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Monitoring Human Exposures to Upper-Room Germicidal Ultraviolet Irradiation

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After decades of neglect, the resurgence of tuberculosis in the United States between 1985 and 1992 renewed interest in the use of upper room ultraviolet germicidal irradiation to interrupt the transmission of airborne infections. More recently the bioterrorism threat and the appearance of new pathogens with the potential for airborne spread, such as severe acute respiratory syndrome (SARS), have stimulated installations of upper-room irradiation systems. The objective is to flood the entire volume of a room above 6.5 ft with high intensity ultraviolet germicidal irradiation, while minimizing unintentional irradiance below 6.5 ft to avoid eye and skin irritation. Air exchanges between the upper and lower room result in air disinfection of the occupied space. Designers of these systems have adopted the practice of limiting the maximum lower room irradiance at every point to less than the continuous 8-hour time-weighted average threshold limit value, severely limiting the irradiation intensity in the upper room and thereby reducing one of the two major factors determining germicidal effectiveness, the other being room air mixing. The hypothesis of this study is that eye and skin exposure will be well below the recommended safe dose even when maximum eye-level irradiance levels in the room exceed the 8-hour continuous exposure threshold limit. The method employed was to have subjects wear a small photometer that recorded total ultraviolet dose over the period of exposure while subjects went about their normal routine, and comparing this value with a hypothetical dose calculated from the highest measured eye-level irradiance. The results of the study, based on a limited number of observations, confirmed the hypothesis. Observed doses were one-third to a factor of a hundred or more lower than the doses calculated from maximum eye-level irradiances measurements in the occupants' spaces.

Keywords airborne infections, ultraviolet germicidal irradiation, UV-C dose, UV-C exposure, UV-C monitor

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INTRODUCTION

The use of upper-room ultraviolet germicidal irradiation to prevent airborne communicable disease has become the subject of renewed interest. The resurgence of tuberculosis (TB) in the United States and other industrialized countries between 1985 and 1992 was the initial reason for increased attention, but more recently the threat of bioterrorism, the potential airborne spread of new pathogens, such as the severe acute respiratory syndrome (SARS) virus, and the continued threat of multidrug resistant tuberculosis (MDR-TB), have maintained interest. Although the germicidal properties of short wave ultraviolet irradiation, (180–280 nm, known as UV-C) have been known for a century, and despite numerous experimental trials to interrupt transmission of certain airborne infections during the first half of the 20th century, UV-C fell into disuse after World War II.[(1−3)] This has been attributed to the success of immunization practices for the control of some of the common respiratory viruses and the advent of chemotherapy for tuberculosis. However, the frailty of these medical advances is now apparent. Viral respiratory illnesses, some of them airborne, continue to cause morbidity and mortality despite the availability of vaccines. The threat of another influenza pandemic comparable to that of 1918–1919 is very real due to ongoing viral mutations. Like influenza and smallpox, SARS is thought to be spread predominantly by large droplets, an extension of direct person to person contact. However, the much more efficient airborne route has been demonstrated for influenza and smallpox, and most recently for SARS on a commercial airliner.[(4)] Despite chemotherapy, tuberculosis remains a major cause of death worldwide. Tuberculosis is almost exclusively an airborne infection, and much of the 1985–1992 resurgence occurred in congregate settings, among the homeless, those incarcerated, AIDS sufferers, and IV drug users. Finally, although smallpox has been officially eradicated, it remains a potential bioterrorism agent.

Although it is possible to disinfect air in ventilation ducts, and by self-contained room-air sterilizing devices, for most applications, upper-room UV is the method of choice because disinfecting the large volumes of the upper room is faster and more efficient. The objective is to flood the entire volume of the room higher than 6.5 ft above the floor with high-intensity UV-C irradiation. Below 6.5 ft it is necessary to minimize the level of UV-C irradiance in units of microwatts per square centimeter (μW/cm^2) in all regions of the occupied room because excessive exposure can cause painful but transitory eye irritation (photoketatoconjunctivitis) and mild skin reddening and irritation (photodermatitis). Eye cataracts and skin cancer are caused primarily by UV-B in sunlight, not by UV-C, which does not penetrate the earth's atmosphere and has extremely limited ability to penetrate the eye's cornea and skin's stratum corneum. However, corneal irritation has especially been recognized as an occupational hazard among arc welders (mostly UV-B) and has been assigned a threshold limit value (TLV®) by the American Conference of Governmental Industrial Hygienists (ACGIH®) Committee on Physical Agents.(5) Their recommendation is that the dose to the eyes should not exceed three millijoules per square centimeter (3.0 mJ/cm^2) during any continuous 8-hour period. This exposure limit was determined empirically through human and animal experiments.(6) To assist in the interpretation of the TLV, ACGIH gives a table of exposure intensities (μW/cm^2) and exposure times for various UV wavelengths that equal the maximum 8-hour recommended dose to the eyes.(5) In this table, 0.1 μW/cm^2 for 8 hours equals the TLV of 3 mJ/cm^2 for irradiance at the 270 nm wavelength, the wavelength that causes the most damage to nucleic acids. Most upper-room UV-C irradiation is emitted from low-pressure mercury arc lamps (like ordinary fluorescent lamps) encased in special tubular glass that is transparent to the principal wavelength ($>$60%) of 254 nm (the mercury line). The ACGIH table shows that a wavelength of 254 nm has one-half the biologically damaging (actinic) activity of 270 nm, making it acceptable to expose the eyes continuously for 8 hours to 0.2 μW/cm^2 of 254 nm irradiance without exceeding the current TLV for UV-C exposure, which is 6.0 mJ/cm^2 at 254 nm.

Although the recommended TLV for an 8-hour period for UV-C is unequivocally stated to be 6.0 mJ/cm^2, designers of upper-room germicidal irradiation systems have adopted a practice of using an optical measuring instrument and limiting stray and reflected irradiance levels in every spot in the lower 6.5 feet of irradiated spaces to no more than 0.2 μW/cm^2, as though every occupant might stare continuously at the nearest UV-C emitting source at the point of highest intensity for 8 hours. Although this practice effectively guarantees that no occupant will experience eye irritation, it also acts to severely limit the UV-C flux in the upper, irradiated zone, thereby potentially reducing germicidal effectiveness, which is the purpose of the installation. Of course, few room occupants stare at any one spot or remain in one position for 8 hours. Instead, most occupants normally move around more or less continuously even while working at a desk. This appears to be especially the case in high-risk common areas such as in shelters, jails, and hospital emergency rooms, although we are unaware of formal time-motion studies in these settings. Hospital personnel tend to move in and out of patient care areas with upper room UV. In homeless shelters where UV is used, residents are often milling about in common areas or sleeping under covers with their eyes shut for the majority of the time they are there. In grade school class rooms, while pupils at desks are usually well below any potentially harmful UV reflected from the upper room, their teachers are often standing and moving around the room. Although some workers' heads are commonly bowed, turning from task to task, increasingly they are focused on a computer screen. For that reason, reflections of upper room UV off a computer screen should be considered as a potential source of overexposure. Fortunately, the structures of the human head that provide highly effective shading for the eyes from UV irradiation from the sun also protect eyes from upper room UV.

These observations lead to the question of what should be the optimum balance between the maximum irradiance level in the upper room for germicidal effectiveness and the maximum level that should be permitted in the lower part of the room to assure eye and skin safety. The purpose of this study was to help resolve the dilemma by monitoring the TWA dose experienced by individuals performing their normal duties in facilities provided with upper-room germicidal irradiation. Our hypothesis is that point measurements of UV irradiance at eye level greatly exaggerate the dose received by room occupants under most circumstances. The study plan called for subjects to wear a personal UV-C monitor that continuously recorded irradiance and ultimately calculated the total dose received, as well as a continuous record of exposure over many hours. These data were compared with eye-level irradiance measurements taken in the same rooms with a handheld optical photometer in the same way an installation engineer does it to find maximum exposure locations. We then calculated the ratio between the two sets of measurements, the measured dose of a subject vs. the predicted dose based solely on the maximum measured eye-level irradiance in the occupied space.

METHODS

Instruments

Monitor

The personal monitor worn by the subjects was a small clip-on dosimeter manufactured by Gigahertz-Optic (model u.c.x2000 25 e.c.; Newburyport, Mass.). It contains two sensors; one responds to UV-A wavelengths (315–400 nm). Readings from this sensor were not used during this study. The second sensor responds to wavelengths in the UV-C, -B, and -A spectra and is designated by the manufacturer as "ACGIH photobiologically weighted" because its relative wavelength sensitivity closely follows the "ACGIH active responsivity," i.e., the table of actinic potency (relative spectral effectiveness) vs. wavelength published in the ACGIH's TLV listing.(5) The relative spectral sensitivity curve for the Gigahertz-Optik instrument is shown in Figure 1. Wavelength 270 nm, the most photobiologically active, shows at 1.0 on the relative scale whereas the 254-nm wavelength shows at 0.5, indicating that its relative actinic potency is as listed in the TLV document.

Radiometer

Direct measurement of irradiance was conducted with a hand-held International Light 1400A instrument (Newburyport,

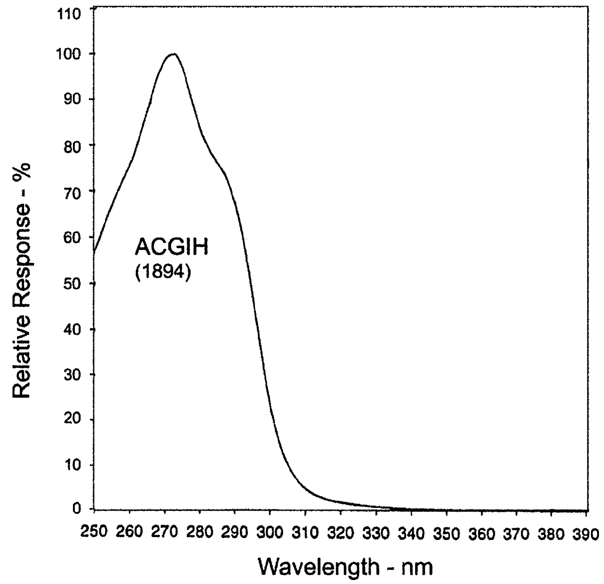

FIGURE 1. Relative spectral sensitivity for the Gigahertz-Optic instrument

Mass.) with an SEL 240 sensor. The relative wavelength response of this photobiologically "unweighted" UV-C, -B measuring instrument is shown in Figure 2. It appears from Figure 2 that the relative response for 254 nm is 0.9; however, using a low-pressure mercury light source with greater than 90% output at 253.7 nm, the manufacturer has electronically readjusted the output of our instrument to read 254-nm irradiance as 1.0, to display the corrected value on the meter. Due to its ACGIH "weighted" spectral sensitivity, the Gigahertz-Optik personal UV monitor displays its 254-nm readings at one-half the values shown on the International Light hand-held radiometer instrument when both are exposed to the same irradiance level. This means that the Gigahertz-Optik meter displays the effective ACGIH irradiance directly, where the IL meter reading must be halved to equal the photobiologically effective irradiance.

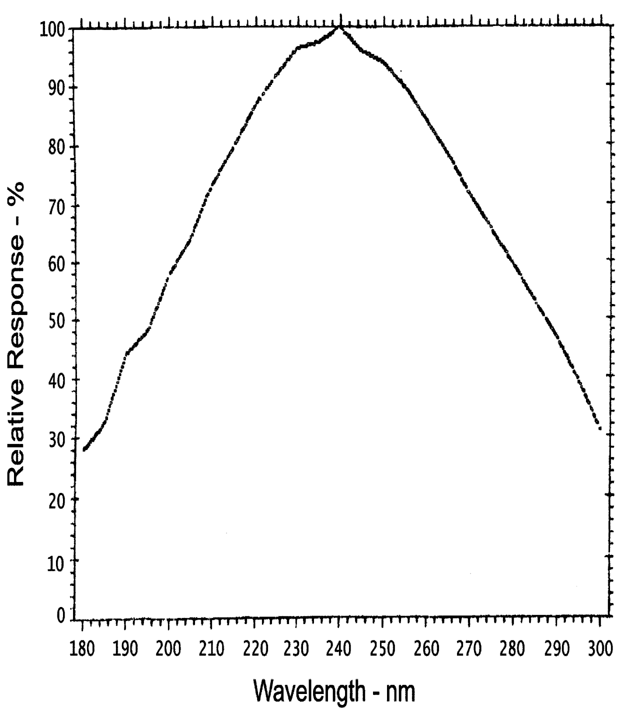

FIGURE 2. Relative spectral sensitivity curve for the International Light, Inc. 1400 A Radiometer with SEL 240 sensor

Emission Characteristics

Neither instrument responds to visible light, nor do they respond more than minimally to wavelengths of radiation emitted from fluorescent light fixtures. Although fluorescent lamps have used metallic mercury to initiate the arc, the glass used for these lamps is essentially opaque to the UV spectrum. Each of the instruments responds to a broad range of UV-C wavelengths, as shown in Figures 1 and 2, but 254 nm was the predominant wavelength present during the course of the entire study, and 254 nm was primarily what was measured since only low pressure mercury sources were employed in the study.

Both instruments were calibrated by their manufacturer at the start of the study and frequently checked against a reference instrument reserved for that purpose.

Study Protocol

Subjects were recruited in five categories: an office worker, shelter workers, nurses at a TB isolation hospital ward, TB patients immured at the same hospital, and a grade school teacher. On all subjects, the UV-C monitor was worn in the middle of the chest approximately one-inch below the top of the breastbone. The authors recognize that the chest monitoring location serves as a surrogate for eye and skin exposure, especially for the purpose of ascertaining the effects of subject movement on cumulative exposure readings.

The Institutional Review Board of Harvard School of Public Health reviewed and approved the protocol and the verbal consent form used in the study.

Facilities and Work Environments

No changes or adjustments were made to the upper-room UV fixtures that were in regular use in the various settings prior to the beginning of the study. Subjects were asked to go about their normal routine without exception. The hospital fixtures had been in use for approximately 15 years and are of an older design, but well maintained, and had significantly higher outputs in the lower room compared to most current, tightly louvered fixtures. However, according to hospital administrators working on the TB ward during the entire period they were used, there have been no complaints of eye or skin irritation. Fixtures of a newer design have been in service in the homeless shelter for 6 years without complaints. Similar fixtures were in use in the office and school settings.

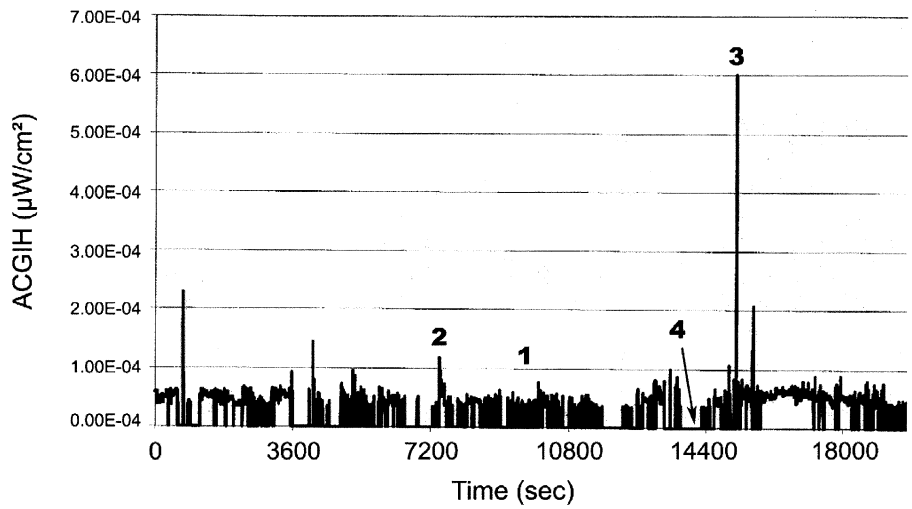

FIGURE 3. Optic-Gigahertz data recording for an office worker

Although there is interest in the magnitude of the doses measured, the principal objective of this study was to compare UV-C doses predicted by eye-level maximum point measurements in the lower room to time-weighted cumulative doses monitored by room occupants.

In all cases, the space(s) occupied by the subjects were surveyed with the International Light, Inc. meter to find points of maximum irradiance at a height from the floor of approximately 173 cm, or 95% of male eye height, a level chosen to assure maximum protection of room occupants. Then the Gigahertz monitor was clipped to the shirt of the subject and allowed to record uninterrupted for the monitoring period. At the termination of the exposure period, accumulated data stored in the monitor were printed in the form of a continuous record of irradiance vs. time of exposure plus summary data on maximum and minimum irradiance plus total dose. Figure 3 is a typical day's monitor record for an office worker.

Office Environment

The single-occupant office equipped with upper-room germicidal UV-C facilities (for experimental purposes) is shown in plan and elevation diagrammatic views in Figure 4. Typical

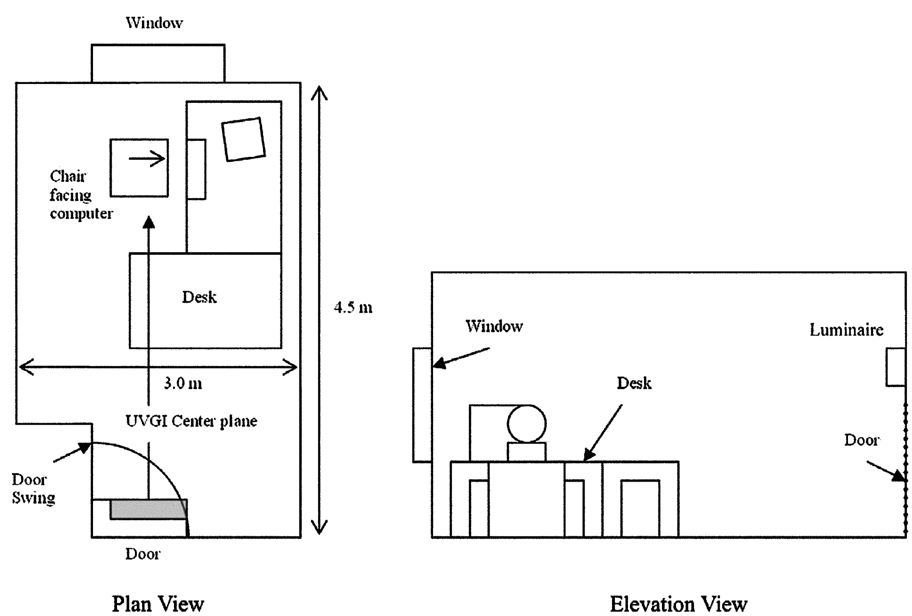

FIGURE 4. Diagram of office worker's room

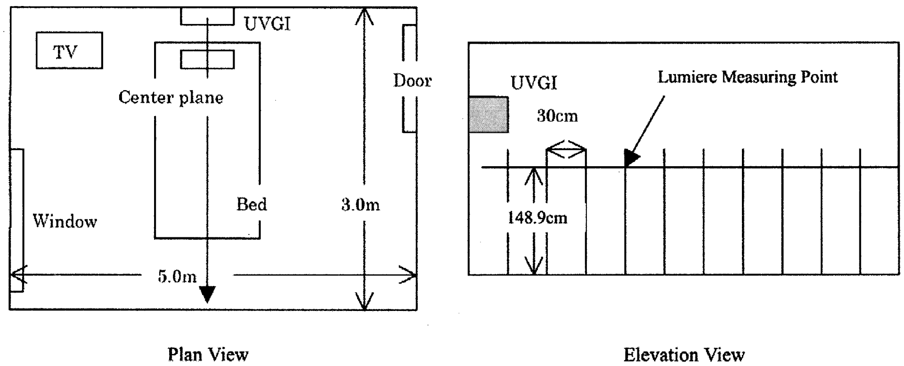

FIGURE 5. Diagram of patient's room

activities include reading and writing at the desk, using the computer, standing and greeting visitors, etc.

Nurse's Hospital Environment

The nurse subjects in this study work 12-hour shifts in a 14-room TB ward in an acute and chronic disease hospital.[7] Each patient room is equipped with a germicidal UV luminaire that directs its upper-room radiation over the patient's bed, as shown in Figure 5. Nurses' duties take them periodically into all the patients' rooms and into an upper-room UV-equipped day room for varying periods, where exposure occurs. The nurses' station is not equipped with upper-room germicidal irradiation. This group of workers, and the patients, are of special concern inasmuch as they could be exposed to UV-C for periods of more than 8 hours at a time.

Patients' Environment

The patients are exposed to germicidal UV continuously to the extent that they remain in their rooms or other irradiated spaces. Newly admitted patients are confined to their rooms for as long as 2 weeks to assure a clinical response to therapy before they can mingle with other TB patients on the ward. They may leave their room occasionally to visit other facilities, such as the shower room, but these absences are brief. As observed, patients spend long periods lying in bed. They also have the option of sitting in their room. When considered no longer infective they may visit the dayroom. Incidentally, there have been no known instances of TB transmission associated with the ward during the 15 years that it has been in existence, either among patients or to the staff, who are tested regularly. This is a remarkable safety record inasmuch as the hospital is used for the state's TB patients most likely to be infectious and does not have mechanical ventilation.

Classroom Environment

Teacher measurements were conducted in an elementary classroom in a traditional, aging school in the Northeast. The UV fixtures were mounted on a wall perpendicular to large, high windows that tended to reflect upper room irradiation. Figure 6 illustrates the relationships. Exposure of the children to UV was assumed to be considerably less than the teachers based on the difference in their statures, amplified by the tendency for students to be sitting while their teachers stand or walk around the room.

Shelter Environment

The homeless shelters where monitoring was done are located in the Northeast. The personnel monitored were engaged in cleaning the facilities, including kitchen, bath, and dining areas. All of these areas were equipped with luminaires with louvers designed to limit reflections into the lower room.

RESULTS

A total of 19 monitoring periods were recorded. In three cases, a single subject was monitored twice to give an indication of day-to-day variability. The results are summarized in Table I. A typical monitoring period for an office worker is seen in Figure 3. It shows low exposures while engaged in desk and computer work (Point 1 on the figure), somewhat higher exposures (Point 2) when facing more toward the UV-C source

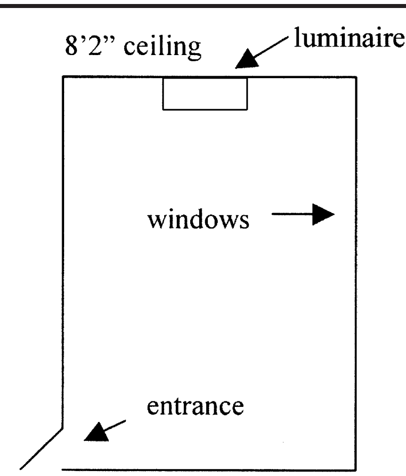

FIGURE 6. Diagram of classroom.

TABLE I. Results of UV-C Measurements

Facility	Location	Subject ID	Subject Description	Measured Dose (mJ/cm^2)	% TLV	Maximum Eye-Level Irradiance (μW/cm^2)	Calculated 8-hr Dose (mJ/cm^2)	Ratio of Measured to Calculated 8-hr Dose
Hospital	Patient room/dayroom	A	Ambulatory	0.19	3.1	1.2	34	0.005
Hospital	Patient room/dayroom	B	Wheelchair	0.17	3	0.27	7.9	0.022
Hospital	Patient foom	C	In bed	1.03	17	0.62	18	0.058
Hospital	Ward	D	Nurse	0.073	1.2	0.62	18	0.004
Hospital	Patient room	E	Wheelchair	1.250	20.8	0.79	23	0.055
Hospital	Patient room	F	In bed	1.060	17.7	0.79	23	0.047
Hospital	Patient room	G	Ambulatory	2.000	33.3	0.79	23	0.088
Hospital	Patient room/dayroom	H	Ambulatory	0.907	15.1	1.15	33	0.027
Hospital	Patient room/dayroom	H	Ambulatory	0.813	13.6	1.15	33	0.025
Hospital	Patient room	I	Ambulatory	0.499	8.3	0.79	23	0.022
Hospital	Ward	J	Nurse	0.246	4.1	1.15	33	0.007
University	Office	K	Professor	0.120	2.1	0.14	4	0.031
University	Office	K	Professor	0.0221	0.4	0.020	0.58	0.038
Shelter	Kitchen-bath-dining	L	Staff	0.0019	0.03	0.020	0.58	0.003
Shelter	Kitchen-bath-dining	M	Staff	0.16	2.6	0.020	0.58	0.27
Shelter	Kitchen-bath-dining	N	Staff	0.21	3.6	0.020	0.58	0.37
Shelter	Kichen-bath-dining	O	Staff	0.077	1.3	0.020	0.58	0.13
School	Classroom	P	Teacher	0.25	4.2	0.028	0.81	0.31
School	Classroom	P	Teacher	0.18	3.0	0.028	0.81	0.22

while working at the table, peak exposure (Point 3) reflects the entrance of a visitor and the rise of the office worker to greet and converse with the visitor while standing and facing the UV-C source. Zero exposure areas (Point 4) represent periods when the office worker was out of the office. Total measured 8-hour dose was 1/64 the dose that would be assumed if it had been based solely on the peak irradiance reading.

Figure 7a is a typical record of a nurse's workday exposure. It shows prominent peak exposures while in the patients' rooms and zero exposures while at the nurses' station. In spite of the frequent peaks, the equivalent 8-hour dose was 1/250 of the dose that would have been received had the nurse stared at the point of peak eye-level exposure for 8 hours continuously.

Figure 7b is a typical patient's isolation room exposure record. It shows peaks when the patient was standing, lower peaks while sitting, and periods of low exposure while lying in bed. Although peak eye-level exposure is 1.15 μW/cm^2, equivalent to an 8-hour continuous dose at that level of 33 mJ/cm^2, the 8-hour dose actually experienced was 0.9 mJ/cm^2, or less than 3% of the amount that would have been predicted if only the peak exposure had been used for the calculation.

Examination of Table I shows that the ratios of monitored dose to calculated dose based on maximum eye-level exposures range from 0.03 to 0.37. Differences within subject categories reflect the range of individuals' daily activities and are remarkable only because none come close to exceeding the 8-hour TLV of 6.0 mJ/cm^2. Most contain one or more peak exposures in excess of 0.2 μW/cm^2. For the hospital, this is because these older fixtures were not designed to comply with the relatively recent interpretation of the TLV, using 0.2 μW/cm^2 at eye level as an upper limit of irradiance for an 8-hour exposure period. Figure 7c is a teacher's daily exposure to UVGI. Peaks occur when she stands and faces the source.

DISCUSSION

The relationship between eye exposure and upper chest exposure when in upper-room germicidal UV-equipped spaces has not been established, nor has such a relationship been established for any other location. Locating a monitor very close to the eye is appealing and yet all feasible locations for a monitor (even a much smaller detector than the one used) fail to reflect the shading provided by the brow, the sunken eye socket, and the eyelid. The nose and cheekbones provide additional eye shading and periodic blinking reduces exposure time somewhat. The monitoring instrument's manufacturer suggests that the monitor may be worn in the center of the forehead using a headband. This location is close to the eye but provides no shading whatsoever, especially important for our overhead source, and for that reason is likely to overestimate eye exposure by a considerable factor. The upper part of the chest is not close to the eyes but faces in the same direction and is shaded by the head and especially by the chin. For these

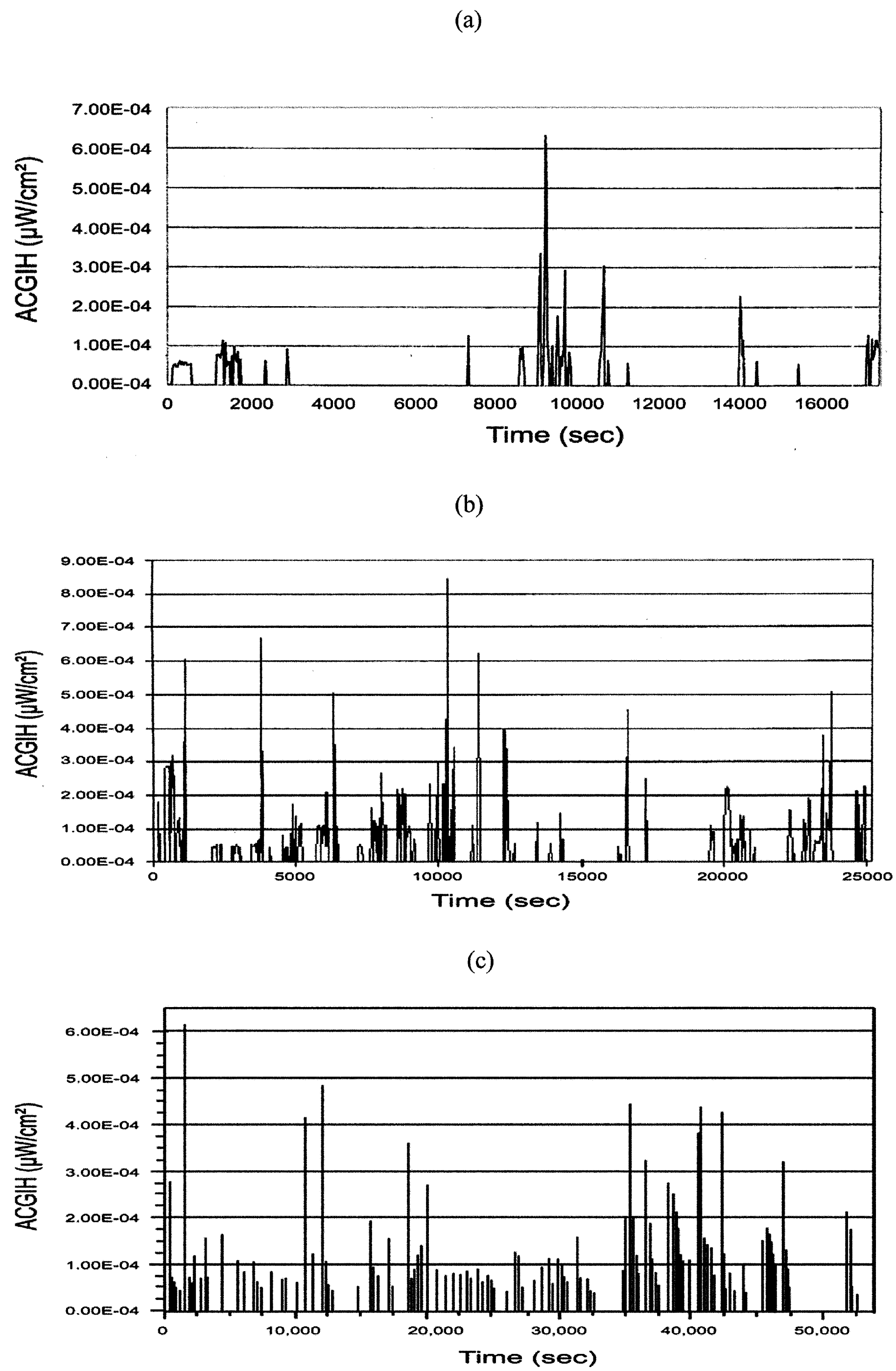

FIGURE 7. (a) Recording of a nurses' workday exposure to germicidal UV; (b) recording of a patient's exposure to germicidal UV; and (c) recording of a teacher's workday exposure to germicidal UV

reasons it may approximate the dose received by the eyes from the upper-room UV source.

The variety of subject categories used for this study was appropriate but modest in number. The results recorded in Table I represent a pilot study to illustrate the need to use established occupational health techniques for measuring personal dose to potential hazards. These established techniques include personal monitoring of one or more individuals out of a similarly exposed cohort who appear from inspection to be maximally exposed, and concluding from this sample that when they are in compliance, the remainder will be as well.

Because the peak eye-level irradiance in the hospital rooms were well above those commonly used (Table I), this was an ideal location to test our hypothesis that point measurements in a room greatly overestimate exposure. Inasmuch as patients and nurses in these rooms were not overexposed despite high point measurements, it may be concluded that persons exposed to less UV from better shielded fixtures will be even less likely to be endangered, as demonstrated in the other setting reported here. The absence of any known complaints after over 15 years of UV use in the hospital is consistent with our finding of total exposure doses well under the TLV.

CONCLUSIONS

The effectiveness of upper-room UV-C is degraded by the current design practice of limiting exposures everywhere in an occupied lower room to no more than 0.2 $\mu W/cm^2$, the 8-hour continuous TLV equivalent of 6.0 mJ/cm^2. Tests conducted during this study demonstrate that the monitored 8-hour UV-C dose was a small fraction of the TLV even when some areas contained irradiance levels that were multiples of 0.2 $\mu W/cm^2$. Acceptance of this principle will free designers and installers of upper-room UV-C systems from the restraint of maintaining every point in an occupied zone at 0.2 $\mu W/cm^2$ or below. Removal of this restraint promises to improve germicidal effectiveness. We recognize that upper room irradiance level is only one of two principal factors determining UV efficacy, the other being room air mixing. Our study indicates that substantially higher peak levels of UVGI can be used without increased risk. In the 19 scenarios studied it is clear, for example, that a maximum peak eye-level irradiance of 0.4 $\mu W/cm^2$ could have been used without danger of overexposure. In South Africa where institutional transmission of TB is a great concern, national guidelines already endorse this higher peak eye-level exposure for design purposes. However, in the absence of personal monitoring in many more situations, it is difficult at this time to suggest an alternative design strategy that assures both maximum efficacy and safety.

RECOMMENDATIONS

To solve this dilemma, we suggest careful personal monitoring of a larger representative sample of occupants deemed to be at risk in a greater variety of room exposure situations, noting peak irradiance in the room, fixture characteristics, and time-motion data, in an effort to establish better design criteria. To the extent that the sample of situations monitored in additional studies covered most of those encountered in common UVGI applications, it would not be necessary to monitor occupants in every installation.

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