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Using Computational Fluid Dynamics Modeling to Evaluate the Design of Hospital Ultraviolet Germicidal Irradiation Systems for Inactivating Airborne Mycobacteria†

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ABSTRACT

This research was conducted to evaluate the design of hospital ultraviolet germicidal irradiation (UVGI) systems and to assess their effectiveness for inactivating airborne mycobacteria. A computational fluid dynamics (CFD) model was developed and tested by simulating previous experiments measuring the effectiveness of a lab-based UVGI system. Model testing showed reasonable agreement with experimental measurements. The model captured trends similar to the experiments: Effectiveness of an upper-room UVGI system is higher when there is no ventilation compared with when there is ventilation, and wintertime ventilation conditions can markedly decrease the performance of an upper-room UVGI system. The CFD model was then applied to evaluate the design of three hospital patient rooms. A patient and an exam room with upper-room UVGI systems, and a patient room with an exhaust duct system were studied. Results showed that one of the UVGI systems was not very effective, due to the very efficient ventilation design. The other two configurations were reasonably to very effective at inactivating airborne mycobacteria. The most effective application was the one in which the room air-exchange rate was very low. CFD modeling can be useful for assessing whether hospital UVGI installations and ventilation systems are effective for infection control.

INTRODUCTION

The transmission of tuberculosis and other infectious diseases in hospitals has been a recognized health hazard for decades. Ultraviolet germicidal irradiation (UVGI) is an engineering control technology used to prevent spread of airborne infections (1,2). An upper-room UVGI system consists of mounting louvered fixtures to the ceiling and/or walls to treat the upper areas of a room. An exhaust duct UVGI system consists of mounting UV lamps in exhaust ventilation ducts, drawing room air past the UVGI, then either recirculating the air back into the room or into the mixing plenum of the building's ventilation system.

Some hospitals have UVGI systems installed in their facilities (3,4). It is difficult to assess the effectiveness of these systems with measurements, which can involve verifying UVGI levels, air mixing and bioaerosol inactivation. A proven model may be useful in new hospital and renovation design (5,6). Airflow patterns have a strong impact on the effectiveness of UVGI systems because airborne microorganisms generated in the lower part of the room must be transported into the upper part of the room or duct where the UVGI is located. An advantage of computational fluid dynamics (CFD) modeling is that it can account for airflow patterns. Airflow patterns are influenced by many factors, including room furnishings, ventilation supply/exhaust locations and air temperatures.

CFD modeling has been used to successfully predict airflow and aerosol transport in rooms (7–10). The application of CFD for modeling upper-room UVGI efficacy has only recently been explored in depth. For this, there are several reasons. First, there is no existing commercial code that can be used directly to accomplish this task. The existing codes can simulate the airflow field and track particle transport, but cannot show the accumulation of UVGI exposure the particle has received. A separate tool is needed to estimate the UVGI exposure based on the particle tracking and the UVGI spatial irradiance distribution data. Second, there is insufficient microbiological data to support such analysis. The UV microbial inactivation rate of many airborne microorganisms remains unknown for air irradiation and is needed to estimate inactivation with CFD. Recently, however, studies concerning CFD and UVGI have provided promising results. Noakes *et al.* (11) modeled the effects of ventilation placement and heat sources on UVGI performance. Sung and Kato (6) used CFD to calculate the UVGI dose of an upper-room system based on predicting ventilation efficiency.

A CFD model was developed in this research to predict the effectiveness of UVGI systems for inactivating mycobacteria and to assess the design of three hospital room installations. The model estimated the dose received by airborne mycobacteria in a room equipped with a UVGI system. The dose was combined with the UVGI inactivation rate to predict the effectiveness of the UVGI system. This model was tested by simulating previously published experiments of the effectiveness of a UVGI system and comparing the results to measurements (12,13). A field investigation was then conducted of three patient rooms in two hospitals where UVGI systems were installed and being used. The data from this investigation were applied in the CFD modeling to predict the effectiveness of the hospital UVGI systems.

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MATERIALS

Computational fluid dynamics model. The commercial code *FLUENT* was used in this study to assess the design of three hospital UVGI installations. The model simulated the airflow and movement of airborne mycobacteria within the hospital rooms. These modeling results were used to estimate the dose of UVGI that the mycobacteria received as they circulated around the room equipped with a UVGI system. Details on modeling are available elsewhere (14). In brief, The RNG k-e turbulence model was used to represent the effects of turbulence in the flow (15). Constant velocity boundary conditions were assumed for air inlet diffusers, based on the airflow rate of the room. Constant pressure boundary conditions were assumed for the air outlets. The wall and ceilings were assumed adiabatic.

Particle tracking. Airborne particle position, velocity profiles and residence times at each location within a room were modeled using CFD. The accumulated UVGI dose the mycobacteria received was estimated by using a stochastic particle-tracking method and a UVGI spatial distribution previously measured (12). The airborne mycobacteria were assumed to be spherical solid particles with an aerodynamic diameter of 1.56 μm, which was the geometric mean size of mycobacteria aerosolized during previous experiments (12). The particles were released from a point location at a height of 1.1 m with an initial velocity of 0.45 m s^{-1} (12). It was assumed that no heat or mass transfer took place between the air and airborne particles and no mycobacteria rebounded once they adhered to surfaces. The stochastic particle-tracking method used was the discrete random walk model in *FLUENT*. This model predicts the turbulent dispersion of particles by integrating the trajectory equations for individual particles along the particle path during the integration using the instantaneous fluid velocity. Particle tracking was performed for a length of time that allowed particles to be removed by the ventilation system, or attach to solid surfaces. The number of particles tracked was such that the average fluence of the particles converged to a stable value within ±5%.

UVGI fluence and effectiveness. Two factors that influence the effectiveness of a UVGI system are the UVGI fluence and *Z* value. *Z* (m^2 J^{-1}) is the UVGI inactivation rate normalized by the fluence rate, which represents a microorganism's resistance to inactivation by UVGI under well-mixed room conditions (16,17). In this study, *Z* for mycobacteria was obtained from Xu *et al.* (12). The fluence was predicted using the CFD model. The fluence rate is denoted as *L* (J s^{-1} m^{-2}); it is the total radiant power incident from all directions onto an infinitesimally small sphere, normalized to the cross-sectional area of that sphere. The fluence or UVGI dose D (J m^{-2}) is the fluence rate integrated over time (D = *Lt*). The fluence that an airborne particle receives was determined in the CFD model by the equation:

$$D = \sum_{i}^{\infty} L_{x,y,z} \cdot \sigma \tag{1}$$

The location of the microorganism in space is denoted by *x, y, z*; $L_{x,y,z}$ is the UV fluence rate at *x, y, z* (J s^{-1} m^{-2}); and σ is the time to which the particle was exposed to UVGI (second); *i* is the tracking iteration. $L_{x,y,z}$ was modeled in three dimensions based on previous measured data from multiple points. Measurements of the UVGI fluence rate were made using both chemical actinometry and radiometry (18).

UVGI effectiveness, *E*, is defined as the ratio of airborne viable mycobacteria concentrations with and without UVGI:

$$E = 1 - \frac{C_{\mathrm{UV}}}{C_{\mathrm{No\_UV}}} = 1 - e^{-\mathrm{DZ}} \tag{2}$$

this expression for *E* assumes that the airborne mycobacteria are inactivated by UVGI as a first-order decay process (19):

$$C_{\mathrm{UV}}(t) = C_0 e^{-\mathrm{IR_{UV}} t} \tag{3}$$

where *t* is time (h); C_0 is the initial number of airborne viable mycobacteria (# m^{-3}); $C_{\mathrm{UV}}(t)$ is the number of viable mycobacteria when the UVGI system operating at time *t* (# m^{-3}); $C_{\mathrm{No\_UV}}(t)$ is the number of viable mycobacteria without the UVGI system operating at time *t* (# m^{-3}) and $\mathrm{IR_{UV}}$ is the inactivation rate due to UVGI (h^{-1}). Also $\mathrm{IR_{UV}} = Z \times L$. Other models have been proposed such as the series-event model (20) or the PPES model (21); these are better suited for when the UV dose–response behavior has a lag or a shoulder such as at high UV fluence rates (13,22).

The CFD model tracked the particles as they moved through the airflow field, from the point of release until they were removed from the airflow by either ventilation or deposition. UV fluence was estimated from Eq. (1) for each position of the particle. UVGI effectiveness was calculated by averaging the fluence of all the tracked particles and using Eq. (2).

CFD model testing. To test the CFD model it was first applied to the chamber used in previous experiments of the effectiveness of a lab-based upper-room UVGI system at the University of Colorado (12,13,23). The geometry and layout of the test chamber simulated are shown in Fig. 1. The system installed in the chamber (87 m^3) consisted of a louvered fixture in each of the upper corners of the room and one hung from the center of the ceiling (Lumalier, Memphis, TN). The UVGI system was rated at 216 W, which provided a spatial average upper-room UV fluence rate of 0.42 ± 0.19 J s^{-1} m^{-2} (18). The chamber was mechanically ventilated with two inlet diffusers and two outlets in the ceiling. Two box fans (48 cm diameter) for air mixing were located opposite of each other at floor level. To simulate room air mixing with the box fans, a constant airflow through the fan area was assumed, based on velocity measurements of the airflow from the fan. Airborne mycobacteria were released from the head of a heated (108 W) sitting mannequin in the middle of the room. Fluence was calculated by Eq. (1), effectiveness was calculated based on Eq. (2) and a *Z* of 1.03 × 10^{-1} m^2 J^{-1} was used (12).

Seven simulations were conducted (Table 1). Two mechanical ventilation conditions were simulated: 0 and 6 air changes per hour (ACH, h^{-1}). Mixing fans on and off were simulated. For 6 ACH and mixing fans off, the supply air temperature was set 10°C warmer than the room air temperature to simulate wintertime ventilation when heating takes place. The supply air temperature was also set at 10°C cooler than the room air temperature to simulate a summertime ventilation condition. For 0 ACH, two cases were considered. One was with the mannequin heating on generating buoyancy-driven flow and the other was with the mannequin heating off.

Field investigation of three hospital UVGI systems. Three rooms in two hospitals were investigated: A patient and an exam room with upper-room systems, and a patient room with an exhaust duct system. The characteristic parameters of the UVGI and ventilation systems, and room configurations in these facilities were measured in duplicate and documented. The UVGI fluence rates were measured by actinometry and with a radiometer (Model IL 1400 A; International Light Inc., MA) (12,18,24). A manometer (Model 1430; Dwyer Instruments Inc., ID) was used to measure the room pressure. The ventilation rates of the hospital rooms were estimated by measuring the velocity at the face of the air supply inlet and exhaust outlet using a velocity transducer probe (TSI 8475; TSI Inc, MN).

CFD modeling of three hospital UVGI systems. The CFD model was used to estimate the effectiveness of the three hospital UVGI systems. Figs 2–4 illustrate the hospital room layouts. The air supply diffusers of the ventilation systems were assumed to supply air at a constant velocity and the return outlets were assumed to be at constant pressure. The values of the velocities and pressures were based on measurement data. Rectangular blocks were used to represent patient beds.

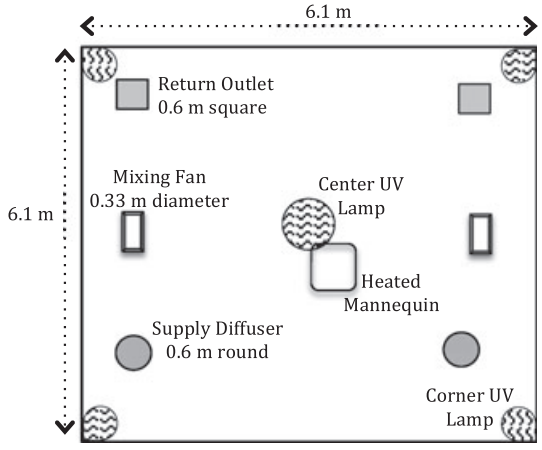

Figure 1. Layout (plan view) of testing chamber at the University of Colorado (12). Height of the room was 2.4 m.

Table 1. Ventilation and mixing conditions for the CFD model validation and predicted average UVGI fluence.

Ventilation	Mannequin heating	Mixing fan	Ventilation supply air temperature (°C)	Room air temperature (°C)	CFD modeled average tracked particle residence time (s)	CFD modeled average (SD) UVGI fluence, D (J m^{-2})
6 ACH summertime	On	Off	14	24	669	12 (3.8)
6 ACH wintertime	On	Off	34	24	651	4.5 (1.4)
6 ACH	On	On	24	24	461	7.5 (3.1)
6 ACH	On	Off	24	24	618	8.0 (2.2)
0 ACH	On	On	N/A	24	212	14 (4.3)
0 ACH	On	Off	N/A	24	821	16 (1.7)
0 ACH	Off	Off	N/A	24	811	8 (2.7)

The effectiveness of the hospitals' upper-room UVGI systems was estimated by CFD modeling as described previously. Particles were tracked in the CFD model as they moved with the airflow field, from the point of release until they were removed from the airflow by either ventilation or deposition. UV fluence was estimated from Eq. (1) for each position of the particle. Equation (2) was used to estimate effectiveness.

The modeling procedure to determine the effectiveness of the duct UVGI system was different from the one described previously. First the single-pass inactivation efficiency was estimated by the equation:

$$\eta_{UV} = 1 - \frac{C_{in}}{C_{out}} \quad (5)$$

where C_{in} and C_{out} are the viable mycobacteria concentrations upstream of the UVGI region and after passing through the UVGI region respectively. Particles were tracked using the CFD model as they passed into the duct and through the UVGI region. Equation (1) was used to estimate the fluence and $L_{x,y,z}$ was modeled in three dimensions based on the measured fluence rate within the duct at multiple points.

The total effectiveness of the system was estimated using Eq. (6):

$$E = 1 - \frac{ACH_V}{ACH_V + (\frac{1}{V})Q_{D_{UV}} \times \eta_{UV}} \quad (6)$$

The measured airflow rate through the duct UVGI system is Q_{D_UV} (m^3 h^{-1}); ACH_V is the room ventilation rate in air-changes per hour (h^{-1}). η_{UV} is the single-pass inactivation efficiency averaged over all the particles tracked in the CFD model. Equation (6) assumes that the room conditions were well mixed and at steady state.

RESULTS

CFD model testing

Figure 5 shows the particle-tracking results from one simulation of the University of Colorado experiments. The predicted average UVGI fluence of each simulation is summarized in Table 1. Figure 6 compares the UVGI effectiveness estimated from the CFD model and measured in the experiments (12,13). Standard deviations are the propagated standard deviations from duplicate experiments and from tracking multiple particles in the CFD model. For the 6 ACH summertime condition, the tracked particles spent relatively equal amounts of time in both the upper level and lower level of the chamber (Fig. 5).

Tracked particle residence times for each simulation are presented in Table 1. When the mixing fans were off, the particles spent a long time within the chamber traveling randomly throughout the room until they were exhausted (14). The mannequin heating had very little impact on the tracked particle residence time and effectiveness; the mixing fans did impact the particle-tracking residence times, but the effectiveness was similar as was the fluence.

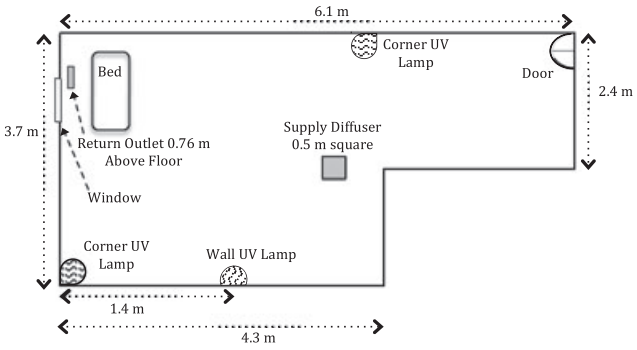

Figure 2. Layout (plan view) of patient room with upper-room UVGI system. Height of the room was 2.6 m.

Field investigation and modeling for three hospital UVGI systems

Table 2 documents the characteristics of the hospital rooms that were investigated and model predictions. Figure 7 presents particle-tracking results from the CFD simulation of the three hospital rooms.

Upper-room UVGI systems. The layout of the patient room is shown in Fig. 2. The patient room had one bed near the window. The room was equipped with three upper-room UVGI fixtures, one near the corner by the entrance and two in the inside corners, located far from the bed to avoid excess UVGI exposure of the patient. The ventilation system's exhaust outlet was installed close to the bed (head side). This configuration created a local ventilation effect and prevented any airborne mycobacteria generated in the bed from being dispersed into other parts of the room. Particles were tracked for two release locations in the patient room: close to the patient bed and at breathing height in the middle of the room (Fig. 7a, b). The particles generated near the patient bed and in the middle of the room were predicted by the CFD model to be exhausted in a very short time period: 8 and 13 s respectively. The overall characteristic residence time of the room due to ventilation was 529 s (1/6.8 h × 60 min h^{-1} × 60 s min^{-1}). There was a strong airflow toward the exhaust over the top of the bed that efficiently removed the airborne mycobacteria out of the room. Because the ventilation system so efficiently moved the airborne mycobacteria out of the room, the UVGI system did not have much of an impact.

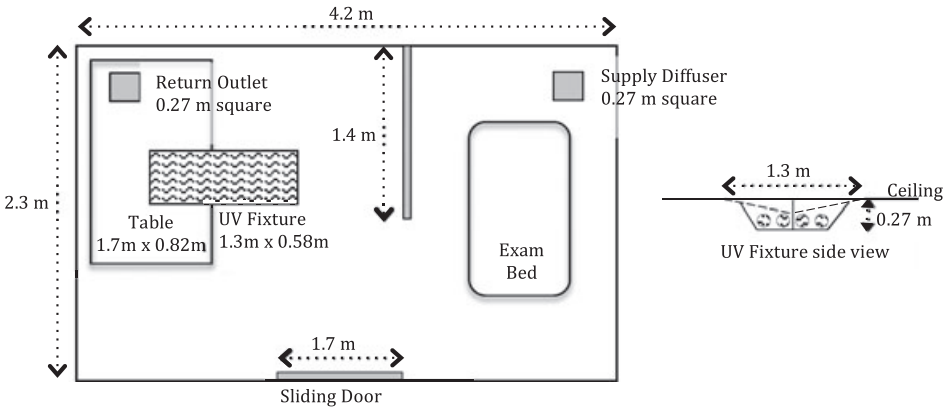

Figure 3. Layout (plan view) of exam room with upper-room UVGI system.

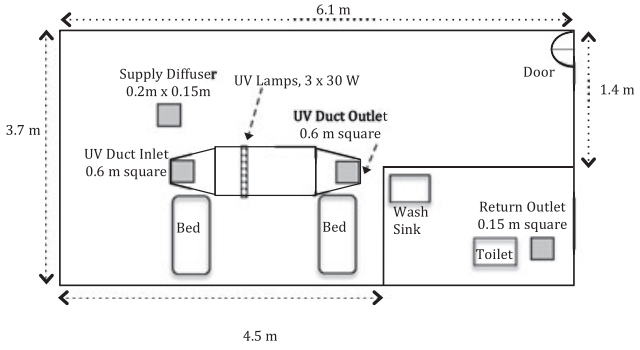

Figure 4. Layout (plan view) of patient room with exhaust duct UVGI system. Height of the room was 2.4 m.

The layout of the exam room is shown in Fig. 3. The exam room was equipped with one UVGI fixture irradiating the upper level of the room. The room had a partition that separated it into two spaces. One side had an exam bed, whereas the other side was an office area. The ventilation supply was in the bed area and the exhaust was in the office area. The UVGI fixture was fastened to the ceiling in the office area. The irradiated area compared to the total size of the room accounted for 12% of the total ceiling area. Because of a partition in the middle of the room separating the air supply from the exhaust, particles released on the side of the room where the supply was located were difficult to exhaust (Fig. 7c). The average particle residence time predicted by the model was 725 s. The overall characteristic residence time of the room due to ventilation was 507 s (1/7.1 h $\times$ 60 min $\times$ 60 s min^{-1}).

Exhaust duct UVGI system. The configuration of the patient room with the duct UVGI system is shown in Fig. 4. A duct UVGI system was installed in the ceiling where room air was drawn by a fan into the duct, it passed by the UVGI lamps and then was discharged back into the room. The inlet was located at one side and exhausted at the other side of the room. There were two patient beds in the room and the supply and return of the duct UVGI system were located above the beds. UV fluence rates at two different distances from the lamps in the duct are presented in Table 3. The total UV fluence rate for a particle passing through the duct was 40.3 J s^{-1} m^{-2}, calculated by integrating the UVGI exposure along the path through the duct. CFD modeling showed that particles released in the room near a patient bed traveled up and down in the room before they were exhausted into the duct UVGI system (Fig. 7d). The average residence time was predicted to be 130 s. The overall characteristic residence time of the room due to ventilation was 121 s (1/29.8 h $\times$ 60 min h^{-1} $\times$ 60 s min^{-1}).

DISCUSSION

Model testing showed that the effectiveness predicted by the CFD model was comparable in most cases with the effectiveness estimated in the University of Colorado experiments. The ratio of experiment-to-model effectiveness ranged from 0.31 to 1.68. The model was able to capture trends similar to the experiments: Effectiveness of upper-room UVGI systems is higher when there is no ventilation compared with when there is ventilation, and wintertime ventilation conditions can markedly decrease the performance of upper-room UVGI systems. Typically, the model underpredicted the experimental results, except for the wintertime condition. Agreement was better for cases in which there was no ventilation, with a percent difference between model and experiments of 10–19%, compared to when there was ventilation, (percent difference was 222% for wintertime and 40% for 6 ACH), indicating that the model did not capture the impact of mechanical ventilation well. It may be that the model performance could be improved by a better representation of the supply diffusers (25).

Two types of UVGI systems used in hospitals were characterized: an exhaust duct UVGI and an upper-room UVGI system. The upper-room system in the patient room had a very low effectiveness, 5%, mainly because of the very effective design of the ventilation system. The ventilation system removed the airborne mycobacteria before they were irradiated sufficiently. The exhaust was located close to the source (the bed in this case) and the room was ventilated at a high rate of 6.8 h^{-1}, so the mycobacteria received very limited UVGI dose. Effectiveness is defined relative to how well the ventilation system works, and the ventilation system was very efficient for this room. To control infectious disease transmission in a hospital facility, a high ventilation rate with a well-designed inlet and outlet configuration or a well-designed upper-room UVGI system can be selected, but a combination of both may not be useful.

The upper-room system in the exam room was reasonably effective, 57%. The system irradiated only a small fraction of the upper room (it was installed close to the ceiling, and therefore,

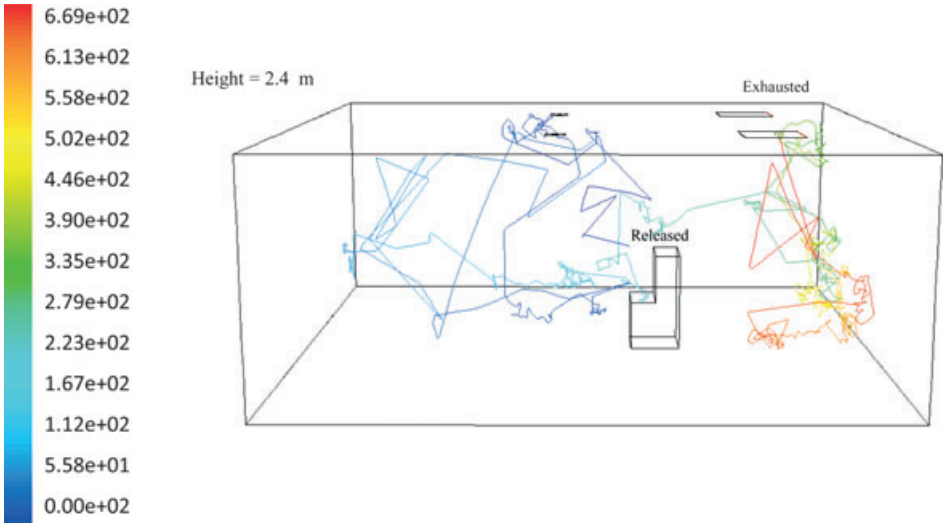

Figure 5. Particle-tracking prediction from the computational fluid dynamics model for the 6 ACH summertime condition. Only one tracked particle is shown in the figure. The color legend is the residence time in seconds of the particle released.

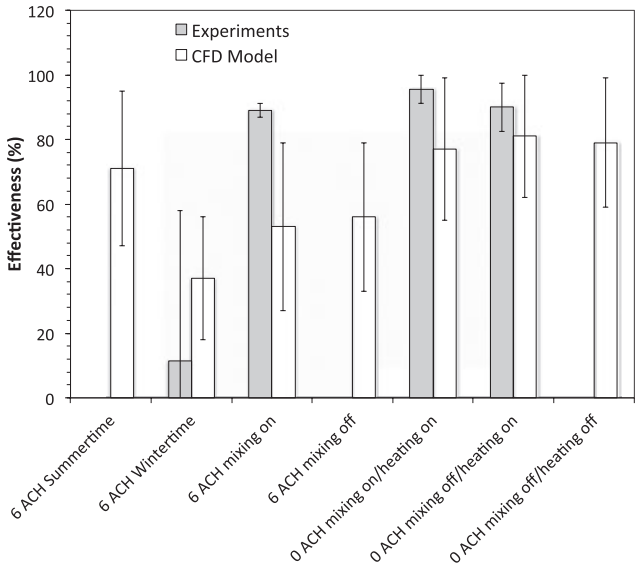

Figure 6. Effectiveness of an upper-room ultraviolet germicidal irradiation system at inactivating airborne mycobacteria predicted by a computational fluid dynamics model compared with the effectiveness based on measurements made in experiments conducted at the University of Colorado. Mixing on indicates mixing fans were operating, heating on indicates the mannequin where the particles originated from was heated, summertime conditions indicate the ventilation supply air was 14°C compared to the room temperature of 24°C and wintertime conditions indicate the ventilation supply air was 34°C compared to the room temperature of 24°C.

only a limited space was irradiated). The air-exchange rate of this room was very similar to the patient room discussed above, 7.1 h^{-1}. The return outlet was located far from the patient bed and source of particles. The partition separating the ventilation supply diffuser from the return outlet allowed the airborne mycobacteria to circulate throughout the room and be irradiated for a reasonable enough time to be inactivated. An improvement in this room's UVGI design might be to not install the system so close to the ceiling, or install an additional fixture.

The exhaust duct system was very effective at inactivating airborne mycobacteria, >90%. This was because the flow rate through the duct system was high and the ventilation system had almost no impact due to the low air-exchange rate. An upper-room UVGI system would most likely have also been a good choice for installation in this room. In some rooms, a duct system is not feasible due to installation difficulty above the ceiling or the added cost of a blower. The duct UVGI system was also noisy. One advantage of a duct system is that high-powered UV lamps can be used without louvering for more UVGI dose without concern of overexposure to the patient in bed.

All of the upper-room UVGI hospital rooms studied were ventilated at an air-exchange rate above the CDC-recommended minimum of 6 ACH, but below their recommended 12 ACH for new and renovated isolation rooms (1). The patient room in which the duct UVGI system was installed had a very low ventilation rate of 0.8 ACH. The negative pressures in all the rooms were maintained throughout the measurement period and were higher than the 0.25 kPa required by the CDC guideline (1). The temperatures and relative humidity were within a reasonable range and no episodes of elevated relative humidity were observed, as expected during the winter in Colorado.

The patient room with the upper-room system was well designed in terms of the location of the ventilation supply diffuser and return outlet—that is, the return outlet was located near the mycobacteria source, the patient in the bed. In the exam room, the return outlet was farther from the exam bed and source of mycobacteria. The location of the UV duct inlet and outlet in the patient room with the duct system was appropriate, near to the patient beds and the probable source. Note that only a couple of release points within the rooms studied were considered and if the particles were released in other locations, the results may be different.

Some of the UV lamps in the fixtures were replaced regularly, such as in the patient rooms, which were replaced every 6 months. The lamps in the duct UVGI system got dirty more quickly than the lamps in the upper-room UVGI systems because air directly from the room was flowing by the duct UVGI lamps continuously. Changing and cleaning the duct lamps every 6 months was probably not enough for the duct UVGI system.

Table 2. Measured and modeled hospital room characteristics.

	Patient room	Exam room	Patient room
Type of UVGI system	Upper-room (3 fixtures)	Upper-room (1 fixture)	Exhaust duct
Room volume (m^3)	23.4	28.4	23.6
Air-exchange rate (h^{-1})	6.8	7.1	0.8 (room infiltration rate), 29 (recycled air through duct)
Upper-room UV fluence rate (J s^{-1} m^{-2})	0.17	8.6	See Table 3
Eye level UV fluence rate (J s^{-1} m^{-2})	0.0005	0.0001	0.0002–0.0018
UV lamps wattage (W)	N/A	4 × 30	3 × 30
Temperature (°C)	22	23	25
RH (%)	57	59	58
Relative room pressure (Pa)	−8.8	−6.4	−10.1
Average modeled particle fluence (J m^{-2})	0.55	8.1	40.3
Average modeled effectiveness (SD) (%)	5 (4)	57 (23)	97
Average modeled single-pass inactivation efficiency (%)	–	–	98

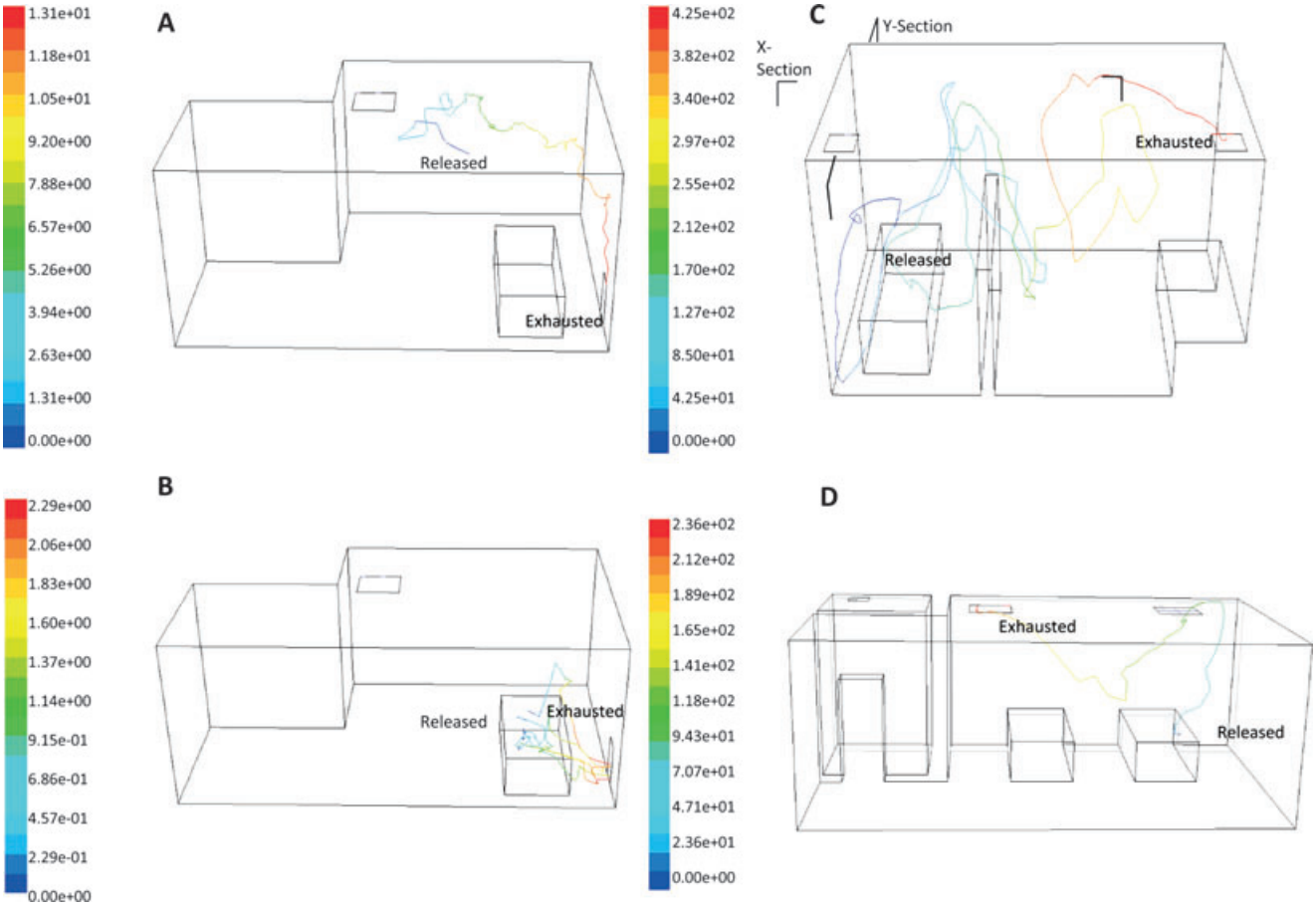

Figure 7. CFD particle tracking in three hospital rooms: (a) patient room with upper-room UVGI and particle released from middle of the room; (b) patient room with upper-room UVGI and particle released from bed; (c) exam room with upper-room UVGI with particle released at exam bed and (d) patient room with ducted UVGI system and particle released from a bed. The color legend is the residence time in seconds of each particle released.

Either more frequent maintenance work is required or the air should be filtered upstream of the duct lamps. The lamps in the upper-room UVGI system of the exam room were not changed regularly. UVGI lamp output can be decreased significantly after passing its designed operation time or if dirty, which would make the system noticeably less effective.

No compliance of UV fluence rates with the National Institute of Occupational Safety and Health (NIOSH) maximum permissible exposure standard was addressed during the investigation. All radiation levels in the occupied part of the rooms were below the NIOSH limit of 0.002 W m^{-2} for an 8 h period (2). All of the rooms were used extensively; the patient rooms were 80% full and the exam room was used on a regular basis. No skin and eye irritation injury due to overexposure from these UVGI systems was reported. TB skin tests of medical workers working around these areas were carried out every 6 months.

Table 3. Measured duct UVGI system fluence rate in patient room.

	Location from lamps (m)	UV fluence rate (J s^{-1} m^{-2})*
Upstream	0.61	8.8
	1.22	4.4
Downstream	0.61	10
	1.22	5.2
Average	–	16

*Average of duplicate measurements.

CONCLUSION

UVGI systems installed in hospital rooms for decreasing the chance of airborne infection should be designed so that they are used to their maximum effectiveness. For the hospital rooms studied in this research, the most effective UVGI systems were the ones installed in rooms with minimal ventilation. The location of the return outlet and supply diffusers should be considered as well as the room air-exchange rate when designing a system. A design guide is available from the National Institute of Occupational Safety and Health that describes best practices with regards to installation of an upper-room UVGI system (2). This study showed that the effectiveness of UVGI systems in hospital rooms could be explored from direct observations and the use of modeling. Modeling tools for predicting performance of a system as installed are very advantageous, but can be difficult to implement and still need refining. More work is needed to optimize CFD modeling for UVGI system design.

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Conflicts of interest—All authors report no conflicts of interest relevant to this article.

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