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Effect of Ultraviolet Germicidal Lamps on Airborne Microorganisms in an Outpatient Waiting Room

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The effectiveness of 254-nm ultraviolet radiation for inactivating airborne microorganisms (and thereby reducing the spread of respiratory infections such as tuberculosis) was evaluated by collecting air samples in an occupied 90-m³ room equipped with four 15-W wall-mounted germicidal lamps. The indoor concentration of airborne bacteria was positively associated with the number of people present, the concentration of bacteria in the ventilation supply air, and the relative humidity, but was negatively associated with operation of the germicidal lamps and with the number of open windows. A generalized linear model suggested that use of the lamps reduced culturable airborne bacteria by 14 to 19 percent. This degree of air disinfection was calculated to be the equivalent of between 1.5 and 2 air changes per hour (ACH_{eq}). This equivalent ventilation was in addition to the 1 to 2.5 ACH that open windows provided and the 8 ACH that the mechanical ventilation system supplied. The microbicidal effect of the lamps on naturally occurring bacteria in this ventilated and occupied space was approximately one-tenth of the level that was measured for an artificially generated aerosol of *Mycobacterium bovis* in another study. There are several possible explanations for this smaller than expected effect: (1) the ambient airborne bacteria measured in the current study may have been less sensitive to 254-nm radiation than the *M. bovis* used in the earlier trial; (2) airborne bacteria may not have remained sufficiently long in the directly irradiated zone near the lamps to receive a bactericidal dose of 254-nm radiation because of the effects on aerosol movement of the open windows and doors, and of the supply air outlet and the exhaust air inlet locations; and (3) although the total wattage from germicidal lamps was higher in this case, low wattage lamps were used, which may not be as effective as higher wattage ones. Users of germicidal lamps should be aware that environmental factors (such as ventilation design and operation, and restrictions on lamp use in order to control occupant exposure) may limit the ability of germicidal lamps to inactivate airborne microorganisms and thus to protect people from airborne infectious agents.
Macher, J.M.; Alevantis, L.E.; Chang, Y.-L.; Liu, K.-S.: Effect of Ultraviolet Germicidal Lamps on Airborne Microorganisms in an Outpatient Waiting Room. Appl. Occup. Environ. Hyg. 7(8):505–513; 1992.

Introduction

Tuberculosis infection is rising, especially among HIV-infected people, and several outbreaks in health care settings recently have been reported.[1–6] Programs to identify and treat infected people, and the exercise of precautions to reduce aerosolization of *Mycobacterium tuberculosis* (the causative agent of tuberculosis), are crucial to the control of this disease. However, these measures are not sufficient to prevent person-to-person transmission of airborne bacteria in all settings or during cough-generating procedures such as bronchoscopy, sputum collection, and administration of aerosolized medications.[7–9] As a result, interest in environmental control measures to reduce, remove, or inactivate airborne microorganisms [e.g., dilution and exhaust ventilation and germicidal ultraviolet radiation (UVR)] is increasing in health care centers, shelters for homeless people, and correctional institutions.[2,7,10–12]

For control of airborne pathogens in isolation rooms for patients with contagious respiratory diseases, the Centers for Disease Control[4] and the American Society of Heating, Refrigerating and Air-conditioning Engineers[13] recommend a ventilation rate of six air changes per hour (ACH), of which at least two are outside air. All of the air from a respiratory isolation room must be exhausted to the outside and the room should be under negative pressure relative to adjacent areas. However, it can be difficult and expensive to modify ventilation systems to meet these recommendations. Because of recent renewed interest in overhead germicidal lamps,[2,9,10,14,15] the operators of an increasing number of high risk facilities are choosing this intervention to provide needed additional protection. "Germicidal" lamps are low-pressure mercury vapor lamps that emit ultraviolet and visible radiation. Over 95 percent of the radiant energy

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is emitted at a wavelength of 253.7 nm,[16,17] which is near the optimum for inactivating microorganisms.[18,19]

The minimum dose of 254-nm radiation required to inactivate a microorganism is a function of the organism's sensitivity, the UVR flux, and the exposure time.[18,20-23] Several investigators found that nonpigmented fungi and mycobacteria were more sensitive to 254-nm radiation than were pigmented strains, but Collins noted no differences for pigmented and nonpigmented variants of the bacterium *Serratia marcescens*.[18,24-26] Riley and Kaufman[21] observed a decreased microbicidal effect from 254-nm radiation at humidities above 70 percent. Kethley and Branch[23] reported that 2.7-μm particles were more sensitive to 254-nm radiation than were 5.2-μm particles, because the bacterial cells in the smaller particles were more exposed. Among the bacteria that have been tested, mycobacteria are intermediate in their sensitivity to 254-nm radiation.[14,26]

Proponents of germicidal lamps for air disinfection cite epidemiological studies in classrooms,[27-29] military housing,[30] and hospitals[31] as evidence that germicidal lamps reduce acute respiratory infections. Prevention of tuberculosis through the use of germicidal lamps has been reported anecdotally and in studies on animals housed within a hospital's air exhaust system.[2,32,33]

Riley and Nardell[2] have expressed UVR inactivation of airborne microorganisms in terms of equivalent particle removal by ventilation: equivalent air changes = $\ln N_0/N$, where N_0 = air concentration with germicidal lamps off and N = air concentration with lamps on. Riley *et al.*[20] tested the effect of 254-nm radiation on a predominantly single-cell aerosol of *M. bovis* in a sealed, unventilated room. On the basis of these experiments, Riley and Nardell[2,9] have stated that in a 19-m^2 room, a 30-W germicidal lamp installed at a height of 2 m with at least 0.6 m ceiling clearance can be expected to provide 20 ACH_{eq}. However, it has not been shown that this rate of inactivation can be achieved in a ventilated and occupied room in which bacterial aerosols are generated continuously from natural sources.

Zeterberg[34] reported that germicidal irradiation for aerosol disinfection has been impressive in the laboratory, but considerably less effective in practical applications. For example, although Williams *et al.*[35] found a considerable reduction in the concentration of airborne streptococci in classrooms, the reduction for general flora was slight. Decker *et al.*[36] reported that an air sterilizer killed only 10 to 12 percent of airborne vegetative cells and almost no spores. Among the possible explanations for these results are (1) lower sensitivity to 254-nm radiation for ambient airborne microorganisms than for laboratory-generated aerosols; (2) the difficulty of achieving microbicidal irradiance levels in occupied rooms without overexposing people; and (3) the difficulty of obtaining adequate exposure times given the effects on aerosol movement of natural and mechanical ventilation. Within a room, air mixing is affected by the locations of supply air outlets and exhaust air inlets, supply air temperature, open windows and doors, and ventilation system operation.[23,34,37-39]

To maximize air disinfection it is desirable to use the highest achievable level of room irradiation. However, 254-nm radiation can damage plants, fade paints and fabrics, and accelerate the deterioration of some materials. Although some older types of lamps produced ozone, currently available ones do not.[2] Short wavelength UVR (between 200 and 300 nm) is absorbed by the outer layers of the skin and the eyes. It is unclear whether chronic exposure to short wave length UVR can cause permanent damage,[15,40-43] but acute overexposure can cause debilitating erythema, photokeratitis, and conjunctivitis.[17,40,41] To avoid these problems, human exposure should be kept below the recommended 8-h limit of 6.0 mJ/cm^2.[40,41] Unfortunately, appropriate radiometers are not now widely available, and occupant exposure in hospitals and clinics is seldom measured. In several health care facilities, National Institute for Occupational Safety and Health (NIOSH) investigators documented excessive levels of 254-nm radiation from germicidal lamps.[17,42]

The efficacy of germicidal lamps to interrupt transmission of tuberculosis could be addressed in an epidemiological study of conversion rates in facilities with and without lamps. However, these studies would be difficult to conduct, given (1) the time interval between exposure and skin-test conversion, the poor skin-test response that immunocompromised people show, and the typically slow progression of the disease to the point where symptoms are noticed; (2) the large numbers of people that would need to be followed and the problems of following uncooperative individuals; and (3) the problem of finding appropriate comparison sites to assess what conversion rates would have been without the lamps.

The purpose of the current study was to determine the effect of 254-nm radiation on airborne microorganisms in an occupied and ventilated facility where the radiation level met both the recommended exposure limit[40] and Riley and Nardell's[2] suggestions for upper air irradiation. Smaller particles were studied separately from larger ones because only respirable bacteria (<10 μm) can initiate pulmonary tuberculosis[44,45] and can remain airborne sufficiently long to travel appreciable distances.[9]

Although a study of the effect of germicidal lamps on naturally produced aerosols of *M. tuberculosis* would most directly assess the ability of germicidal lamps to prevent the spread of tuberculosis, we considered this approach impractical. In the first place, even in high risk settings, the concentration of airborne *M. tuberculosis* would depend on the unpredictable presence of people with active disease. Second, even when sputum-positive patients were present, Riley *et al.*[33] calculated that the concentration of *M. tuberculosis* was only between 0.001 and 0.2 infectious units per cubic meter of air, which is near the detection limit of methods for sampling viable bioaerosols. Third, our attempt to isolate mycobacteria from the ambient air was not very successful. This bacterium is fairly fastidious in its

growth requirements and multiplies more slowly than many other microorganisms. Because of the long incubation period needed to recover *M. tuberculosis,* other collected bacteria and fungi often overgrow the culture plates. For these reasons, and because mycobacteria have been shown to be intermediate in their sensitivity to 254-nm radiation relative to other bacteria,[14,26] the ambient airborne bacteria present at the test site were sampled as surrogates.

Materials and Methods

Study Site

The study site was the waiting room of an outpatient clinic in an Alameda County, California hospital. This site was chosen because the clinic served a population at high risk of tuberculosis and other communicable respiratory infections. Treatments that the HIV-infected patients received occasionally induced coughing, which increased the likelihood that they could spread respiratory infections. The clinic staff previously had discussed installing germicidal lamps to protect themselves and their high risk patients better, but had not yet done so. Facilities already using germicidal lamps were not considered for study because we judged it unreasonable to request that the lamps be turned off for the project, thereby risking transmission of disease that otherwise might have been prevented.

The study was conducted between mid-July and mid-September, 1990. Between 13 and 22 patients were seen at the clinic between 1 and 5 p.m. on Mondays, Wednesdays, and Fridays. The room generally was unoccupied from 12 noon to 1 p.m. A short explanation of the study was posted in the waiting room and in a nurses' station, and copies were available for interested staff and patients.

Mechanical room ventilation was measured at the beginning and the end of the study with an airflow hood (Alnor Balometer, Skokie, Illinois) at the supply diffuser and the exhaust grille (see Figure 1). The average supply ventilation rate (reportedly 100 percent outdoor air) was used to estimate the air change rate for the room. The door to the 90-m^3 (6 × 5 × 3 m) room was always open, but the occupants adjusted the four casement windows as needed. The room was carpeted and was illuminated with ceiling-mounted fluorescent lamps. The wall to the left of the entrance was covered with wallpaper (see Figure 1), whereas the other walls were covered with beige semigloss paint. Smoking was not permitted in the building, therefore there were no particles of tobacco smoke in the air to interrupt transmission of the UVR. The sampling site in the waiting room was chosen to avoid, as much as possible, interference with the occupants' usual activities and the effects of the open doorway and windows.

Germicidal Lamp Operation

Four new 15-W wall-mounted germicidal lamps (46 × 20 × 10 cm fixtures, G15T8 tubes, American Ultraviolet Co., Santa Ana, California) were installed at a height of approximately 2 m (see Figure 1). For structural reasons, the lamps

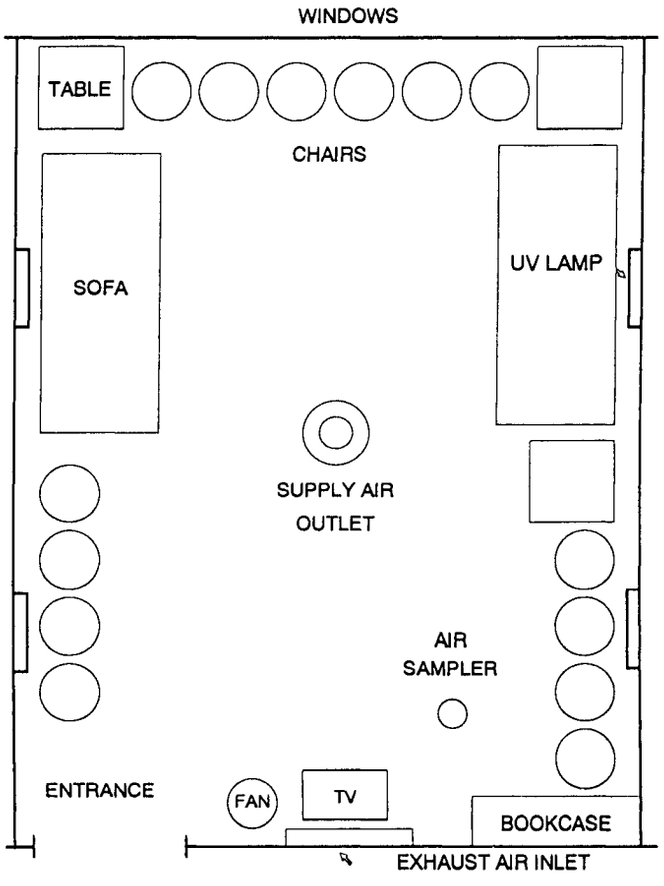

FIGURE 1. Outpatient waiting room.

were not suspended from the ceiling. Louvers on the fixtures restricted radiation between the horizontal plane (0°) and 45°, with peak intensity between 5° and 20°.

The germicidal lamps were used in either the first or second half of nine 4-h clinic sessions to balance the effect of day-to-day fluctuations in environmental conditions and number of room occupants. If a session began with the lamps off, several 10-min air samples were collected consecutively and then the lamps were turned on. No samples were collected for approximately 30 min, after which several samples were collected with the lamps on. On alternating sampling days, the sequence was reversed. On these occasions, the lamps were turned on for at least 30 min before sampling began, after which the lamps were turned off for at least 30 min before sampling resumed. The lamps were not operated at any other time. A waiting period of 30 min was chosen for convenience and because during this time the ventilation system theoretically removed 98 percent of the air in the room at the end of the previous sampling session ($C = C_0 e^{-at}$, where C = concentration remaining, C_0 = original concentration, a = air change rate, and t = time).

Ultraviolet Radiation Measurements

To determine occupant exposure to 254-nm radiation, measurements were made at 35 equally spaced locations in

horizontal planes, at heights of 1 and 2 m, with a radiometer sensor (Model IL1700, SED240 sensor, NS254 filter, International Light, Newburyport, Massachusetts) held vertically and facing each wall. To determine lamp output on each sampling day, lamp intensities were measured at the faces of the louvers (in the centers of the tubes and 10 cm from each end) after a warm-up period of more than 5 min.

Air Sampling for Ambient Bacteria and Mycobacteria

Less- and more-respirable ambient bacteria were collected with the first and last stages of a six-stage impactor (Andersen Instruments, Inc., Atlanta, Georgia; cutpoint diameters (d_{50}) = 7 and 0.6 μm, respectively). Between samples, the impactor was cleaned with 70 percent ethanol. In the waiting room the impactor was placed on a tripod at a height of approximately 1.25 m (see Figure 1). Ten-minute air samples were collected at a rate of 28 L/min with a sampling pump that was located in an unoccupied, adjacent room. To determine the concentration of bacteria in the air supplied to the building, daily air samples were collected near the supply diffuser in the unoccupied room.

Air samples for ambient bacteria were collected on trypticase soy agar (BBL Microbiology Systems, Cockeysville, Maryland) and incubated at 30°C. Pigmented and nonpigmented colony-forming units (cfu) were counted separately and the total counts were adjusted for the likelihood that more than one particle entered each impactor hole.[46] Bacterial colonies that were representative of each morphologically different type were stained and the slides examined by microscope. The cells were classified as gram-positive or gram-negative, and as cocci, rods, or other (i.e., those in which the cells were neither coccoid nor rod-shaped, and those that were not stained because growth on the plates was too dense to examine every colony).[47] Although the culturing methods (i.e., growth medium and incubation temperature) were not optimal for recovering saprophytic fungi, those that were isolated were noted.

Air samples for mycobacteria were collected on 7H10 agar [18 g 7H10 agar, 100 ml OADC (Difco Labs, Detroit, Michigan), 5 ml glycerin, and 900 ml distilled water]. Sample collection was as described above, except that only the sixth impactor stage was used. The plates were incubated at 35°C in 6 percent carbon dioxide for 7 days and then in air. The plates were examined for growth weekly for 6 weeks or until fungi overgrew the plates. Colonies resembling mycobacteria were stained for acid fastness.[48] Mycobacteria are acid-fast, straight, or slightly curved rods (0.3 μm–0.6 μm × 1 μm–4 μm), which stain gram-positive, although poorly.[49]

Other Measurements

During collection of each air sample, a record was made of the number and location of people in the waiting room, the number of open windows, the operation of an oscillating room fan, the carbon dioxide concentration (Model RI-411, Gas Tech, Newark, California), and air temperature and relative humidity (Model RH-201F, Omega Engineering, Inc., Stamford, Connecticut). The general activity level in the room during each sampling period was judged as (1) quiet (i.e., the occupants sat and watched television, talked, or read), (2) moderate (i.e., one or two people moved around the room), or (3) high (i.e., three or more people moved around the room).

Data Analysis

The normality of the measurements was tested using the Shapiro–Wilk statistic (Univariate Procedure, SAS/STAT, Version 6, SAS Institute, Inc., Cary, North Carolina). To evaluate the joint effect of environmental parameters that could affect microbiological air concentration, a generalized linear model[50] was fitted to the logarithms of the concentrations using a stepwise procedure based on Mallows' C_p statistic (Reg Procedure, SAS/STAT). Carbon dioxide concentrations for missing measurements were estimated with a regression model that included variables that were predictive of carbon dioxide concentration (i.e., the number of people present, the number of open windows, and the relative humidity during sample collection).

Ventilation rate (ACH, room volume per hour) can be estimated from aerosol generation rate (F, cfu/h) and microbiological air concentration (C, cfu/m^3): ACH = F/C. We assumed that the aerosol generation rate was equal when the lamps were and were not in use [$F_{UVon} = F_{UVoff} = F = (C)$ ACH]. The average measured air supply rate for the room (see above) was taken as the air change rate when the germicidal lamps were not operating (ACH_{UVoff}). By substituting [(C_{UVoff}) ACH_{UVoff}] for F, the ventilation rate when the germicidal lamps were on was estimated as $ACH_{UVon} = (C_{UVoff}/C_{UVon})(ACH_{UVoff})$. The expected concentrations (C_{UVoff} and C_{UVon}) were determined from the generalized linear model. The equivalent ventilation that the germicidal lamps provided was estimated from the difference between ACH_{UVoff} and ACH_{UVon}. The model also was used to estimate the air concentrations when 0–3 windows were open.

Results

All 254-nm radiation measurements made at a height of 1 m were ≤ 0.2 μW/cm^2 and those taken at a height of 2 m were ≤ 1.1 μW/cm^2. Reflection from the papered wall was approximately twice that from the painted walls. During the nine weeks of the study, the lamps were used for a total of approximately 25 h and the average lamp flux declined from 1.00 W/cm^2 to 0.92 W/cm^2.

The initial and final measured air flow rates, respectively, were 225 L/s supply, 175 L/s exhaust, and 189 L/s supply, 212 L/s exhaust. On the basis of these measurements, the mechanical ventilation system provided approximately 8 ACH, or 10 L/s · person at maximum seated room occupancy (20 people).

The environmental conditions and number of occupants in the waiting room were approximately the same during sampling periods with and without the germicidal lamps

TABLE I. Environmental Measurements

Parameter	Germicidal Lamps On (n = 31)			Germicidal Lamps Off (n = 30)			Supply Air (n = 24)		
	Average	S.D.[A]	Range	Average	S.D.	Range	Average	S.D.	Range
Air temperature (°C)	24	2	22-27	24	2	21-27	23	3	20-26
Relative humidity (%)	58	10	41-70	57	8	45-67	62	8	46-74
Carbon dioxide concentration (ppm)	430	62	300-600	427	41	365-525	363	30	300-400
Number open windows	1.6	0.9	0-3	1.7	1.0	0-3	—	—	—
Total number people	6.0	2.9	1-13	7.5	2.5	2-11	—	—	—
Total number people near sampler[B]	0.6	0.8	0-3	0.7	0.7	0-2	—	—	—
Activity level[C]	1.4	0.7	1-3	1.6	0.8	1-3	—	—	—
Room fan[D] operation	0	0	0	0.07	0.25	0-1	—	—	—

[A]S.D. = Standard deviation.
[B]People seated in the four chairs nearest the sampling site.
[C]Quiet = 1, moderate activity = 2, high activity = 3.
[D]Room fan off = 0, room fan on = 1.

(Table I). There was no evidence that the occupants changed their behavior during sample collection or when the lamps were used, although they could observe both. The occupants usually sat on the sofas or on the chairs near the windows or the doorway because these places provided better views of the television set and the entrance. As could be expected, the total number of people present, number of people near the sampling site, activity level, and carbon dioxide concentration were positively correlated (r range: 0.31-0.64). No other correlations were statistically significant ($p \leq 0.05$).

The distributions of microbiological air concentrations were approximately lognormal. The supply air contained much lower levels of bacteria and fungi than did the air at the sampling site in the waiting room (Table II). When the germicidal lamps were on, the fungal (see Table II and Figure 2) and bacterial (see Table II and Figure 3) air concentrations were somewhat lower than when the lamps were off. It was estimated from a generalized linear model (see Table III) that during germicidal lamp use the overall bacterial concentration was approximately 86 percent of the level without the lamps (see Appendix). The apparent ventilation rate during lamp use, therefore, was approximately 1.2 times the ventilation rate without the lamps, or approximately an additional 1.6 ACH_{eq}. The model indicated that one, two, and three open windows provided approximately 0.7, 1.5, and 2.3 ACH of ventilation, respectively.

Seven statistically significant model parameters explained 44 percent of the variance in the total bacterial air concentration, whereas four significant parameters explained 64 percent of the total fungal variance (see Table III). The number of open windows in the waiting room was positively associated with the concentration of fungi but was negatively associated with bacterial concentration. This finding suggested that although the outdoor air was a source of fungi, it diluted the indoor concentration of bacteria from other sources.

The majority of the culturable airborne bacteria were gram-positive cocci (70 percent of all bacteria in the supply air, 67 percent when the lamps were off, and 65 percent when the lamps were on). The remaining bacteria were identified as gram-positive rods (24, 13, 19 percent), gram-negative rods (6, 7, 6 percent), gram-negative cocci (<1, 2, <1 percent), or other or unidentified (<1, 11, 10 percent, respectively). In separate linear models, germicidal lamp use was negatively associated with the concentration of gram-positive cocci (coefficient for lamp use: −0.215; 1.9 ACH_{eq}), but not with the concentrations of the other groups of bacteria.

TABLE II. Concentrations of Culturable Airborne Microorganisms

	Waiting Room Air Samples						Supply Air Samples (n = 24)		
	UVR Lamps On (n = 31)			UVR Lamps Off (n = 30)					
	Less Resp[A]	More Resp[B]	Total	Less Resp	More Resp	Total	Less Resp	More Resp	Total
Bacteria (colony-forming units/m^3)									
Median	76	133	208	106	191	307	25	47	70
Average	104	144	248	120	187	307	29	53	82
Standard deviation	87	53	124	85	72	113	22	30	38
Range	25-373	52-271	84-634	29-476	64-312	114-676	4-108	7-128	26-163
Fungi (colony-forming units/m^3)									
Median	18	104	135	22	113	149	4	63	66
Average	33	133	166	30	128	159	6	90	95
Standard deviation	35	82	98	26	69	74	7	66	70
Range	0-131	53-412	60-435	0-92	57-353	66-364	0-29	33-284	33-313

[A]Less-respirable particles.
[B]More-respirable particles.

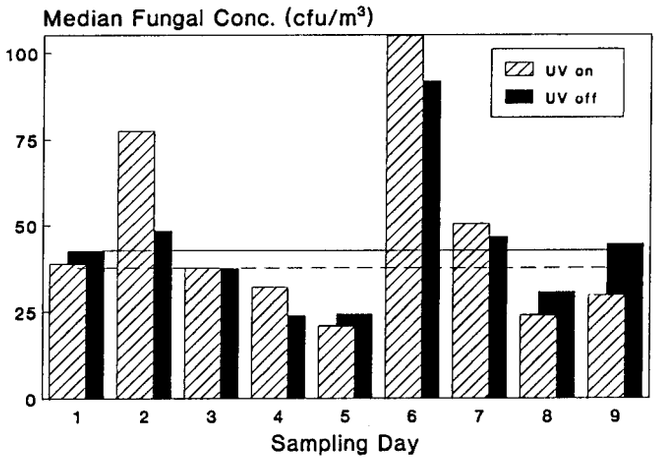

FIGURE 2. Daily median fungal air concentrations. Overall median concentrations: germicidal lamps on (- - -), germicidal lamps off (———).

Lamp use was significant for pigmented bacteria (38 percent of the total), but not for nonpigmented ones (62 percent). The lamp effect was approximately the same for less- and more-respirable bacteria (see Table III).

Due to fungal overgrowth of the 7H10 plates, 33 of the 51 samples for mycobacteria (19 of 22 samples collected with the germicidal lamps on, 14 of 23 collected with the lamps off, and 0 of 6 supply air samples) were discarded before 3 weeks of incubation. Rapid-growing acid-fast bacilli were recovered from one waiting room sample (which was collected while the germicidal lamps were on), and from two supply air samples.

Discussion

Germicidal lamp use in a typical hospital waiting room did not affect the concentrations of gram-positive, rod-shaped bacteria (many of which were spore formers and nonpigmented). For the fungi that were isolated in this study, the germicidal lamps had a small but not statistically significant effect. Fungi and bacteria spores are known to be more resistant to 254-nm radiation than vegetative bacteria.[14,16,18,26,36] Lamp use did reduce the concentration of gram-positive cocci (of which many that are found in indoor air are normal human flora shed from skin, scalp, and respiratory secretions).[35,51] Gram-positive cocci were the most prominent group of bacteria present and consequently the reduction for this group alone was on the same order as the reduction of total bacteria. The gram-positive cocci that have been tested have been found to be as, or more, sensitive to 254-nm radiation than the tested mycobacteria.[20,24,26] Were naturally produced *M. tuberculosis* as susceptible to 254-nm radiation as this most sensitive group of ambient airborne bacteria, one could expect that the reduction in the concentration of *M. tuberculosis*, had it been present, would have been similar.

Lamp effectiveness in this study may not have been as high as predicted by Riley *et al.*[2,20] because the experimental settings clearly differed. Rather than measuring germicidal lamp effect on the concentration of one bacterial species in a single-cell aerosol from a burst source, we observed lamp effect on a mixture of bacteria in a range of particle sizes that were introduced continuously from outdoors and from the room's occupants and their activities. The current study also differed in the use of wall- rather than ceiling-mounted lamps. Lower wattage lamps were used in this study because they provided more uniform irradiation of the room and allowed better control of occupant exposure. Furthermore, delivery of supply air at the ceiling (a preferred design for health care facilities),[13,52] may have reduced mixing between the cleaner, highly irradiated air in the upper portion of the room and the more contaminated, poorly irradiated air below[39] (where aerosol generation and sampling occurred). However, these conditions are typical of what may be found in the high risk settings where overhead germicidal lamps are being used. In 1990 NIOSH investigators concluded that information was not available regarding optimum ventilation conditions that both assured good air mixing and provided sufficient exposure to 254-nm radiation for effective killing of airborne pathogens.[42]

The term "equivalent ventilation" has been used to compare bacterial inactivation by germicidal lamps and particle removal by ventilation.[2,20] However, 254-nm radiation affects only viable air contaminants; therefore, the equivalent ventilation provided by germicidal lamps cannot be substituted for the recommended minimum supply of outdoor air that is needed for occupant comfort.[53]

Because occupant safety must be considered, higher irradiance levels could not have been used at this test site. As it was, the total lamp wattage in the 30-m² test room exceeded Riley and Nardell's recommendation[2] of one 30-W lamp for every 19 m² of floor area. Even though the lamps had louvers, the UVR levels exceeded the 8-h exposure limit above a height of 1 m. However, the patients and staff members were not overexposed because they usually spent less than 1 h in the room and were seated.

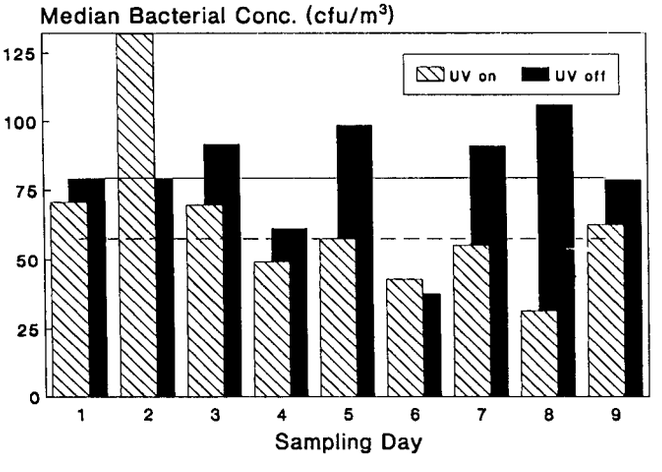

FIGURE 3. Daily median bacterial air concentrations. Overall median concentrations: germicidal lamps on (- - -), germicidal lamps off (———).

TABLE III. Multiple Regression Model Selected by the Stepwise Method

Respose Variable	Step[A]	Significant Explanatory Variable	Coefficient
Total bacterial air concentration[BC]		Intercept	0.770
	1.	Total number people	0.037
	2.	Relative humidity	0.033
	3.	Supply air concentration[B]	0.594
	4.	Room fan operation	0.473
	5.	Activity level	0.124
	6.	Number open windows	−0.089
	7.	Germicidal lamp use	−0.154
Less-respirable bacterial air air concentration[B]		Intercept	0.595
	1.	Supply air concentration[B]	0.595
	2.	Relative humidity	0.030
	3.	Activity level	0.170
	4.	Germicidal lamp use	−0.188
More-respirable bacterial air concentration[B]		Intercept	4.925
	1.	Total number people	0.061
	2.	Number open windows	−0.134
	3.	Germicidal lamp use	−0.170
Total fungal air concentration[B]		Intercept	−3.716
	1.	Supply air concentration[B]	0.669
	2.	Room air temperature	0.071
	3.	Activity level	0.155
	4.	Number open windows	0.068
Less-respirable fungal air concentration[B]		Intercept	−5.655
	1.	Room air temperature	0.259
	2.	Supply air concentration[B]	0.504
	3.	Activity level	0.480
	4.	Carbon dioxide concentration[B]	−2.096
More-respirable fungal air concentration[B]		Intercept	−3.412
	1.	Supply air concentration[B]	0.509
	2.	Activity level	0.112
	3.	Room air temperature	0.027
	4.	Relative humidity	−0.016
	5.	Number open windows	0.092
	6.	Carbon dioxide concentration[B]	0.740

[A] Step at which explanatory variable entered model.
[B] Logarithm-transformed variables.
[C] See Appendix.

The determination that the decorative wallpaper in the waiting room reflected more 254-nm radiation than the painted wall surfaces (although it was not visibly glossier) illustrated the importance of measuring UVR exposures with an appropriate radiometer.[19,54] When necessary, excessive irradiation of occupied areas can be reduced by altering lamp position, redirecting louvers, painting ceilings and walls with nonreflecting coatings, and using lower wattage lamps and transparent barriers.[17,42]

Recommendations

The risk of exposure to tuberculosis, multidrug resistant tuberculosis, and other communicable respiratory infections is rising in health care centers, homeless shelters, and detention facilities. The reasons for the recent rise involve increased exposure and susceptibility, and inadequate treatment of disease once it is diagnosed.[1,3,5–7,11,12] While some aspects of tuberculosis as a public health problem are changing, recommendations for preventing transmission remain the same.[4] The most effective means of avoiding tuberculosis transmission are (1) preventing generation of infectious droplet nuclei (e.g., by early identification, treatment, and isolation of infected people); (2) using source-control measures to prevent the spread of infectious particles (e.g., tissues or face masks to contain coughs and sneezes, and local exhaust ventilation, such as sputum collection booths); (3) reducing microbiological contamination of the air once infectious particles are released (e.g., by dilution ventilation, and the use of germicidal lamps and other air cleaners); and (4) providing exposed health care workers with personal protection (e.g., particulate respirators).[4]

Beside being mounted on ceilings or walls, germicidal lamps can be placed inside ventilation ducts to treat supply or return air. Room air cleaners (equipped with blowers and with high efficiency filters or enclosed germicidal lamps) also can be used to remove or inactivate airborne microorganisms. Self-contained air cleaners generally are designed to provide approximately 3 ACH (Atlantic Ultraviolet, Bay Shore, New York), which may be similar to the benefit that exposed germicidal lamps can provide in many facilities. Self-contained air cleaners and lamps inside ventilation ducts are attractive alternatives to overhead germicidal lamps, because (1) there is no risk of occupant exposure to UVR, (2) air movement and ventilation system operation affect the performance of these units less, (3) particles passing through a high efficiency filter have a high probability of being collected and those that pass within a short distance of an intense source of 254-nm radiation have a high probability of being inactivated, (4) the cost of these units is similar to that of overhead germicidal lamps, and (5) people cannot tamper easily with the units.

In addition to an increased risk for tuberculosis, immunocompromised people are susceptible to infection from environmental strains of mycobacteria[55] (several of which were recovered in this study) and from other opportunistic pathogens. It would be useful to know to what degree environmental control measures could reduce the concentrations of naturally occurring airborne mycobacteria. Fungal overgrowth on the 7H10 medium was a problem that could be overcome in future studies by treating the samples before plating to reduce contamination, by adding antibiotics to the growth medium, or by using a different detection system.

In light of the exposures to 254-nm radiation that NIOSH investigators measured in health care facilities, they recommended that germicidal lamps not be used indiscriminately and that worker exposure to these sources be reduced to the lowest feasible level.[42] Managers of facilities that already have or are preparing to install germicidal lamps should review Riley's instructions[14] on lamp mounting and operation. After installation, an experienced person should measure occupant exposure, instruct the workers on how to recognize the symptoms of overexposure, and train the staff members who will maintain the

lamps.[42] Infection control experts recommend using all available precautions for preventing the transmission of tuberculosis.[4] Germicidal lamp users should evaluate carefully the benefit that they can expect to derive from this intervention, and should not overlook other environmental control measures such as exhaust and dilution ventilation and air cleaners.

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Appendix

How the Model Was Used

To predict the concentration of airborne microorganisms, one multiplies the values for the variables that were included in the model by their coefficients. For example, the equation for total bacterial air concentration given in Table III can be written as

ln(air concentration) = [0.770 + 0.037(total number people) + . . . − 0.089(number of open windows)] − 0.154(germicidal lamp use).

This can be simplified to

$$\ln(C) = K - 0.154(z),$$

where: C is the air concentration, K represents the values for the first terms in the equation [i.e., those in brackets, which were assumed to be unaffected by lamp use (See Table I)], and z is the value of the lamp variable. When the lamps were off, the value of z was 0, and when the lamps were on, z was 1.

Taking the antilog of the concentration gives us

$$C = e^{K-0.154(z)} = e^{K}e^{-0.154(z)}.$$

As described earlier, we can estimate the ventilation rate when the germicidal lamps were on from the ratio of the air concentrations when the lamps were and were not used or

$$C_{UVoff}/C_{UVon} = e^{K}e^{-0.154(0)}/e^{K}e^{-0.154(1)} = 1/0.86.$$

Thus, with the lamps on, the loss of viable airborne bacteria apparently was 1/0.86 times the rate that occurred by ventilation alone (i.e., without the lamps), or 1.2 times the measured ventilation rate of 8 ACH. The difference between these ventilation rates (9.6 ACH_{UVon} − 8 ACH_{UVoff} = 1.6 ACH_{eq}) is the equivalent ventilation rate that can be attributed to the lamps. If the air concentration when the lamps were on was 86 percent of the concentration when the lamps were off, then use of the lamps appeared to reduce the concentration of total airborne bacteria by: (1 − 0.86)(100) = 14 percent.