Evidence on the effectiveness and safety of ultraviolet germicidal irradiation technologies in reducing SARS-CoV-2 in the air of occupied rooms

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Introduction

What is the effectiveness and safety of UVGI technologies in reducing SARS-CoV-2 in the air of occupied rooms?

Ultraviolet germicidal irradiation (UVGI) is a method of disinfection that uses ultraviolet-C (UV-C) radiation (200-280nm) to inactivate microorganisms and pathogens on surfaces, in air, and in water. UV-C has demonstrated the ability to effectively and safely inactivate the SARS-CoV-2 virus up to 99.9% [1]. UVGI technologies that use UV-C, commonly at a peak wavelength of 254 nm, have been used to disinfect indoor spaces such as hospitals and clinical settings for years, but are generally used when there are no people present as UV-C wavelengths >230nm can have negative effects on human tissue directly exposed to the UV-C [2]. Some of these effects include phototoxicity (skin irritations) and photokeratitis (eye irritations) [3].

There are four methods to disinfect the air with UVGI technologies: 1) irradiating the upper-room air only (upper-room UVGI), 2) irradiating the full room, whole-room far UV-C when rooms are occupied, 3) UVGI placed in portable air cleaners, and 4) irradiating air as it passes through enclosed spaces which commonly include in-duct UVGI placed in heating, ventilation, and air-conditioning (HVAC) systems. The latter is excluded from this review as there is no evidence that SARS-CoV-2 has been transmitted through ventilation systems. This review will focus on evidence for the application of the first three methods when rooms are occupied. Of these methods, upper-room UVGI has been used for more than 70 years to reduce transmission of pathogens such as tuberculosis (TB) [4].

The studies in this review cover various UVGI technologies that can be used in rooms with people present, including UV-C lamps that are wall-mounted, UV-C ceiling fans, and portable UV-C air cleaners. This evidence brief summarizes the literature regarding the safety and effectiveness of UVGI technologies in reducing SARS-CoV-2 in the air of occupied rooms up to March 18, 2022.

Key points

Nine studies were included, nine reporting on the effectiveness (Table 1-3) and two reporting on the safety (Table 4) of UVGI technologies to reduce SARS-CoV-2 in the air of occupied rooms. The evidence was from simulation (n=8) and observational (n=1) studies and overall the level of evidence in this review is considered low.

Effectiveness

Nine studies were in agreement that UVGI technologies can be effective in reducing SARS-CoV-2 in the air of occupied rooms. The technologies investigated included whole-room UVGI using far UV-C (n=1), upper-room UVGI (n=7), and portable UV air cleaners (n=1).

One study investigated the effectiveness of a new UVGI technology using a far UV-C lamp.

- A whole room UV simulation demonstrated a far UV-C lamp (207-222nm) could further reduce SARS-CoV-2 by 50-85% compared to ventilation alone and with both far UV-C and high ventilation the SARS-CoV-2 viral count was reduced by 90% in 6 minutes and 99% in 11.5 minutes [5].

The upper-room UVGI technologies investigated included wall-mounted UV-C lamps (n=6) and UV-C ceiling fans (n=1). Both the wall mounted and ceiling fan fixtures have disinfecting UV-C lamps that aim up at the ceiling. These technologies were effective in reducing SARS-CoV-2 in the air of occupied rooms in both observational (n=1) and simulation (n=6) studies.

- A Russian hospital reported only community acquired COVID-19 cases among staff April to June 2020 and no transmission among patients to staff in hospital rooms with wall-mounted upper room UVGI fixtures (low-pressure mercury lamps, 254nm) [6].
- When the UV-C susceptibility constant for SARS-CoV-2 is 0.038 m^2/J, SARS-CoV-2 disinfection rates >90% can effectively occur in a 2.5m high room with ventilation rates between 1-6 air changes per hour (ACH), and one UV lamp (30 W) located every 18.6 m^2 (average fluence rate = 50 $\mu W/cm^2$), where fluence is a measure of UV dose and is defined as the total radiant energy on an infinitesimal sphere [7].
- A dose response relationship was demonstrated where a UV-C lamp (254nm) with a power of 55 watts (W) was more effective at inactivating SARS-CoV-2 in the air over a period of 10 seconds compared to 25 W [8].

Two simulation studies in a college and university setting suggest that SARS-CoV-2 infection risk was lowest when upper-room UVGI technology was used in combination with other public health measures [9, 10].

- In a classroom study, SARS-CoV-2 infection risk was lower when using general ventilation and upper room UVGI technology (28%), compared to using general ventilation and masking (35%) [10].
- The addition of UV-C ceiling fans (upper room UVGI technology) in every classroom reduced the risk of SARS-CoV-2 infections, hospitalizations, and deaths more than universal masking alone. A combination of masking and UV-C ceiling fans shows the greatest reduction in risk [9].

Portable UV air cleaners were effective in reducing SARS-CoV-2 from the air of occupied rooms.

- The use of a portable UV air cleaner can effectively filter up to 82% of airborne droplets with SARS-CoV-2 in a patient room [11].

Safety

Two studies reported on the safety of using UV-C lamps for inactivating SARS-CoV-2 in rooms with people present. The main safety concerns are about exposure to UV wavelengths >230nm that can penetrate the skin and eye tissue resulting in damage. Exposure prevention through proper UVGI system design and professional maintenance is recommended. Other safety concerns about ozone by-products or volatile organic compounds were not measured or discussed in the identified literature.

- A field investigation from Russia reported that upper room UVGI low-pressure mercury lamps (254 nm, 30 W) used 24 hours a day, 7 days a week, in occupied hospital rooms were safe, as no overexposure cases were reported [6].
- One simulation study examined the impact of different room design parameters on the safety of using an upper room UVGI lamp for SARS-CoV-2 inactivation:
  - A rectangular room with one UVGI lamp (25.47 W) mounted at a height of 2.29m on the short wall, was the safest configuration due to the ideal distance between the wall-mounted UVGI lamp and the opposite wall, resulting in less UV-C radiation reflected to the occupied lower area of the room [12].
  - The higher the UVGI lamp is located on the wall, the lower the risk of over-exposure [12].
  - In an L-shaped room, UVGI lamp use was most likely to lead to overexposure when one upper zone UVGI lamp (25.6 W) was placed on both short walls of the room, compared to on one long wall of the room [12].

Overview of the evidence

There were 9 studies that reported on the effectiveness and safety of UVGI technologies in reducing SARS-CoV-2 in the air of occupied rooms included in this review. This includes simulation studies (n=8) and a field investigation (n=1). Seven studies reported on effectiveness and two reported on both safety and effectiveness. All studies were peer reviewed with the exception of one pre-print study that had not undergone peer review.

The evidence from the observational study designs is at high risk of bias as they are subject to missing information, selection bias, and confounding factors. Simulation experiments were highly variable in their objectives and approaches. These studies aim to mimic a real world scenario to explore options for different UVGI interventions. There was no attempt to assess the validity of these studies. Their results should be interpreted with caution as they may not reflect what would happen in a field setting. For this review, no formal risk of bias assessment was conducted. Overall there was a low level of evidence and the outcomes of this review may change with future research. Additional studies, analyses, and reporting of real-world evidence are required to improve confidence in the outcomes of this review.

What is the effectiveness of UV-C lamps used for whole-room far UV-C to reduce SARS-CoV-2 in the air of occupied rooms?

New UV-C technology produces consistent short UV-C at a narrow bandwidth range 207-222nm which does not penetrate the outer surface of the skin or eye. Due to this unique attribute these UV-C lamps may be projected into an occupied space. The far UV-C lamps are excimer lamps made of krypton-chloride that emit 222nm or light-emitting diodes such as those made of aluminum nitride that emit UV-C 210nm [13]. One simulation study reported on the effectiveness of whole room far UV-C to inactivate SARS-CoV-2 (Table 1).

- The use of a far UV-C lamp (207-222 nm) located in the upper corner of a 3x3 meter air conditioned room projecting down into the room occupied by a single person was simulated [5]. When the far UV-C lamp was used with high ventilation, the SARS-CoV-2 viral count was reduced by 90% in 6 minutes and 99% in 11.5 minutes [5]. This viral count reduction was performed in less than half the time it took for high ventilation of 8.0 air changes per hour (ACH) alone to reduce viral count [5].

What is the effectiveness of UV-C lamps used for upper-room UVGI to reduce SARS-CoV-2 in the air of occupied rooms?

Seven studies assessed the effectiveness of UV-C lamps to reduce SARS-CoV-2 in the air of rooms with people present. This included simulation studies (n=6), and a field investigation (n=1). High level points are listed below, and details on individual studies can be found in Table 2.

- While community acquired COVID-19 cases were reported among staff in a hospital in Russia from April to June 2020, there was no SARS-CoV-2 transmission reported among TB and HIV patients located in hospital rooms with wall-mounted upper UVGI fixtures (low-pressure mercury lamps, 254nm) [6].
- Four simulation studies on upper-room UVGI (254nm) [7, 8, 12, 14] suggest that this application is effective in reducing SARS-CoV-2.
    - A simulation of the use of upper-room UVGI (254nm) in three room configurations effectively disinfected SARS-CoV-2 (fluence rate less than 48 μW/cm^2). The ceiling height/UVGI mounting device height (C/M heights) of 2.44m/2.13m was most effective at SARS-CoV-2 upper zone disinfection (average fluence rate = 56.56 μW/cm^2), while all other C/M heights had an average fluence rate of less than 48 μW/cm^2, which is the threshold for average fluence rate [12].

  - Another upper room UVGI study suggested when the UV-C susceptibility constant for SARS-CoV-2 is 0.377 m^2/J and ventilation is 8 ACH, the average irradiation needed for 50%, 70%, and 90% SARS-CoV-2 inactivation is 2.6 $\mu W/cm^2$, 4.4 $\mu W/cm^2$, and 8.5 $\mu W/cm^2$, respectively. Even in the worst-case scenario (0.0377 m^2/J), SARS-CoV-2 disinfection rates >90% can effectively occur in a 2.5m high room with ventilation rates between 1-6 ACH, and one UV-C lamp (30 W) located every 18.58 m^2 (average fluence rate = 50 $\mu W/cm^2$) [7].
  - A dose response relationship was shown in a third simulation where a UV-C lamp (254nm) with a power of 55 watts (W) was more effective at inactivating SARS-CoV-2 in the air over a period of 10 seconds compared to 25 W [8].
  - Increasing the number of UV beams and the separation between the angles of UV beams hitting the virus particle resulted in reduced SARS-CoV-2 survival fraction in a simulation study [14].

Two simulation studies in a college and university setting suggest that SARS-CoV-2 infection risk was lowest when upper-room UVGI technology was used in combination with other public health measures [9, 10].

- A simulation of a college with ~11,000 students and faculty suggests that the addition of UV-C ceiling fans in every classroom reduces the risk of SARS-CoV-2 infections, hospitalizations, and deaths more than no intervention and universal masking alone. A combination of masking and UV-C ceiling fans show the greatest reduction in SARS-CoV-2 infection risk [9].
- A simulation study in a university setting suggests that SARS-CoV-2 infection risk was lowest when upper room UVGI technology was used with general ventilation (increased air changes per hour), masking, and HEPA filtration [10]. In a classroom, SARS-CoV-2 infection risk was lower when using general ventilation and upper room UVGI technology (28%), compared to using general ventilation and masking (35%) [10].

What is the effectiveness of portable UV air cleaners to reduce SARS-CoV-2 in the air of occupied rooms?

One simulation study reported on the effectiveness of portable UV air cleaners in inactivating SARS-CoV-2 in the air of rooms with people present (Table 3).

- The use of a portable UV air cleaner can effectively filter up to 82% of airborne droplets with SARS-CoV-2 in a patient room [11]. Increasing the flow rate of the UV air cleaner may improve SARS-CoV-2 filtration efficiency, however, there may be a risk of wider distribution of SARS-CoV-2 in the room [11].

What is the safety of UVGI technologies to inactivate SARS-CoV-2 in the air of occupied rooms?

Two studies reported on the safety of using UV-C lamps for inactivating SARS-CoV-2 in rooms with people present. This included a field investigation and a simulation study. High level points are listed below and details on individual studies can be found in Table 4.

- A field investigation from Russia reported that upper room UVGI low-pressure mercury lamps (254 nm, 30 W) used 24 hours a day, 7 days a week, in occupied hospital rooms were safe [6]. No overexposure cases were reported in 17 years of use to disinfect tuberculosis and at the beginning of the SARS-CoV-2 pandemic [6].
- One simulation study examined the impact of different room design parameters on the safety of using an upper room UVGI lamp for SARS-CoV-2 inactivation:
    - A rectangular room shape (dimensions=4.57m x 3.44m x 2.74m) with one UVGI lamp (254 nm, 25.47 W) mounted at a height of 2.29m on the short wall of the room, was the safest configuration due to the ideal distance between the wall-mounted UVGI lamp and the opposite wall [12]. This resulted in less UV-C radiation reflected from the wall to the occupied lower area of the room [12].
    - The higher the UVGI lamp is located on the wall, the lower the risk of over-exposure. If the ceiling height is 2.74 m, a UVGI lamp mounting height of 2.29 m results in a reduced level of UV-C radiation reflected into the lower zone of the room, compared to a mounting height of 2.13m [12].
    - In an L-shaped hospital room (7.32m x 4.57m x 2.74m), UVGI lamp use was most likely to lead to overexposure when one upper zone UVGI lamp (25.6 W, 254 nm) was placed on both short walls of the room [12]. When both UVGI lamps were located on one long wall of the room, it resulted in the lowest risk of overexposure [12].

Methods

A daily scan of the literature (published and pre-published) is conducted by the Emerging Science Group, PHAC. The scan has compiled COVID-19 literature since the beginning of the outbreak and is updated daily. Searches to retrieve relevant COVID-19 literature are conducted in Pubmed, Scopus, BioRxiv, MedRxiv, ArXiv, SSRN, Research Square and cross-referenced with the COVID-19 information centers run by Lancet, BMJ, Elsevier, Nature and Wiley. The daily summary and full scan results are maintained in a refworks database and an excel list that can be searched. Targeted keyword searching was conducted within these databases to identify relevant citations on COVID-19 and SARS-COV-2. Search terms used included: UVGI, ultraviolet germicidal irradiation, upper room, far UV, near UV, far ultraviolet, near ultraviolet, portable air clean*, UV robot, ultraviolet robot, UV-C, UVC, UV disinfect*, UV-C disinfect*, UVC disinfect*, and UVX. This review contains research published up to March 18, 2022. Each potentially relevant reference was examined to confirm it had relevant data and relevant data was extracted into the review.

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Evidence tables

Table 1: Evidence on the effectiveness of UV-C lamps for whole-room far UV-C in inactivating SARS-CoV-2 in the air of occupied rooms (n=1)

Study	Method	Key outcomes
Simulation study (n=1)		
Buchan (2020) [5] Simulation study UK Nov 2020	Researchers simulated the use of a far UV-C lamp (new technology that emits a narrow bandwidth of 207-222 nm, which are safe for humans) located in the upper corner of a 3 meter by 3 meter air conditioned room projecting down into the room (whole room UVGI), occupied by a single person. There were two vents located in the upper corners of the room, and tests were conducted at two different velocities (0.1 ms^{-1} / 8.0 air changes per hour (ACH) and 0.01 ms^{-1} / 0.8 ACH). This was to determine the efficacy of far UV-C in inactivating SARS-CoV-2 when different velocities of ventilation were used alone, or in combination with far UV-C. To represent far UV-C inactivation values of SARS-CoV-2, the inactivation value of other human coronaviruses was used. The viral load of SARS-CoV-2 was released into the room using	• When the far UV-C lamp was used with high ventilation, the SARS-CoV-2 viral count was reduced by 90% in six minutes and 99% in 11.5 minutes. This viral count reduction was performed in less than half the time it took for high ventilation of 8.0 ACH alone to reduce viral count. • The use of a far UV-C lamp in combination with ACH ventilation at 0.8 and 8.0 velocities resulted in quicker SARS-CoV-2 inactivation at all distances, compared to using 0.8 or 8.0 ACH ventilation alone. • When the viral load of SARS-CoV-2 was released using two second pulses and two second pauses to represent breathing, the use of the far UV-C lamp in combination with 0.8 or 8.0 ACH ventilation, resulted in a ~20% or 57% further reduction in viral concentration, respectively, compared to 0.8 or 8.0 ACH ventilation used alone.

Study	Method	Key outcomes
	two second pulses and two second pauses to represent breathing.	

Table 2: Evidence on the effectiveness of UV-C lamps used for upper-room UVGI in inactivating SARS-CoV-2 in the air of occupied rooms (n=7)

Study	Method	Key outcomes
Field investigation (n=1)		
Volchenkov (2021) [6] Field investigation Russia 2003-2020	Researchers examined the effectiveness and safety of upper and whole room UVGI in reducing SARS-CoV-2 and TB transmission among employees and patients within a hospital building. The UVGI source consisted of 240 wall-mounted UV-C fixtures (one fixture per 18 m^2). Each UV-C fixture contained two low-pressure mercury lamps (T8 30W, wavelength = 254 nm) for upper and whole-room UVGI, respectively. The upper-room UVGI lamp was used 24 hours per day, 7 days per week, when people were present and absent from the hospital rooms, while the whole-room UVGI lamp was only used when people were not present in the room.	• There was no SARS-CoV-2 transmission reported among TB and HIV patients located in hospital rooms with the UV-C fixtures, while community acquired COVID-19 cases were reported among staff from April-June 2020. • Safety results found in Table 5.
Simulation studies (n=6)		
Li (2021) [10] Simulation study China Jul 2021	This study aimed to evaluate the SARS-CoV-2 infection risk in different indoor locations at a university, and the efficacy of engineering control measures (including upper room UVGI) in different exposure scenarios. The Wells-Riley equation was used to model SARS-CoV-2 infection risk. The model assumed that the inactivation	For the scenarios in a classroom, gym, library, and dining hall: • The average SARS-CoV-2 infection risk was lower when UVGI was used in addition to masking and general ventilation, compared to only masking and general ventilation.

Study	Method	Key outcomes
	rate for upper room UVGI was 12± 1.3 h^{-1} (based on prior research using mycobacteria). Wavelength and power of the UVGI was not specified. General ventilation looked at increasing air change rates from 0.5 to 4 per hour. Masks included a range of risk reduction estimates from surgical, dental, homemade and N95s. The five exposure scenarios included: sleeping or talking in a dormitory, studying or talking in a classroom, playing basketball in a gym, studying or whispering in a library, and eating in a dining hall.	• The infection risk was approximately the same when general ventilation was used with HEPA vs. with UVGI. • The lowest infection risk was found when a combination of general ventilation, masking, UVGI, and HEPA was used. For the scenario in a classroom: • The SARS-CoV-2 infection risk was 35% with general ventilation and masking vs. 28% with general ventilation and UVGI (exposure time was 24 hours). • Note: The model did not take into account the type of UVGI technology or its installation location.
Hill (2021)[14] Simulation study USA Jul 2021	This study aimed to examine the optimization of a UVGI disinfection system on the survival fraction of SARS-CoV-2 virions that are within host particles (shielding them from UVGI) in the air or on surfaces. For the purposes of this review, only the upper room UGVI applications were considered. In the simulations, virions in a group of particles were exposed to UV light and the average survival fraction of the virions was calculated under varying conditions regarding the number of light beams and the distance between the angles of light. UV wavelengths of 260 nm and 302 nm were studied.	• When exposed to UVGI, the survival fraction of SARS-CoV-2 virions in host particles increased as the particle size increased. • Increasing the number of UV light beams hitting the particle resulted in a lower virion survival fraction, even though the total UV energy emitted remained the same. • Increasing the separation between the angles of UV light beams hitting the particle resulted in a lower virion survival fraction (compared to light beams coming from a similar direction).
Swanson (2021) [9] preprint Simulation study	This simulation characterized the probabilities of SARS-CoV-2 infection, hospitalization, and death associated with aerosol exposure from in-person classes and the impacts of masking	• Upper room UV-C ceiling fans in every classroom reduces the risk of infection (>40%) more than universal masking alone.

Study	Method	Key outcomes
USA Apr-May 2021	and UV-C ceiling fans. The UV-C ceiling fans have disinfecting ultraviolet lights built into the base of the fan that are aimed up at the ceiling, thus an upper room UVGI application. A semester of courses in a real college with approximately 11,000 students embedded within a larger university was modelled. The schedule input for the model included 11,968 students and 342 faculty in 1,025 courses. Immunity rates from 60-95% were used in the simulation to determine the impacts of masking and UV-C fan ceiling interventions.	• Compared to no intervention, a combination of masking and UV-C fans show the greatest reduction SARS-CoV-2 infection risk. • Under a low SARS-CoV-2 transmissibility scenario with 60% immunity and using UV-C ceiling fans, the probability of exceeding 50, 100, 250, and 500 student infections was >0.999, 0.997, <0.001, and <0.001 respectively. The probability of exceeding 1, 2, 10, and 20 faculty infections was 0.936, 0.156, 0.002, and <0.001, respectively. At 90% immunity probabilities drop to <0.001 for the above thresholds in students and staff. • Under a high SARS-CoV-2 transmissibility scenario with 60% immunity and using UV-C ceiling fans, the probably of exceeding 50, 100, 250, and 500 student and 1, 2, 10, and 20 faculty infections was >0.999, and at 90% immunity was 0.814, 0.034, <0.001, and <0.001 for students and 0.652, 0.008, 0.002, and <0.001 for staff, respectively. Adding masking decreased the probability of exceeding 500 student and 20 faculty infections at 60% immunity to 0.554 and 0.005, respectively. • Scenarios for 70%, 80%, and 95% immunity were also provided. • Similar trends were shown for hospitalizations and death.
D'Alessandro (2021) [8] Simulation study	An Eulerian–Lagrangian model was developed to examine the effect of UV-C irradiation on inactivation of airborne virus/bacteria particles in a	• UV-C irradiation was shown to effectively inactivate the majority of SARS-CoV-2 particles in a cloud of saliva droplets after 4 seconds.

Study	Method	Key outcomes
Italy Mar 2021	cloud of saliva droplets. Clouds produced from one, two, and three cough ejections were modelled. The UV-C source was a lamp at a wavelength of 254 nm, with a power of 25 watts (W) or 55 W. In the model, the radiation dose sufficient to inactivate SARS-CoV-2 was used as the “susceptibility constant” for the virus/bacteria (8.5281 x 10^{-2} m^2/J).	• The UV-C lamp with a power of 55 W was more effective at inactivating SARS-CoV-2 over a period of 10 seconds compared to 25 W. • Note: visualizations were provided in the study that show SARS-CoV-2 inactivation in a cloud of droplets produced from one, two, and three cough ejections.
Hou (2021) [12] Simulation study USA Mar 2021	Researchers used ray-tracing to simulate the impact of different room design parameters on the safety and effectiveness of UV-C irradiation of SARS-CoV-2. The simulation involved the use of an occupied test room (24 x 30 feet, floor area = 15.80 m^2), which had one wall-mounted UVGI lamp (254 nm, 25.47 W). Three room configurations were examined: configuration 1 (square, 3.97m length x 3.97m width, UVGI lamp located on one wall), configuration 2 (rectangle, 4.57 m x 3.44m, UVGI lamp located on long wall), configuration 3 (rectangle, 4.57m x 3.44m, UVGI lamp located on short wall). Four ceiling height / UVGI device mounting heights (C/M height) were examined: C/M height 1 (2.44m / 2.13m), C/M height 2 (2.74m / 2.13m), C/M height 3 (2.74m / 2.29m), and C/M height 4 (3.05m / 2.44m). A simulated case study involving an occupied hospital room (7.32m length x 4.57m width, default ceiling height = 2.74 m, floor area = 27.87 m^2) with	Simulation study: • Configuration 3 resulted in the highest SARS-CoV-2 disinfection effectiveness of all three room configurations (average fluence rate = 41.94 μW/cm^2). However, all three room configurations resulted in the effective deactivation of SARS-CoV-2 within 19 seconds, at a fluence rate less than 48 μW/cm^2. • C/M height 1 has the most effective SARS-CoV-2 upper zone disinfection effectiveness (average fluence rate = 56.56 μW/cm^2), while all other C/M heights had an average fluence rate of less than 48 μW/cm^2, which is the threshold for average fluence rate. • Accounting for both SARS-CoV-2 disinfection effectiveness and safety, C/M height 3 is the optimal option. Case simulation study: • Scenarios 1 and 4 had the most effective SARS-CoV-2 upper zone disinfection coverages of 18.85% (average upper zone fluence rate = 48.19 μW/cm^2) and 14.83% (average upper zone fluence rate = 48.61 μW/cm^2), respectively.

Study	Method	Key outcomes
	two upper zone UVGI lamps (Atlantic Ultraviolet Corporation *Hygeaire* model LIND24-EVO, lamp power = 25.6 W each, 254 nm) was also performed to determine the impact of different room design parameters on the safety and effectiveness of UV-C irradiation of SARS-CoV-2. Four scenarios for UVGI fixture location were examined: scenario 1 (UVGI fixtures located above the bed), scenario 2 (UVGI fixtures located opposite of the bed), scenario 3 (UVGI fixtures located on the left and right side walls from the bed), and scenario 4 (UVGI fixtures located above and beside the bed). Three patient room layouts were examined: layout 1 (L-shaped, 7.32m length x 4.57m width, default), layout 2 (rectangular, 6.01m x 4.57m), layout 3 (rectangular, 7.01m x 3.96m). Three room surface UV-C reflectance coefficients were examined (0.05 (default), 0.1, and 0.2). Three scenarios for ceiling height / UVGI fixture mounting height were examined: height 1 (2.74 m / 2.13m), height 2 (2.74m / 2.29m; default), and height 3 (3.05 m / 2.44m). SARS-CoV-2 disinfection effectiveness was measured using average fluence rate ($\mu W/cm^2$).	• All three room layouts resulted in effective SARS-CoV-2 disinfection (maximum irradiance at the 1.83m to 1.98m range: layout 1 = 0.31 $\mu W/cm^2$ for a maximum of 5.2 hours; layout 2 = 0.28 $\mu W/cm^2$ for a maximum of 5.7 hours; layout 3 = 0.33 $\mu W/cm^2$ for a maximum of 4.9 hours). • Safety results found in Table 5.

Study	Method	Key outcomes
Beggs (2020) [7] Simulation study UK Oct 2020	In this study, researchers simulated the best and worst case scenarios for using upper-room UVGI (~254 nm) to determine its efficacy in decreasing SARS-CoV-2 transmission in occupied buildings. The upper room UV-C susceptibility constant for SARS-CoV-2 was assumed to be 0.377 m^2/J (best case) and 0.0377 m^2/J (worst case), and the amount of UV irradiation (UV flux) required to inactivate 50%, 70%, and 90% of the SARS-CoV-2 virus in a 1 to 8 ACH ventilated room (dimensions = 4.2m x 4.2m x 2.5m) with an upper room UVGI lamp (height = 2.1m above floor) was determined. The UV-C lamp (30 W) used was assumed to have an average upper-room flux of 50 $\mu W/cm^2$.	• Best-case scenario: When the UV-C susceptibility constant for SARS-CoV-2 is 0.377 m^2/J, at the highest ventilation rate of 8 ACH, the average irradiation needed for 50%, 70%, and 90% SARS-CoV-2 inactivation is 2.6 $\mu W/cm^2$, 4.4 $\mu W/cm^2$, and 8.5 $\mu W/cm^2$, respectively. • Worst-case scenario: When the UV-C susceptibility constant for SARS-CoV-2 is 0.0377 m^2/J, at the highest ventilation rate of 8 ACH, the average irradiance needed for 50%, 70%, and 90% SARS-CoV-2 inactivation is 25.5 $\mu W/cm^2$, 44.4 $\mu W/cm^2$, and 84.8 $\mu W/cm^2$, respectively, which is a ~10 factor increase compared to the best-case scenario. • Even in the worst-case scenario (0.0377 m^2/J), SARS-CoV-2 disinfection rates >90% can effectively occur in a 2.5m high room with ventilation rates between one to six ACH, and one UV lamp (30 W) located every 18.58 m^2. This will result in an average UV flux of 50 $\mu W/cm^2$.

Table 3: Evidence on the effectiveness of portable UV air cleaners in inactivating SARS-CoV-2 in the air of occupied rooms (n=1)

Study	Method	Key outcomes
Simulation study (n=1)		
Feng (2020) [11] Simulation study USA	This study aimed to evaluate the effectiveness of a novel portable UV air cleaner in reducing airborne droplets with SARS-CoV-2 in a patient's room (4.8m length x 4.3m	• A portable UV air cleaner could filter up to 82% of airborne droplets with SARS-CoV-2. • Increasing the flow rate of the UV air cleaner could improve its efficiency in

Study	Method	Key outcomes
Jan 2021	width x 2.4m height). Simulations were conducted using a computational fluid-particle dynamics model. In these simulations, a patient emitted droplets with SARS-CoV-2, and the effectiveness of the portable UV air cleaner was assessed under different flow rates and ventilation conditions. Wavelength and power of the UV air cleaner was not specified. Effectiveness was measured by the reduction in concentration of droplets with SARS-CoV-2 suspended in the room and in the main ventilation system.	filtering droplets with SARS-CoV-2, which meant a higher number of droplets filtered in a unit time. • However, increasing the flow rate could also increase convection and airflow recirculation in the room, resulting in a wider distribution of airborne droplets with SARS-CoV-2 in the room. • Note: Simulated visualizations are provided, which show the SARS-CoV-2 droplet deposition patterns in the room under different UV air cleaner flow rates and ventilation conditions.

Table 4: Evidence on the safety of UV-C technologies in inactivating SARS-CoV-2 in the air of occupied rooms (n=2)

Study	Method	Key outcomes
Field investigation (n=1)		
Volchenkov (2021) [6] Field investigation Russia 2003-2020	Researchers examined the effectiveness and safety of upper and whole room UVGI in reducing COVID-19 and TB transmission among employees and patients within a hospital building. The UVGI source consisted of 240 wall-mounted UV-C fixtures (one fixture per 18 m^2). Each UV-C fixture contained two low-pressure mercury lamps (T8 30W, wavelength = 254 nm) for upper and whole-room UVGI, respectively. The upper-room UVGI lamp was used 24 hours per day, 7 days per week, when people were present and absent	• In 17 years of using the UV-C fixtures in the hospital, no cases of overexposure have been reported due to upper-room UVGI, while some cases of overexposure were reported due to whole-room UVGI (people were not supposed to be present). • Effectiveness results found in Table 1.

Study	Method	Key outcomes
	from the hospital rooms, while the whole-room UVGI lamp was only used when people were not present in the room for sterilization purposes.	
Simulation study (n=1)		
Hou (2021) [12] Simulation study USA Mar 2021	Researchers used ray-tracing to simulate the impact of different room design parameters on the safety and effectiveness of UV-C irradiation of SARS-CoV-2. The simulation involved the use of an occupied test room (24 x 30 feet, floor area = 15.80 m^2), which had one wall-mounted UVGI lamp (254 nm, 25.47 W). Three room configurations were examined: configuration 1 (square, 3.97m length x 3.97m width, UVGI lamp located on one wall), configuration 2 (rectangle, 4.57m x 3.44m, UVGI lamp located on long wall), configuration 3 (rectangle, 4.57m x 3.44m, UVGI lamp located on short wall). Four ceiling height / UVGI device mounting heights (C/M height) were examined: C/M height 1 (2.44m / 2.13m), C/M height 2 (2.74m / 2.13m), C/M height 3 (2.74m / 2.29m), and C/M height 4 (3.05m / 2.44m). A simulated case study involving an occupied hospital room (7.32m length x 4.57m width, default ceiling height = 2.74 m, floor area = 27.87 m^2) with two upper zone UVGI lamps (Atlantic	Simulation study: • Configuration 3 is the safest room configuration for individuals occupying the lower zone, as it has the optimal distance between the UVGI device and the opposite wall, which allows less UV light to be reflected off the wall and onto those occupying the lower zone. • C/M height 4 is the safest option with the lowest likelihood of UV overexposure to occupants in the room, because it has the largest difference between the ceiling and the UVGI device mounting height, causing lower amounts of UV light to be reflected from the ceiling to the lower zone. • Accounting for both SARS-CoV-2 disinfection effectiveness and safety, C/M height 3 is the optimal option. Case simulation: • The highest risk of UV-C overexposure for humans was in Scenario 3, while Scenario 1 had the lowest risk of UV-C overexposure. • As the UVGI fixture mounting height increased, there was a decrease in room areas with UV-C irradiance

Study	Method	Key outcomes
	Ultraviolet Corporation *Hygeaire* model LIND24-EVO, lamp power = 25.6 W each, 254 nm) was also performed to determine the impact of different room design parameters on the safety and effectiveness of UV-C irradiation of SARS-CoV-2. Four scenarios for UVGI fixture location were examined: scenario 1 (UVGI fixtures located above the bed), scenario 2 (UVGI fixtures located opposite of the bed), scenario 3 (UVGI fixtures located on the left and right side walls from the bed), and scenario 4 (UVGI fixtures located above and beside the bed). Three patient room layouts were examined: layout 1 (L-shaped, 7.32m length x 4.57m width, default), layout 2 (rectangular, 6.01m x 4.57m), layout 3 (rectangular, 7.01m x 3.96m). Three room surface UV-C reflectance coefficients were examined (0.05 (default), 0.1, and 0.2). Three scenarios for ceiling height / UVGI fixture mounting height were examined: height 1 (2.74 m / 2.13m), height 2 (2.74m / 2.29m; default), and height 3 (3.05 m / 2.44m). SARS-CoV-2 disinfection effectiveness was measured using average fluence rate ($\mu W/cm^2$).	above the safety threshold (0.2 $\mu W/cm^2$). • Height 2 had a reduced level of lower zone UV-C irradiance compared to Height 1, indicating that the higher the UVGI lamp is located on the wall, the lower the risk of over-exposure. • Increasing the surface reflectance coefficients from 0.05 (default) to 0.1 and 0.2, increased the upper zone average fluence rate, and caused lower zone UV-C irradiance greater than the safety threshold (0.2 $\mu W/cm^2$), when the wall height was below 1.83 m. The greatest lower zone UV-C irradiance was observed at a reflectance coefficient of 0.2. • Effectiveness results found in Table 1.

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