtures' UV emission rate was 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 half 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 half of the lamp, whereas slightly less than 79% of the UV radiation exiting the Lumalier corner fixture is emitted from the front half 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 six-year period. These three fixtures got minimal usage during these six years. Error bars are based on three replicated measurements by technicians #2 and #3 and five by technician #1. Based on Figure 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 ANOVA analysis and Tukey multiple comparison tests showed that measurements on the Lumalier corner fixture C by technician #1 was 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 [25], 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:

Table 1.
UV emission rates of fixtures measured by gonioradiometry and UV sensor traverse

	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%

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 and conclusions

4.1. Influence of fixture design on UV emission rate

A comparison of Figures 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 power 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 efficiency 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 [21], [22], and [23]. The Hygeaire wall and Lumalier corner fixtures require 25 W 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 power 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 Figure 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. Using the UV sensor traverse method to measure the emission rates of fixtures may be helpful in improving manufacturing methods.

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

As discussed in Appendix A, 0.106 W of the UV radiation exiting the Lumalier corner fixture is emitted directly from the front half of the lamps, whereas only 0.028 W of the exiting UV radiation is emitted from the back half of the lamps and via the reflector exits the fixture. Also from Appendix A, 0.0757 W of the UV radiation exiting the Hygeaire wall fixture is emitted directly from the front half of the lamp, whereas 0.397 W of the exiting UV radiation is emitted from the back half of the lamp and leaves the fixture via the reflector. Thus, in marked contrast to the Lumalier corner fixture, which has about one fourth as much of the UV radiation exiting the fixture from the back of the lamps as from the front, the Hygeaire wall fixture has about five times as much of the 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 the Lumalier corner fixture is very much inferior to that of the Hygeaire wall fixture.

Lumalier corner fixtures have two 18-W compact lamps, whereas Hygeaire wall fixtures have a single 25-W tubular lamp. If like the Lumalier corner fixture, the lamp in a Hygeaire wall fixture used 36 W instead of 25 W of electrical input, all else remaining the same, its energy-use efficiency would remain essentially the same based on Equation 3. The exiting UV radiation it emitted directly from the front of the lamp would be 0.109 W (0.0757 x 36/25), which is very close to the 0.106 W that is emitted 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 0.572 W (0.397 x 36/25), which is about 20 times greater than the 0.028 W emitted from the back of the lamps in the Lumalier corner fixture. This factor of 20 and the fact that the exiting UV radiation emitted directly from the front of the lamp(s) is essentially the same in both fixtures explains why the flat reflector and compact lamps in the Lumalier corner fixture are very much inferior to the cylindrical parabolic reflector and tubular lamp in the Hygeaire wall fixture. The reflector in the Hygeaire wall fixture redirects 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 the Lumalier wall fixture, which simply changes 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 lamp. Thus, the UV radiation is not horizontally collimated, so its energy-use efficiency (0.73%) is considerably less than 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%). Nevertheless, the energy-use efficiency of all three of these fixtures is very much less than that of the UV lamps 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.

4.4. Validation of UV sensor traverse method

The primary objective of this paper was to propose and validate a simple method for measuring the UV emission rate for louvered fixtures designed for upper-room UVGI. This method, which we named “UV sensor traverse” because the entire louvered face of a fixture is traversed by a UV sensor in order to determine a mean irradiance, was compared to gonioradiometry. As discussed in Section 4.4, the emission rates measured by the two methods compared very favorably.

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 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 and 0.407 W using an integrated sphere.[5] Due to the 92-mm wide opening, the UV sensor traverse method required a minor modification of the method described in Section 2.3.

Additional indirect confirmation of the UV sensor traverse method was obtained by comparison of our results with that of Mphahlele et al. [11]. After more than 100-hour 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.

Both gonioradiometry and integrating spheres utilize expensive instrumentation and equipment that require expertise and experience to be used properly. They are both available in many lighting laboratories, but are usually designed for measurement of visible light and require modification to be used for UV radiation. The UV sensor traverse method requires only a UV meter with an adequate measurement range.

4.5. Applications of the UV sensor traverse method

For upper-room UVGI, some of the potential applications for the UV sensor traverse method are listed below:

1. Determining 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 m^3 of *irradiated-zone volume* [9]. 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 12.6 mW of *fixture* UV emission rate per m^3 of *room volume*.

[5]Personal communication with Grigory Volchenkov, MD, Vladimir Regional TB Control Center, Vladimir, Russia. Measurements using the UV sensor traverse method were made in his lab. Measurements using an integrated sphere were made in the lab of Prof. Wilhem Leuschner, Department of Electrical, Electronic & Computer Engineering, University of Pretoria, South Africa.

2. Evaluating the energy-use efficiency of UV fixtures—that is, the fraction of electrical power input that is emitted by fixtures as UV radiation. Efficiency is particularly important for fixtures used for upper-room UVGI because for most applications, fixtures are never turned off.
3. Improving the design of specific UV fixture models (e.g., optimizing parabolic reflectors and their positioning relative to the lamp and louvers).
4. Ranking UV fixtures from different manufacturers and for different models made by the same manufacturer.

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Appendix A. The reason for 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 half 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 half of lamp.)

From Figure 9, the UV emission rate of Lumalier wall fixture C is 0.134 W. From Figure 12, about 21% of this UV radiation is emitted from the back half of the lamp, then strikes the reflector, and finally exits the fixture. Consequently, about 79% or 0.106 W (0.79 x 0.134) of the exiting UV radiation is emitted directly from the front half of the lamp and only 0.0281 W (0.21 x 0.134) of the exiting UV radiation is emitted from the back half of the lamps.

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

Lumalier wall fixture C has two 18-W compact lamps, requiring a total of 36 W of electricity, whereas both Hygeaire wall fixtures D and E have a single 25-W tubular lamp, requiring 25 W of electricity. If the lamp in a Hygeaire wall fixture required 36 W of electricity instead of 25 W, the exiting UV radiation it emitted directly from the front half of the lamp would be 0.109 W (0.0757 x 36/25), which is very close to the 0.106 W that is emitted directly from the front half of the lamps in the Lumalier corner fixture. However, the exiting UV radiation emitted from the back half of the lamp in the Hygeaire wall fixture would be 0.572 W (0.397 x 36/25), very much greater than the 0.0281 W emitted from the back half of the lamp in the Lumalier corner fixture.

The difference in overall emission rate between these fixtures appears to be 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.

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