OPTIMUM INDOOR AIR UV GERMICIDAL IRRADIATION SYSTEM FOR APPLICATION IN COMMUNITY HOSPITALS

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Abstract

This research investigated the optimum design and operation of an ultraviolet germicidal irradiation (UVGI) system for a tuberculosis (TB) isolation room modified from a patient's room of the type found in community hospitals in Thailand. The goal was to obtain the maximum germicidal irradiation effectiveness while still keeping safety standards for the occupants and staff. The study was carried out in an actual size replicated patient's room with different positions for the air inlet and outlet openings to allow 3 different ventilation patterns. The air change rates tested were 6, 9, and 12 air changes per hour (ACH). Furthermore, the relevant factors that were studied for the irradiation using UV light were the tube power, the installation height, the number of tubes, and the installation pattern. The air velocity and the distribution of the UV intensity in the replicated room were measured. The fluid dynamics model, ANSYS Fluent, was used to simulate the flow path of the disease particles and the time that they spent in the upper zone of the room where the irradiation occurred. Results showed that that the best germicidal irradiation efficiency could be obtained with 4-sided installation of 16W UV tubes at a height of 3.3 m.\ above the floor, with an in-low/out-high ventilation pattern and 6 ACH ventilation rate. This optimum system design could achieve 98.19% efficiency, which was 16% better than the standard design. The findings of this study can be beneficial for both the improvement of the care of TB disease patients and contamination prevention in Thai community hospitals.

Keywords: ultraviolet, germicidal, irradiation, indoor air, hospital

Introduction

There are approximately 40,000 patients and 13,000 deaths from tuberculosis (TB) each year in Thailand (Office of Policy and Strategy, 2010). The policy of the Ministry of Public Health requires that every community hospital in Thailand has at least one isolation room for treating patients infected with this airborne disease. The standard design of room, the Wor Sor 1/2549 design, is equipped with both the high-efficiency particulate arresting (HEPA) filter and the ultraviolet germicidal irradiation (UVGI) system to control the spread of the disease to nearby areas (Division of Medical Engineering, 2006). Due to the limitation on the number of rooms, however, most community hospitals can allocate only one of their

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special-type patient's rooms for modification into the required isolation room. Moreover, some modified isolation rooms are not equipped with the mandatory disease prevention systems due to an inadequate installation and operation budget. This has resulted in inadequate and substandard treatment facilities, while more than half of these hospitals have to handle 1-6 tuberculosis cases per day (Chuchottaworn, 2008). TB patients who are treated in normal rooms without a germicidal system could spread the airborne disease to other places, hence causing infection within hospitals – a nosocomial infection. There was a report indicating that as many as one out of ten patients contracted an infection in a hospital (Mertens *et al*. 1987). In Thailand, 71 hospital staff members were infected in 2009, which was approximately 1.2 cases per one million of the population. Therefore, better control of nosocomial infection is very important for Thailand.

To control TB disease, the Centers for Disease Control and Prevention (2005) recommend 2 methods for using a room's ventilation system to kill the disease from the vented air: a HEPA filter or a UVGI system. Since many community hospitals have had problems with the high cost of a HEPA filter system, the UVGI system seems to be a more reasonable choice from the economical standpoint. The UVGI system is an indoor air cleaning system which can prevent airborne disease infection efficiently. It uses the 254 nanometer wavelength UVC ray to destroy the disease's DNA. The main factors which have an effect on the killing efficiency are the ray's intensity and the contact time. There are two types of system: the in-duct system and upper room system (Centers for Disease Control and Prevention, 2005). The former is appropriate for muliple isolation rooms which share a ventilation system. The latter is used for a single room. In the case of Thai communitiy hospitals, most isolation rooms are a single room so the upper room UVGI is clearly more suitable. In this system, the room is divided into a lower zone – from the floor to a height 2.1 m above the floor, and an upper zone – from the height of 2.1 m to the ceiling. The UV system is designed to irradiate only the upper zone of the room, while keeping the lower zone at a safe level of UV intensity – less than 0.2 $\mu W/cm^2$ at a height of 1.7 m above the floor.

Various studies have reported the effects of factors such as radiation power, installation pattern, air change rate, relative humidity, and temperature on the germicidal irradiation efficiency of the UVGI system. Noakes *et al*. (2004) found that the efficiency decreased when the ventilation inlet/outlet openings were high above the floor. This outcome agreed with other studies (Zhang and Chen, 2006; Khan *et al.,* 2006). Beggs and Sleigh (2002) reported that the upper room UVGI system performed better at lower ventilation rates. In addition, they pointed out that the efficiency did not increase proportionally with the power of the UV tube. Their experiment yielded germicidal irradiation efficiency values in the range of 9.5% to 92.2%. Furthermore, some studies concluded that the UVGI efficiency is inversely varied with the relative humidity (Ko *et al.,* 2000; Peccia, 2000). Peccia and Hernandez (2001) explained that the ability of the bacteria to repair their DNA that has been damaged by UV increases when the relative humidity increases. As for the temperature effect, a number of studies indicated that a temperature higher or lower than the designed level could hinder the irradiation by means of the UV tube and thus reduce the efficiency of the system (Van Osdell and Foarde, 2014; ASHRAE, 2007; American Institute of Architects, 2006).

In an attempt to improve the situation relating to the scarcity of isolation rooms, this research aimed to find the optimum design of a UVGI system for application in community hospitals in Thailand, based on the Division of Medical Engineering's Wor Sor 1/2549 room type, the standard-design of room.

Materials and Methods

An actual size replicate of a real patient's room in a hospital was constructed for this study. The patient's room in this case was similar to the Wor Sor 1/2549 room type. This type of room has been commonly modified into a TB isolation room. The room was 3 m wide, 5 m long, and 3.3 m high. It was divided into 2 sections: an anteroom and an isolation room. The 3 × 1.5 m^2 anteroom is a preparation section before entering the isolation room. The isolation room is the main section where the patient stays. A patient's real bed of a size 0.9 m × 2.0 m × 0.65 m was placed in the middle of the isolation room. Figure 1 shows the drawing of the replicated patient's room. Figure 2 shows pictures of the outside and inside of the room.

In order to study the effect of the ventilation pattern, 4 ventilation openings were created in the isolation room: in-high, in-low, out-high, and out-low. Each of the two outlet openings was equipped with a 20-cm diameter ventilation fan with an adjustable speed. This allowed for 3 intended ventilation patterns: (1) the air comes in at the low opening and goes out at the high opening (L/H), (2) the air comes in at the high opening and goes out at the low opening (H/L), and (3) the air comes in at the

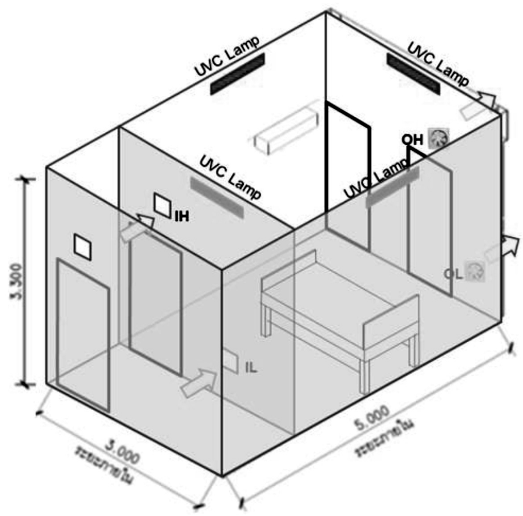

Figure 1. Drawing of the replicated patient's room

Figure 2. Pictures of the outside and inside settings of the replicated patient's room

high opening and goes out at the high opening (H/H). For example, when the L/H pattern was used, the in-low opening was open and the fan was running at the out-high opening, while the other two openings were closed. Furthermore, the fan speed can be varied to create 3 intended ventilation rates: 6, 9, and 12 air changes per hour (ACH). Therefore, there were 9 combinations of the ventilation pattern and rate for the experiment in this study.

As for the UVGI system, the effects of 3 factors were considered: the UV tube power, the installation height, and the installation pattern, i.e. the number of tubes and sides of the walls on which they were installed. The UV tubes were Philips 254 nm low pressure mercury vapor type. Three power levels were used in the experiment: 8W, 16W, and 32W. One set of tubes was installed on each of the 4 sides of the room. All possible installation patterns were tested as follows: (1) one-sided, front or back wall, (2) one-sided, left or right wall, (3) two-sided, front and back walls, (4) two-sided, left and right walls, (5) three-sided, and (6) four-sided. Finally, the height of the tubes above the floor was investigated using 3 installation height values: 2.7, 3.0, and 3.3 m.

The temperature in the room was controlled between 24–26°C using an 18000 BTU air conditioner. The relative humidity was controlled between 40–60% using a humidifier located in the anteroom. The UV tubes were turned on for 100 hours before the first usage to make the radiation constant. In addition, they had to be warmed-up for 30 minutes before each experiment to obtain a steady radiation.

The upper zone of the room was the zone 2.1 m above the floor where the intended irradiation took place. To measure the UV intensity and the time the disease particles spent in different positions of the zone, the upper zone was divided into blocks. It was divided vertically into two 0.6 m thick layers: height 2.1–2.7 m. and height 2.7–3.3 m. In each layer, a division was made horizontally into 9 units of 1 x 1 m^2. As a result, the upper zone was divided into 18 cube-like blocks. For each block, the UV intensity was measured using a UV light meter and simulation was done to estimate the average time the disease particles spent inside a block using the ANSYS Fluent model. Details of the model simulation can be found in Warissarangkul (2014). The UV dose was then calculated as the product of the 2 factors (Lytle and Sagripanti, 2005):

$$UV_{Dose} = I \times t \qquad (1)$$

where,

UV_{Dose} = UV dose (W.s/m^2 or J/$m^2$2)
I = UV Intensity, from measurement (W/m^2)
t = Contact time, estimated from the simulation (s)

Consequently, the TB germicidal irradiation efficiency was calculated via the killing rate (KR) equation (Kowalski *et al*., 2000):

$$KR = [1 - \exp(- Z \times UV_{Dose)}] \times 100 \qquad (2)$$

The parameter Z was the UV sensitivity constant, which in the case of TB was equal to 0.4721 m^2/J (Beggs *et al*., 2006).

Results and Discussion

Air Velocity Comparison

Measurement of the air velocity in the experimental room was carried out according to the ANSI/ASHRAE 41.2-1987 (RA 92) standard (ASHREA, 1992). Air velocity was measured at a height 1.7 m above the floor at 5 points in a horizontal plane: the 4 points near the corners and 1 point in the middle of the room. The average of the measured velocity values was then compared with the corresponding simulated velocity value obtained from the ANSYS Fluent model to assess the closeness of the velocity prediction. Comparison showed that both values were close and they varied in the same direction. In most cases the measured air velocity values were lower than the simulated values. When considering the difference using the t-test, there were 5 out of 9 cases which showed no significantly different conclusion at $\alpha = 0.05$ level. Therefore, it was considered that the simulation could represent the actual airflow pattern in the room with an acceptable degree of error.

Time Spent in the Upper Zone

The size of the saliva droplets created by a patient's coughing ranges from sub-microns to 1000 microns. For the purpose of the simulation, this study divided the droplet size into 2 groups, less than 5 microns and 6-20 microns, which composed 59% and 33% of the total droplets created by the patient's coughing, respectively. Droplets larger than 20 microns, 8% of the total, were excluded from the simulation because they were not airborne. The time that these disease particles spent traveling in the upper zone of the room and being radiated by the UV ray was simulated for different ventilation patterns and air change rates. The results are presented in Table 1. The shortest time belonged to the particles smaller than 5 microns in the H/H ventilation pattern at 12 ACH. On the other hand, the longest time belonged to the particles 6-20 microns in the L/H ventilation pattern at 6 ACH. The average values of the time spent in the upper zone ranged from 43.17-105.74 s. It can be seen that the time spent is inversely proportional to the air change rate. When considering the particle size, the larger particles spent more time in the upper zone than the smaller ones in every case. This could be because the larger particles had a higher terminal settling velocity so it was harder for them to be carried along the airflow path. From the ventilation pattern standpoint, the H/H pattern had the shortest time, followed by the H/L and L/H patterns. The reason may be that the H/H pattern had the shortest distance between the air inlet and outlet so the particles could leave the room faster than in the other 2 patterns.

UV Intensity from One UV Tube

In order to study the UV light distribution, 1 UV tube was installed on the front wall at 3 different heights above the floor: 2.7, 3.0, and 3.3 m. The power of the UV tube was also varied with 8, 16, and 30W. This resulted in 9 cases of experiments. The average values were calculated, as shown in Table 2. For each power level, the average intensity of the UV light in the upper zone was highest at the 3.0 m installation height. The values were 1.54, 2.43, and 10.55 $\mu W/cm^2$ for the 8, 16, and 30W, respectively. The 2.7 m installation had less intensity because it was the farthest from the ceiling so there was less additional UV light from the ceiling's reflection. On the other hand, the 3.3 m installation was the farthest from the floor so there was lower intensity at the lower area of the upper zone and thus it caused the average value to be low.

The same set-up as described above was also used to study the horizontal distribution of the UV intensity across the room. With 1 UV tube and varying installation heights and power levels, the UV intensity was measured at various horizontal distances away from the middle of the tube. Five measurement heights were used: 2.1, 2.4, 2.7, 3.0, and 3.3 m. It was found that in all cases the intensity first increased with the distance and peaked around 0.75-1.25 m away from the tube, then decreased as the distance approached 3.5 m. Figure 3 shows an example of the results for the case of the 8W tube installed at 3.0 m above the floor. The highest intensity was found at the same height as the tube, 3.0 m, and at a distance 0.75 m from the tube. The

Table 1. Time disease particles spent in the upper zone

Ventilation Pattern	Time Disease Particles Spent in The Upper Zone (sec)								
	6 ACH			9 ACH			12 ACH		
	≤ 5 µm	6-20 µm	Avg.	≤ 5 µm	6-20 µm	Avg.	≤ 5 µm	6-20 µm	Avg.
L/H	97.12	122.86	105.74	67.56	70.44	69.00	60.10	64.31	62.21
H/L	61.40	72.47	66.94	56.60	59.79	58.19	46.03	51.05	48.54
H/H	56.80	65.72	61.28	48.73	51.88	50.31	41.24	45.09	43.17

lower part of the upper zone, however, had little intensity levels no matter how close the position was to the tube.

UV Intensity from Multiple Tubes

Table 3 summarizes the average UV intensity values in the upper zone for different installation patterns. Each value was the average value from 3 installation heights. The results illustrate that the intensity values varied with both the number of tubes and the tube power levels. Moreover, for the 1-sided and 2-sided cases, it can be seen that the rectangular shape of the room caused the difference in the values obtained. For example, with an 8W tube, installing one on the front or back wall yielded an intensity value of 1.37 μW/cm², while installing it on the right or left wall yielded less at 1.23 μW/cm². This is because the radiation from a tube that was installed on the front or back wall covered more space than that installed on the right or left wall (Figure 4).

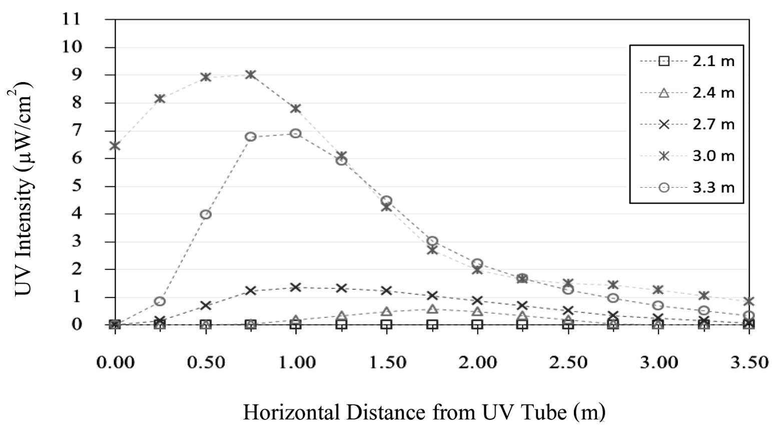

Figure 3. Horizontal distribution of UV intensity (1 tube at 3.0 m. installation height)

Table 2. Average UV intensity in the upper zone from 1 tube

Tube Power (W)	Tube Height (m)	Average UV Intensity in the Upper Zone (μW/cm²)
8	2.7	1.30
	3.0	1.54
	3.3	1.25
	Average	1.37
16	2.7	1.81
	3.0	2.43
	3.3	2.02
	Average	2.09
30	2.7	10.30
	3.0	10.55
	3.3	10.39
	Average	10.41

Maximum UV dose and Efficiency

Based on the results reported above, the ventilation pattern and rate which yielded the longest time with disease particles in the upper zone were L/H and 6 ACH, respectively. Moreover, the installation height with the highest UV intensity was found to be 3.0 m above the floor. Hence, these design configurations would yield the maximum values for the UV dose and germicidal irradiation efficiency. Table 4 presents the maximum UV dose and Table 5 the efficiency values for 3 UV tube power levels and different installation patterns, respectively. Both the UV dose and efficiency values varied with the number and the power of the tubes. The maximum dose ranged from 144.13-4,418.61 μW.s/cm^2, and the maximum irradiation efficiency ranged from 49.36-100.00%. To achieve more than 90% efficiency with the 8W power tube, one needs to use at least 3 tubes (90.53% for 3-sided installation). For 16W, the minimum was 2 tubes with front and back installation (91.19%).

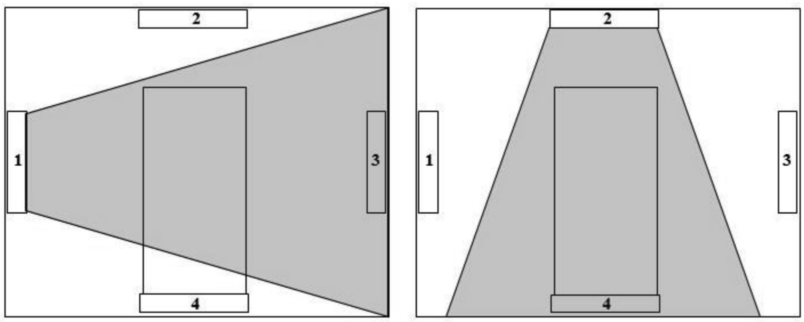

Figure 4. Radiation coverage from 1 tube installed on the front wall (left picture) covers more room space than that on the right wall (right picture)

Table 3. Average UV intensity in the upper zone from multible tubes

Tube Power (W)	Average UV Intensity in the Upper Zone (μW/cm^2)						
	1-Sided (F/B)[1]	1-Sided (L/R)[2]	2-Sided (F&B)[3]	2-Sided (L&R)[4]	3-Sided	4-Sided	6-20 μm
8	1.37	1.23	2.73	2.46	4.20	5.44	64.31
16	2.09	1.89	4.17	3.76	6.39	8.30	51.05
30	10.41	9.59	20.82	18.84	31.61	41.28	45.09

[1] Front or back, [2] Left or right, [3] Front and back, [4] Left and right

Table 4. Maximum UV dose (L/H ventilation pattern and 6 ACH flow rate)

Tube Power (W)	Maximum UV Dose (μW.s/cm^2)					
	1-Sided (F/B)[1]	1-Sided (L/R)[2]	2-Sided (F&B)[3]	2-Sided (L&R)[4]	3-Sided	4-Sided
8	162.65	144.13	325.30	288.65	499.36	645.06
16	257.23	229.08	514.46	457.16	787.87	257.23
30	1115.21	1018.76	2230.42	2007.87	3392.45	4418.61

[1] Front or back, [2] Left or right, [3] Front and back, [4] Left and right

For 30W, only 1 tube would be adequate to achieve near 100% efficiency, regardless of the wall installation pattern.

Optimum System Design

For hospital personnel to be able to operate safely, the lower zone of the room has to remain at a safe level of UV intensity. The criterion is that the intensity level should not exceed 0.2 μW/cm² at a height 1.7 m above the floor. Table 6 summarizes the average UV intensity measured at a height 1.7 m above the floor for every power level, installation height, and installation pattern. It was found that there were 20 cases that passed the criterion. The lowest tube power, 8W, could be used for 3 installation heights, although for the 2.7 m height only 1 tube could be used. The 16W tube could be used only at the highest installation height, 3.3 m. The 30W, however, exceeded the criterion in all cases.

For the 20 cases of configurations that passed the criterion, their germicidal irradiation efficiency values were calculated, as shown in Table 7. The values ranged from 44.60% to 98.19%. To achieve the maximum germicidal irradiation efficiency at 98.19%, the optimum system design was: 4-sided installation of 16W UV tubes at the height of 3.3 m above the floor, with a L/H ventilation position and 6 ACH flow rate.

Furthermore, according to the standard design Wor Sor 1/2549 room type, the isolation room has a H/L ventilation pattern and uses a 12 ACH flow rate. Hence, the germicidal irradiation efficiency values for such a system

Table 5. Maximum germicidal irradiation efficiency (L/H ventilation pattern and 6 ACH flow rate)

Tube Power (W)	Maximum Germicidal Irradiation Efficiency (%)					
	1-Sided (F/B)[1]	1-Sided (L/R)[2]	2-Sided (F&B)[3]	2-Sided (L&R)[4]	3-Sided	4-Sided
8	53.60	49.36	78.47	74.40	90.53	95.24
16	70.31	66.09	91.19	88.45	97.58	99.19
30	99.48	99.18	100.00	99.99	100.00	100.00

[1] Front or back, [2] Left or right, [3] Front and back, [4] Left and right

Table 6. Average UV intensity at room height 1.7 m. (values below 0.2 μW/cm² are in bold and with asterisks)

Tube Power (W)	Tube Height (m)	Average UV Intensity at Height 1.7 m. (μW/cm²)					
		1-Sided (F/B)[1]	1-Sided (L/R)[2]	2-Sided (F&B)[3]	2-Sided (L&R)[4]	3-Sided	4-Sided
8	2.7	**0.14***	**0.13***	0.29	0.25	0.34	0.54
	3.0	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***
	3.3	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***
16	2.7	0.31	0.34	0.62	0.68	0.98	1.30
	3.0	0.31	0.33	0.63	0.66	0.98	1.29
	3.3	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***	**0.00***
30	2.7	5.49	5.41	10.98	10.82	16.66	21.80
	3.0	1.76	1.37	3.53	2.75	4.94	6.28
	3.3	1.77	1.41	3.55	2.83	4.99	6.37

[1] Front or back, [2] Left or right, [3] Front and back, [4] Left and right

design were also considered for comparison purposes. This particular ventilation pattern and flow rate yielded less time spent by the disease particles in the upper zone and thus resulted in lower germicidal irradiation efficiency values (Table 8). The maximum efficiency for the standard design room was 84.64%. It could be acheived with the 4-sided installation of 16W UV tubes at the height of 3.3 m above the floor, with the H/L ventilation position and 12 ACH flow rate. Hence, the optimum system design in this study could achieve approximately 16% more germicidal irradiation efficiency than the standard design.

Conclusions

The findings of this study suggest several aspects of the design and operating condition for maximizing the germicidal irradiation efficiency. The efficiency is a function of the UV dose, which in turn is a function of 2 factors: UV intensity and irradiation time. A lower ventilation rate will allow more irradiation time, as well as an in-low/out-high ventilation patern. The in-high/out-high pattern yielded the shortest time and should not be used. The installation height which yielded the highest average UV intensity in the upper zone was at 3.0 m above the floor. This height gave a more complete coverage and also benefited from the additional reflection of light from the ceiling. Once these factors were determined and the safety criterion for occupants was considered, 20 possible system designs were identified. Their germicidal irradiation efficiency values ranged from 44.60% to 98.19%. The optimum system design suggested by this study, with 98.19% efficiency, was a system with the 4-sided installation of 16W UV tubes at the height of 3.3 m above the floor, using the L/H ventilation position and 6 ACH flow rate. This design had a 16% better

Table 7. Germicidal irradiation efficiency of possible UVGI system design (L/H ventilation pattern and 6 ACH flow rate)

Tube Power (W)	Tube Height (m)	Germicidal Irradiation Efficiency (%)					
		1-Sided (F/B)[1]	1-Sided (L/R)[2]	2-Sided (F&B)[3]	2-Sided (L&R)[4]	3-Sided	4-Sided
8	2.7	47.84	44.60	-	-	-	-
	3.0	53.60	49.36	78.47	74.40	90.53	95.24
	3.3	46.50	43.51	71.38	67.92	85.44	91.82
16	3.3	63.45	60.49	86.64	84.00	95.40	98.19

[1] Front or back, [2] Left or right, [3] Front and back, [4] Left and right

Table 8. Germicidal irradiation efficiency of standard-design Wor Sor 1/2549 room type (H/L ventilation pattern and 12 ACH flow rate)

Tube Power (W)	Tube Height (m)	Germicidal Irradiation Efficiency (%)					
		1-Sided (F/B)[1]	1-Sided (L/R)[2]	2-Sided (F&B)[3]	2-Sided (L&R)[4]	3-Sided	4-Sided
8	2.7	26.20	24.10	-	-	-	-
	3.0	30.13	27.21	51.18	47.07	66.73	75.87
	3.3	25.33	23.40	44.24	41.19	59.33	68.92
16	3.3	37.49	35.18	60.92	57.50	76.24	84.64

[1] Front or back, [2] Left or right, [3] Front and back, [4] Left and right

performance than the standard design Wor Sor 1/2549. The results could be used by community hospitals which need to improve or increase their modified isolation rooms to provide an adequate service for their patients.

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References

American Institute of Architects (AIA). (2006). Guidelines for Design and Construction of Health Care Facilities. American Institute of Architects, Washinton, DC, USA, 352p.

ASHRAE. (1992). Standard 41.2-1987 (RA 92), Standard Methods for Laboratory Airflow Measurement. I-P edition. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, USA, 32p.

ASHRAE. (2007). Health care facilities. In: 2007 ASHRAE Handbook – Heating, Ventilating, and Air-Conditioning Applications. American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Atlanta, GA, USA, p. 7.1-7.16.

Beggs, C.B., Noakes, C.J., Sleigh, P.A., Fletcher, L.A., and Kerr, K.G. (2006). Methodology for determining the susceptibility of airborne microorganisms to irradiation by an upper-room UVGI system. J. Aerosol Sci., 37(7):885-902.

Beggs, C.B. and Sleigh, P.A. (2002). A quantitative method for evaluating the germicidal effect of upper room UV fields. J. Aerosol Sci., 33:1681-1699.

Centers for Disease Control and Prevention. (2005). Guidelines for Preventing the Transmission of Mycobacterium tuberculosis in Health-Care Settings. Morbidity and Mortality Weekly Report, 54 / No. RR-17, 142p.

Chuchottaworn, C. (2008). Tuberculosis. Central Chest Institute of Thailand, Department of Medical Service, Nonthaburi, Thailand.

Division of Medical Engineering. (2006). Manual for Airborne-disease Patients Isolation Room. Department of Health Service Support, Ministry of Public Health, Nonthaburi, Thailand.

Khan, A.N., Feigley, C.E., Lee, E., Ahmed, M.R., and Tamanna, S. (2006). Effects of inlet and exhaust locations and emitted gas density on indoor air contaminant concentrations. Build. Environ., 41(7):851-863.

Ko, G., First, M.W., and Burge, H.A. (2000). Influence of relative humidity on particle size and UV sensitivity of Serratia marcescens and Mycobacterium bovis BCG aerosols. Tubercle Lung Dis., 80:217-228.

Kowalski, W.J., Bahnfleth, W.P., Witham, D.L., Severin, B.F., and Whittam, T.S. (2000). Mathematical modeling of ultraviolet germicidal irradiation for air disinfection. Quantitative Microbiology, 2:249-270.

Lytle, C.D. and Sagripanti, J.L. (2005). Predicted inactivation of viruses of relevance to biodefense by solar radiation. J. Virol., 79:14244-14252.

Mertens, R., Kegels, G., Stroobant, A., Reybrouck, G., and Lamotte, J.M. (1987). The national prevalence survey of nosocomial infections in Belgium. J. Hosp. Infect., 9:219-229.

Noakes, C.J., Beggs, C.B., and Sleigh, P.A. (2004). Modelling the performance of upper room ultraviolet germicidal irradiation devices in ventilated rooms: Comparison of analytical and CFD methods. Indoor Built Environ., 13:477-488.

Office of Policy and Strategy. (2010). Public Health Statistics. Office of the Permanent Secretary, Ministry of Public Health, Nonthaburi, Thailand.

Peccia, J.L. (2000). The response of airborne bacteria to ultraviolet germicidal radiation, [Ph.D. thesis]. Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, CO, U.S.A.

Peccia, J.L. and Hernandez, M.T. (2001). Photoreactivation in airborne Mycobacterium parafortuitum. Appl. Environ. Microb., 67:4225-4232.

Van Osdell, D. and Foarde, K. (2014). Defining the effectiveness of UV lamps installed in circulating air ductwork. Arlington, VA, USA: Air-Conditioning and Refrigeration Technology Institute. Available from : http://www. osti.gov/energycitations/servlets/purl/810964-SRS2Dd/native /810964.pdf. Accessed date: Jan 31, 2014.

Warissarangkul, W. (2014). Optimum condition of ultraviolet germicidal irradiation system in Tuberculosis isolation room, [M.Eng. thesis]. School of Environmental Engineering, Institute of Engineering, Suranaree University of Technology, Nakhon Ratchasima, Thailand, 178p.

Zhang, Z. and Chen, Q. (2006). Experimental measurements and numerical simulations of particle transport and distribution in ventilated rooms. Atmos. Environ., 40(18):3396-3408.