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Field study of early implementation of UV sources and their relative effectiveness for public health and safety

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ABSTRACT

The emergence of COVID-19 and its corresponding public health burden has prompted industries to rapidly implement traditional and novel control strategies to mitigate the likelihood of SARS-CoV-2 transmission, generating a surge of interest and application of ultraviolet germicidal irradiation (UVGI) sources as disinfection systems. With this increased attention the need to evaluate the efficacy and safety of these types of devices is paramount. A field study of the early implementation of UVGI devices was conducted at the Space Needle located in Seattle, Washington. Six devices were evaluated, including four low-pressure (LP) mercury-vapor lamp devices for air and surface sanitation not designed for human exposure and two krypton chloride (KrCl*) excimer lamp devices to be operated on and around humans. Emission spectra and ultraviolet (UV) irradiance at different locations from the UV devices were measured and germicidal effectiveness against SARS-CoV-2 was estimated. The human safety of KrCl* excimer devices was also evaluated based on measured irradiance and estimated exposure durations. Our results show all LP devices emitted UV radiation primarily at 254 nm as expected. Both KrCl* excimers emitted far UVC irradiation at 222 nm as advertised but also emitted at longer, more hazardous wavelengths (228 to 262 nm). All LP devices emitted strong UVC irradiance, which was estimated to achieve three log reduction of SARS-CoV-2 within 10 sec of exposure at reasonable working distances. KrCl* excimers, however, emitted much lower irradiance than needed for effective disinfection of SARS-CoV-2 (>90% inactivation) within the typical exposure times. UV fluence from KrCl* excimer devices for employees was below the American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLVs) under the reported device usage and work shifts. However, photosensitive individuals, human susceptibility, or exposure to multiple UV sources throughout a worker's day, were not accounted for in this study. Caution should be used when determining the acceptability of UV exposure to workers in this occupational setting and future work should focus on UVGI sources in public settings.

KEYWORDS
COVID-19; far UVC; SARS-CoV-2; ultraviolet germicidal irradiation; UVC

Introduction

The Space Needle is one of the most recognizable landmarks since it was built in 1962. The tower stands at 184.4 m and provides 360° panoramic views of the city of Seattle, the Puget Sound, and neighboring mountain ranges. The Space Needle is privately owned and employs up to 300 staff with significant variability due to cyclic peak seasons attributed to summer and vacation schedules. The unique layout of the building lends itself to significant guest and staff interaction as guests navigate through the experience with the help of staff. Ticketholders start at the facility entry, then walk along outdoor and indoor ramps to the elevators for a 43-sec ride up to the tower's Tophouse, which features two floors with an indoor/outdoor Observation Deck and the world's first rotating glass floor. While there, guests can purchase food or beverages and interact with several kiosks and cameras to enhance their visit. When they are ready to depart, guests exit via the elevators, which take them down to the gift shop on the ground floor.

This world-famous tourist and visitor destination typically hosts more than a million guests annually. However, this all halted at the onset of the COVID-19 pandemic. Specifically, on March 12, 2020, consistent

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with Washington State Governor Jay Inslee and Seattle Mayor Durkan's guidance, the Space Needle decided to suspend operations as a precautionary measure. Subsequent extensions of this suspension continued until July 21, 2020. When the Space Needle was ready to reopen, they implemented several controls in both response to SARS-CoV-2, and for continuous and long-term safety and health enhancements for their staff and visitors. They implemented a multi-layered approach with the following highlighted controls, including reduced guest occupancy, increased ventilation, enhanced cleaning protocols, social distancing, touch-free entry gates, timed ticketing, ticket self-scans, and self-checkouts, limiting elevator capacity to 50%, 100% fresh air intake in all elevator cabs, asking guests to not talk during the elevator trip up top, and the procurement and installation of UVGI devices throughout their complex.

All UVGI devices installed at the Space Needle advertised UVC or far UVC radiation emission wavelengths. UVC is a classification of UV that includes wavelengths from 200 to 280 nanometers (nm) (IES 2020). UVC has been recognized as an effective germicidal disinfectant but is also known to be hazardous to exposed human skin and eyes. UVC overexposure to the skin can cause erythema or sunburn while overexposure to the eye can result in photokeratitis, a painful condition of the eye (LBNL 2018). Far UVC, increasing in popularity and interest for its germicidal properties, is part of the UVC band that encompasses wavelengths in the range of 200–225 nm. Far UVC has demonstrated disinfection efficacy, yet studies suggest that these wavelengths do not cause human health issues typically associated with UVC exposure (Simons et al. 2020).

The American Conference of Governmental Industrial Hygienists (ACGIH®) develops and publishes occupational exposure guidelines for exposure to UV with wavelengths between 180 and 400 nm. These guidelines are presented as Threshold Limit Values (TLVs®). TLVs represent levels of exposure to which nearly all workers may be repeatedly exposed 8 hr a day, 40 hr per week for a working lifetime, without adverse health effects. These values are established at exposure levels sufficient to minimize or eliminate adverse health effects for average healthy workers. Due to variation in human susceptibility, exposure of an individual at, or even below, the TLVs may result in adverse health conditions. For UV radiation, the TLV states that it does not apply to workers considered to be photosensitive or are concomitantly exposed to photo-sensitizing agents (e.g., tetracycline, imipramine, and sinequan). The TLV further explains that "Hypersensitivity should be suspected if workers present skin reactions when exposed to sub-TLV doses or when exposed to levels (generally UV-A) that did not cause a noticeable erythema in the same individual in the past" (ACGIH 2022). These TLVs vary with wavelengths and are expressed as a dose (mJ/cm^2). The dose is calculated as the product of irradiance (mW/cm^2) and exposure time (seconds). According to both the 2020 and 2021 ACGIH TLVs, the lowest TLV for the different UV wavelengths is 3 mJ/cm^2 at 270 nm, at which UV irradiance has the highest hazardous effectiveness. The hazardous effectiveness at other wavelengths is represented using a wavelength-specific relative spectral effectiveness relative to the value at 270 nm (i.e., ratio of TLV at 270 nm to TLV at respective wavelength).

Commercial UV devices have entered the retail market promoting the operation of far UVC lamps in occupied spaces for intentional human exposure to mitigate SARS-CoV-2 transmission. However, early in the pandemic, some within the UV radiation community published statements and white papers cautioning the potential expanded application of germicidal UVC technology in occupied spaces for intentional human exposure in response to SARS-CoV-2. In April 2020, the International Ultraviolet Association (IUVA) released an article notifying the public of the IUVA and RadTech North America's position, discouraging the use of UV directly on the human body, as there are "no protocols to advise or to permit the safe use of UV light directly on the human body at the wavelengths and exposure proven to effectively kill virus such as SARS-CoV-2" (IUVA 2020). The article also discusses information related to far UVC disinfecting viruses without damaging skin and eyes but states information is preliminary and lacking protocols for construction and operations of such devices. Also in May 2020, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) released a statement regarding the use of far UVC lamps to inactivate SARS-CoV-2. In their article, "UVC lamps and SARS-COV-2," ICNIRP discusses new 222 nm lamps becoming available but encourages caution since evidence exists that some lamp models may have minor emissions at longer, more hazardous, wavelengths (ICNIRP 2020).

These early cautionary statements coupled with the increased availability of far UVC commercial products emphasized the need to evaluate UV sources and to use prudence when considering the application of far UVC for intentional human exposure. In concert with this

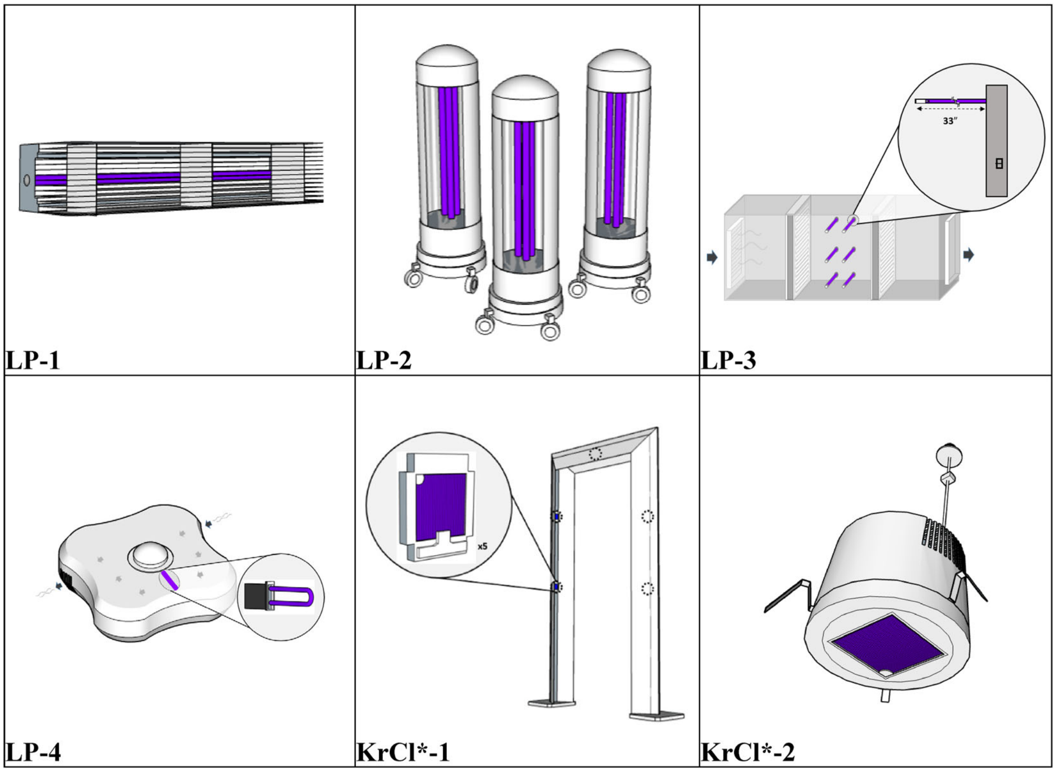

Figure 1. Schematic diagram of evaluated UV devices in this study including Upper Air UV (LP-1), Mobile UV Disinfection System (LP-2); UV Air Handling System (LP-3); Personal Air Sanitizer (LP-4), UV Sanitizing Entry Gate (KrCl*-1), and UV Elevator Lights (KrCl*-2).

guidance, a field study of the early implementation of UV sources was conducted for the Space Needle in a collaboration between the Space Needle Corporation, the University of Colorado, and the University of Washington. During this field study, four LP mercury-vapor lamp devices (the Upper Air UV [LP-1], Mobile UV Disinfection System [LP-2], UV Air Handling System [LP-3], and Personal Air Sanitizer [LP-4]) not designed for human exposure and two KrCl* excimer lamp devices (UV Sanitizing Entry Gate [KrCl*-1] and UV Elevator Lights [KrCl*-2]) designed to be operated on and around humans were evaluated. Spectrometric and radiometric measurements were collected for five of the six devices and one of the six devices included radiometric measurements only. Fluence was calculated for the KrCl* lamp devices and compared to the existing ACGIH TLVs. Germicidal effectiveness was evaluated based on measured irradiance and estimated exposure durations.

Methods

Evaluated UV devices

Six devices, four low pressure (LP) mercury-vapor lamp devices not designed for human exposure and two KrCl* excimer lamp devices to be operated on and around humans, were evaluated in this field study (Figure 1). A brief description of each device and operational details are provided below.

LP-1

The Upper Air UV fixture is an upper room UV device designed to expose a space to germicidal UV without exposing the lower, potentially occupied, portion of a room. This fixture includes one LP mercury-vapor lamp (25 watt) advertised to produce UVC at 253.7 nm with non-reflective baffles to direct UVC energy into the upper air irradiance zone. At the Space Needle, these devices are operated in the core stairwells, and operations and management offices continuously 24 hr a day, 7 days a week.

LP-2

The Mobile UV Disinfection System is a portable UV system that is dispatched and operated daily to disinfect surfaces in unoccupied spaces of the Space Needle. The device includes three 2 m portable towers each equipped with three LP lamps (156 watt total), advertised to produce UVC at 253.7 nm, that are positioned throughout a space and operated simultaneously. Treatment time is dependent on room size and space configuration that can be determined by a user or by a room scanning function internal to the Mobile UV Disinfection System. At the Space Needle, the device's scan feature is used to initially assess a new space selected for treatment. UV-sensitive stickers are placed through the space to determine adequate dosage. Once the dosage is determined, the information is logged, and future treatments are run manually. UVC treatment times vary, on average a small room is approximately 3 min, and for a medium and large room, the average treatment time is 5 min per space. The device is controlled via a tablet computer and employees are required to be trained before the operation of this device. At the Space Needle, these units are usually operated for less than 3 hr per day.

LP-3

The UV Air Handling UVC device is designed to be installed in ducting for heating, ventilation, and air-conditioning (HVAC) systems. The Space Needle incorporated 10 installations throughout its HVAC system. The evaluated installation for this field study included six 83.8 cm LP mercury-vapor lamps (75 watt per lamp) installed within the in-duct coils upstream of the systems air filters that advertise to emit 250–260 nm wavelengths. The devices are intended to irradiate both the air and mechanical in-duct components simultaneously and are operated continuously. Air flow for the evaluated system typically ranges between 2208.7 and 5097.0 m^3/hr. Signs were posted on the exterior of the air handling units (AHUs), warning of UV light hazards and instructing to disconnect power to all UVC devices before servicing.

LP-4

Personal Air Sanitizers are designed for air purification in small areas. These small plug-in devices pull air into an enclosure that contains one LP mercury-vapor bulb that advertised to emit 254 nm wavelengths. Units were distributed to the office staff for personal use.

KrCl*-1

The UV Sanitizing Entry Gate is advertised as an air and surface sanitizing device. Each entry gate includes five 222 nm emitting KrCl* excimer lamps (12 watt per lamp) secured to the interior of an aluminum frame. People passing through the entry gate are instructed to enter and perform two slow full rotation turns for 20 sec, with their hands facing upwards over their heads. During the operation of the entry gate, Space Needle employees work within the vicinity of the units. Employees are positioned approximately 182 cm away from the operating entry gate and rotate posts every hour during 8-hr shifts. The average time a Space Needle employee is deployed near this device is estimated to be 240 min per day. There are approximately 20 to 25 employees that work within the proximity of these entry gates placed through the Space Needle facility.

KrCl*-2

UV Elevator Lights are air and surface disinfection units designed to be installed in occupied spaces. These devices have been installed in the ceilings of the three Space Needle Elevators toward the center of the elevator cab and are operated continuously during hours of operation. Each elevator is equipped with two UV Elevator lights with one KrCl* excimer bulb (18 watt) in each light. Each bulb is advertised to emit a 222 nm wavelength. The Space Needle employs 10 Elevator Operators positioned next to the elevator operating panel, near the elevator doors (not directly under the bulbs). Elevator Operators rotate positions with 2 hr in an elevator and 1 hr out of an elevator for up to 10 hr per day. The average exposure time for Elevator Operators is estimated to be 420 min per day and the average exposure time for an employee using the elevator for one ride is estimated to be 4 min (i.e., the estimated average time for one complete elevator ride including two 43 sec ascending/descending durations and estimated loading/unloading durations). During this field study, Elevator Operators were required to wear a brimmed hat, UVA, UVB, and UVC eye protection, long-sleeve shirts, and gloves.

UV device characterization

The emission spectra between 200 nm and 400 nm were measured using a Maya 2000 Pro spectrometer (Ocean Insight, Dunedin, FL). Triplicate measurements were taken for each device after it was turned on for at least 5 min to allow sufficient warm-up. Triplicate measurements of ambient spectra were also taken by placing the spectrometer at the same location without the UV device being turned on. Normalized emission spectra (i.e., relative lamp emission; RLE) were calculated by excluding any signals from the ambient environment and then normalized to the maximum reading.

The UV irradiance was measured using a handheld International Light Technologies (ILT) 2400 radiometer (International Light Technologies, Peabody, MA) calibrated between 200 and 400 nm. The detector was set to measure the irradiance at the peak emission

Table 1. Inactivation rate constants (in log_{10}-scale) for coronaviruses using LP UV lamp and KrCl* excimer from previous studies.

Coronavirus[a]	k (cm^2/mJ)[b]	Note	References
LP UV lamp			
HCoV 229E	0.59	Tested in phosphate buffered saline (pH 7.4)	(Ma et al. 2021)
MHV	0.93	Tested in phosphate buffered saline (pH 7.4)	(Ma et al. 2021)
SARS-CoV-1	0.83	Estimated from a prediction model	(Rockey et al. 2021)
SARS-CoV-2	0.81	Tested in cell culture supernatant	(Biasin et al. 2021)
	0.87	Estimated from a prediction model	(Rockey et al. 2021)
	0.79	Tested in phosphate buffered saline (pH 7.4)	(Ma et al. 2021)
Range	0.59–0.93		
Average	0.80		
KrCl* excimer			
HCoV 229E	1.33	Tested in phosphate buffered saline (pH 7.4)	(Ma et al. 2021)
	1.78	Tested in cell culture supernatant aerosols	(Buonanno et al. 2020)
HCoV OC43	2.56	Tested in cell culture supernatant aerosols	(Buonanno et al. 2020)
MHV	1.22	Tested in phosphate buffered saline (pH 7.4)	(Ma et al. 2021)
SARS-CoV-2	0.84	Tested using dried viruses on polystyrene plates	(Kitagawa et al. 2021)
SARS-CoV-2	0.64	Tested in cell culture supernatant	(Robinson et al. 2021)
	1.52	Tested in phosphate buffered saline (pH 7.4)	(Ma et al. 2021)
Range	0.64–2.56		
Average	1.41		

Note:
[a]HCoV: Human coronavirus; MHV: Murine hepatitis virus (mouse coronavirus).
[b]The inactivation rate constants were calculated based on data from previous studies using a pseudo-first-order inactivation kinetics model shown in Equation 5.

wavelength (i.e., a wavelength where RLE = 1) of the source being measured. To capture the spatial variation in UV irradiance for each device, multiple irradiance measurements were taken by placing the radiometer detector at various locations (i.e., distance from UV lamps) with different orientations.

The incident irradiance (E, in mW/cm^2) from each UV device was calculated by correcting radiometer reading (E_0) using the lamp correction factor (f_p) as shown in Equation 1, according to Bolton and Linden (2003):

$$E = E_0 \times f_p = E_0 \times \frac{\sum_{i=200}^{i=400} RLE_i}{\sum_{i=200}^{i=400} (RLE_i \times S_i)} \quad (1)$$

where RLE_i is the RLE value at wavelength i nm, S_i is the radiometer sensitivity value normalized to the sensitivity value at the peak emission wavelength. Irradiance within a certain range of wavelengths ($E_{a\text{-}b}$; irradiance from a to b nm in mW/cm^2) was calculated using Equation 2.

$$E_{a\to b} = \frac{\sum_{i=a}^{i=b} RLE_i}{\sum_{i=200}^{i=400} (RLE_i)} \times E \quad (2)$$

The UV fluence (D, in mJ/cm^2, where a J = W*s) for a certain exposure time (T, in s) was calculated using Equation 3.

$$D = E \times T \quad (3)$$

Calculated UV irradiance (E_2, mW/cm^2) for a given distance (d_2, in cm) was calculated using Equation 4 adopted from the inverse square law, where the measured irradiance (E_1, mW/cm^2) from a measured distance (d_1, in cm) was used.

$$E_2 = E_1 \left(\frac{d_1}{d_2}\right)^2 \quad (4)$$

Evaluation of device effectiveness & safety

Effectiveness against SARS-CoV-2

Inactivation rate constants for SARS-CoV-2 and its potential surrogates, including murine hepatitis virus (i.e., mouse coronavirus), human coronavirus (HCoV) 229E and OC43, and SARS-CoV-1, were used to evaluate the effectiveness of UV inactivation of SARS-CoV-2. These rate constants were measured in various testing conditions or estimated using a prediction model based on the viral molecular characters (Table 1). The average of the inactivation rate constants for LP UV lamp devices and KrCl* excimer devices were calculated to represent the mean effectiveness of these two UVC devices against SARS-CoV-2 (Table 1). The virus infectivity reduction after UV exposure was estimated using a pseudo-first-order inactivation kinetics model in Equation 5.

$$log_{10} I = log_{10}\left(\frac{N_0}{N}\right) = k \times D \quad (5)$$

where $Log_{10}\ I$ is infectivity reduction in log_{10} scale, N_0 and N are the virus sample infectivity before and after UV exposure, D is UV fluence in mJ/cm^2, and k is the pseudo-first-order inactivation rate constant in cm^2/mJ.

Safety

Since the UV Sanitizing Entry Gate and UV Elevator Lights are designed for human exposure, the daily maximum exposure time without any acute adverse health effect (T_{exp}) was calculated by first computing the weighted spectral effectiveness (i.e., hazardous effectiveness relative to a monochromatic source at 270 nm, at which UV irradiation has the highest hazardous effectiveness), RS_{device} for these two devices using Equation 6.

$$RS_{device} = \frac{\sum_{i=200}^{i=400} E_i \times RS_i}{E} \tag{6}$$

E_i is the incident irradiance at wavelength i nm and RS_i is the relative spectral effectiveness at wavelength i nm according to ACGIH 2021 and 2022 (Supplementary material, Figure S1). Then, T_{exp} for a UV device was calculated using Equation 7.

$$T_{\text{exp}} = \frac{TLV_{device}}{E} = \frac{TLV_{270}}{RS_{device} \times E} \tag{7}$$

TLV_{device} is the TLV for a UV device and TLV_{270} is 3 mJ/cm^2 (TLV at 270 nm in ACGIH 2021, 2022). The T_{exp} values were compared to the daily exposure time of operators, and employees, to guide in the control of exposure to UV sources.

Results

Emission spectra

Emission spectra for five UV devices installed at the Space Needle are shown in Figure 2. Three devices for air sanitation (i.e., LP-1, LP-3, and LP-4) exhibited a peak emission wavelength of 254 nm (Figure 2; LP-1, LP-3, & LP-4), which is expected because they are LP mercury-vapor lamps. Emitted radiation at 313 and 365 nm were also observed for these devices, however, these wavelengths are not considered effective in virus disinfection and should not be considered germicidal. The emission spectrum for the Mobile UV Disinfection System (LP-2) was assumed to be the same as these three devices because it is an LP UV system. UV devices KrCl*-1 and KrCl*-2 emit radiation mainly from 212–228 nm (58.2% and 63.1% of the total UVC irradiance for KrCl*-1 and KrCl*-2, respectively; Figure 2), which is shown to have little to no penetration into human skin and eyes and recent research indicates it is likely safe for human exposure (Narita et al. 2018; Buonanno et al. 2020). Irradiation emitted at 228–262 nm (peak emission at 258 nm) was also observed. The percent output of the total germicidal irradiance between 230–250 nm and 250–270 nm was

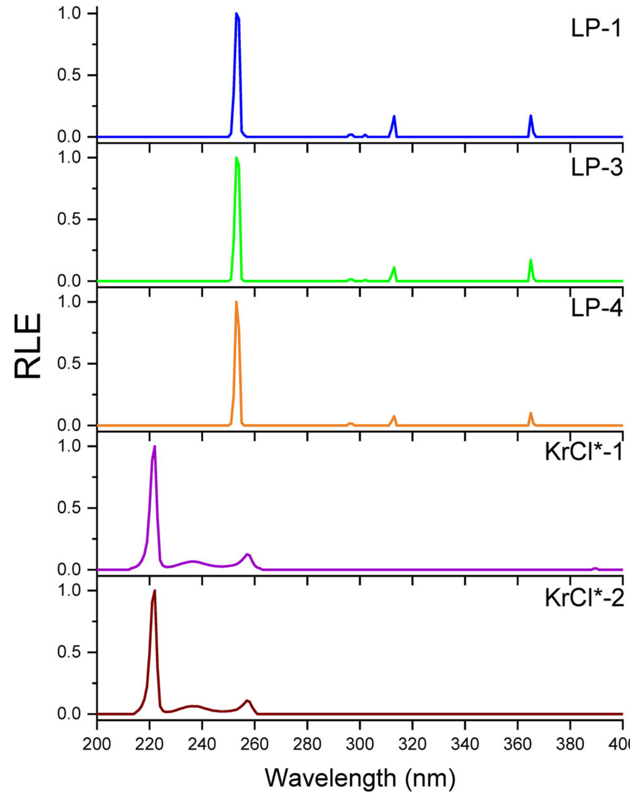

Figure 2. Relative lamp emission (RLE) for five UV devices measured during this field study.

15.5% and 12.4% for KrCl*-1 and 16.3% and 11.0% for KrCl*-2, respectively. Since the time of this study, it is more customary to filter the KrCl* lamp emission to eliminate the emission above 230 nm. An emission spectrum for a filtered KrCl* lamp is presented in Figure S2 (Supplementary material).

Irradiance

Irradiance measurement results are presented in Tables 2 and 3 and summarized below by device.

LP-1

UV Irradiance from the Upper air UV system decreased minimally over a short distance from the lamp baffle, with mean UVC irradiances of 0.98 ± 0.46 vs. 0.86 ± 0.27 mW/cm^2 at a distance of 5.1 cm and 15.2 cm from the lamp baffle, respectively (Table 2 and Figure 3 LP-1). At the same distance, the highest values were always detected in the center when the detector was placed toward the center of the lamp.

LP-2

A similar effect of distance was also observed for the Mobile UV Disinfection System, with the UVC irradiance reduced to 22.8% at a distance of 182.9 cm

Table 2. UV irradiance from four LP UV devices installed at Space Needle.

#	Radiometer detector location[a]	Detector direction	Radiometer reading (mW/cm^2)	UVC incident irradiance (mW/cm^2)	Exposure time (s) needed for 99.9% (3 log) reduction of SARS-CoV-2 (Mean; Min-Max)	
LP-1: Upper air UV						
A-1	5.1 cm from lamp baffles, left edge	Toward Lamp	0.482	0.471	7.9	(6.8–10.8)
A-2	15.2 cm from lamp baffles, left edge		0.574	0.559	6.6	(5.8–9.1)
A-3	5.1 cm from lamp baffles, 14 cm from left edge		1.288	1.256	2.9	(2.6–4.0)
A-4	15.2 cm from lamp baffles, 14 cm from left edge		1.044	1.018	3.6	(3.2–5.0)
A-5	5.1 cm from lamp baffles, center		1.536	1.498	2.5	(2.2–3.4)
A-6	15.2 cm from lamp baffles, center		1.259	1.228	3.0	(2.6–4.1)
A-7	5.1 cm from lamp baffles, 14 cm from right edge		1.307	1.275	2.9	(2.5–4.0)
A-8	15.2 cm from lamp baffles, 14 cm from right edge		0.989	0.965	3.8	(3.3–5.3)
A-9	5.1 cm from lamp baffles, right edge		0.392	0.382	9.7	(8.4–13.3)
A-10	15.2 from lamp baffles, right edge		0.556	0.542	6.8	(6.0–9.4)
A-11	182.9 cm from center of the lamp		0.131	0.127	29.2	(25.4–40.0)
A-12	304.8 cm from center of the lamp		0.031	0.030	123.5	(107.5–169.5)
LP-2: Mobile UV disinfection system[b]						
B-1	83.3 cm in height, 61 cm from the lamp	Toward Lamp	3.160	3.082	1.2	(1.0–1.6)
B-2	83.3 cm in height, 182.9 cm from the lamp		0.720	0.702	0.5	(0.5–0.7)
LP-3: UV Air Handling Unit (AHU)						
C-1	3.8 cm right below bottom right bulb	Toward lamp	12.190	11.942	0.3	(0.3–0.4)
LP-4: Personal air sanitizer						
D-1	1 cm from the bulb	Toward lamp	1.300	1.272	2.9	(2.5–4.0)

Note:
[a]Radiometer detector locations for device A and C irradiance measurements are shown in Figure 3.
[b]UVC incident irradiances from LP-2 were estimated using emission spectrum of LP-1.

Table 3. UV irradiance from two KrCl* excimer UV devices installed at Space Needle.

#	Radiometer detector location[a]	Detector direction	Radiometer reading (mW/cm^2)	UVC incident irradiance (mW/cm^2)	Exposure time (s) needed for 90% (1 log) reduction of SARS-CoV-2 (Mean; Min-Max)	
KrCl*-1: UV Sanitizing entry gate[b]						
E-1	25.4 cm right from bulb B	Left	0.0119	0.01178	60.5	(33.1–132.4)
E-2	25.4 cm right from middle of bulbs A and B		0.0019	0.00192	375.9	(205.6–822.4)
E-3	25.4 cm right from bulb A		0.0128	0.01262	56.7	(31.0–124.0)
E-4	25.4 cm right from middle of bulb A and bottom		0.0012	0.00120	595.2	(325.5–1302.1)
E-5	25.4 cm below bulb C	Up	0.0093	0.00917	77.6	(42.5–169.8)
E-6	50.8 cm below bulb C		0.0030	0.00297	238.1	(130.2–520.8)
E-7	101.6 cm below bulb C		0.0015	0.00148	476.2	(260.4–1041.7)
E-8	25.4 cm left from bulb D		0.0018	0.00179	396.8	(217.0–868.1)
E-9	58.4 cm from bulb D, directly below bulb C		0.0029	0.00290	246.3	(134.7–538.8)
E-10	25.4 cm right from bulb B		0.0012	0.00123	595.2	(325.5–1302.1)
E-11	182.9 cm right from bulb A and B[b]	–	–	0.00047	–	
KrCl*-1: UV elevator lights						
F-1	5.1 cm directly below left bulb (223.5 cm in height)	Up	0.1628	0.15840	4.5	(2.5–9.9)
F-2	25.4 cm directly below left bulb (203.2 cm in height)		0.0086	0.00837	85.0	(46.5–186.0)
F-3	50.8 cm directly below left bulb (177.8 cm in height)		0.0029	0.00279	255.1	(139.5–558.0)
F-4	101.6 cm directly below left bulb (127 cm in height)		0.0010	0.00097	714.3	(390.6–1562.5)
F-5	222.3 cm directly below left bulb (detector at elevator floor)		0.0003	0.00031	2381.0	(1302.1–5208.3)
F-6	5.1 cm directly below left/right bulbs overlap center (223.5 cm in height)		0.00001	0.00001	51954.2	(28412.4–113649.8)
F-7	25.4 cm directly below left/right bulbs overlap center (203.2 cm in height)		0.0013	0.00129	549.5	(300.5–1201.9)
F-8	50.8 cm directly below left/right bulbs overlap center (177.8 cm in height)		0.0020	0.00192	375.9	(205.6–822.4)
F-9	101.6 cm directly below left/right bulbs overlap center (127 cm in height)		0.0011	0.00107	649.4	(355.1–1420.5)
F-10	222.3 cm directly below left/right bulbs overlap center (detector at elevator floor)		0.0002	0.00022	3571.4	(1953.1–7812.5)
F-11	Operator position, 177.8 cm in height from elevator floor[c]	Toward lamp	0.0002	0.00020	3571.4	(1953.1–7812.5)
F-12	Operator position, 152.4 cm in height from elevator floor[c]		0.0003	0.00031	2381.0	(1302.1–5208.3)

(*Continued*)

Table 3. Continued.

#	Radiometer detector location[a]	Detector direction	Radiometer reading (mW/cm^2)	UVC incident irradiance (mW/cm^2)	Exposure time (s) needed for 90% (1 log) reduction of SARS-CoV-2 (Mean; Min-Max)
F-13	Operator position, 127 cm in height from elevator floor[c]		0.0004	0.00038	1785.7 (976.6–3906.3)
–	154.9 cm in height directly below a bulb[d]	–	–	0.00203	
–	154.9 cm in height below two bulbs overlap center[d]	–	–	0.00188	

Note:
[a]Radiometer detector locations for irradiance measurements are shown in Figure 4.
[b]Irradiance at a distance of 182 cm from bulb A and B (i.e., the distance between employee and the UV sanitizing entry gate) was estimated using the Equation 4 with the measured irradiances at #E-1 and #E-3.
[c]Operator's position was to the side of elevator (near elevators operating panel) and not directly below KrCl* bulbs.
[d]Irradiance at a height of 154.9 cm was estimated using Equation 4 with the measured irradiance at #F-4 and #F-5 for the value below a bulb, and at #F-9 and #F-10 below two bulbs overlap center. Only the two furthest measurements were used for this estimate since the inverse square law (Equation 4) fits better at greater distances when the light source can be assumed to be a point source.

compared to that of 61 cm (0.7 *vs.* 3.1 mW/cm^2; Table 2) when assessing one of the three portable towers.

LP-3

The UV lamps emit strong UV radiation, with an average UVC irradiance of 11.9 mW/cm^2 measured at a distance of 3.8 cm for just one lamp.

LP-4

UVC irradiance of 1.3 mW/cm^2 was determined at a distance of 1 cm from the UV bulb within the personal air sanitizer (Table 2), which is the distance between the bulb and the device cover.

KrCl*-1

The UVC irradiance from the UV Sanitizing Entry Gate ranged from 0.00120–0.01262 mW/cm^2 from various locations, with a mean ± S.D. of 0.00470 ± 0.00436 mW/cm^2 (Table 3 and Figure 4: KrCl*-1).

KrCl*-2

Irradiance from the UV Elevator Lights at different distances from the bulb were measured at two different locations: right below a bulb and equidistance between two bulbs. In general, the irradiance decreased with the distance from the lamp and the values measured right below a bulb were higher than those below the overlapping center, with a maximum UVC irradiance of 0.15840 mW/cm^2 measured at 5.1 cm right below a bulb (Table 3, location F-1 and Figure 4: KrCl*-2).

Effectiveness against SARS-CoV-2

Although the UV inactivation kinetics for SARS-CoV-2 may vary with the exposure conditions (e.g., virus suspended in water vs. aerosol), three of the four LP UV devices investigated in this study, including Upper Air UV (LP-1), Mobile UV Disinfection System (LP-2), and the Personal Air Sanitizer (LP-4) would achieve 3 log-reduction of SARS-CoV-2 within a 10-sec exposure at a reasonable working distance based on the UV inactivation rate values of SARS-CoV-2 and its surrogates from previous studies listed in Table 1. For the UV air handling system (LP-3), only 0.3 sec is required to achieve 3-log reduction at 3.8 cm from any single UV lamp and shorter times with all lamps on as is normal operation. While there are many operational and installation characteristics, this suggests this device achieves reasonable disinfection performance when operating. The air circulation

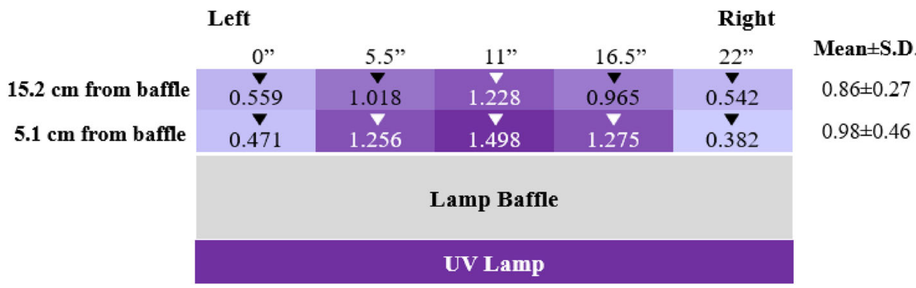

Figure 3. UV irradiance (in mW/cm^2) measured from the Upper Air UV (LP-1) at 5.1 cm and 15.2 cm from lamp baffle. LP UV lamp shown in purple, lamp baffle shown in gray, and arrows represent the direction which the detector was facing.

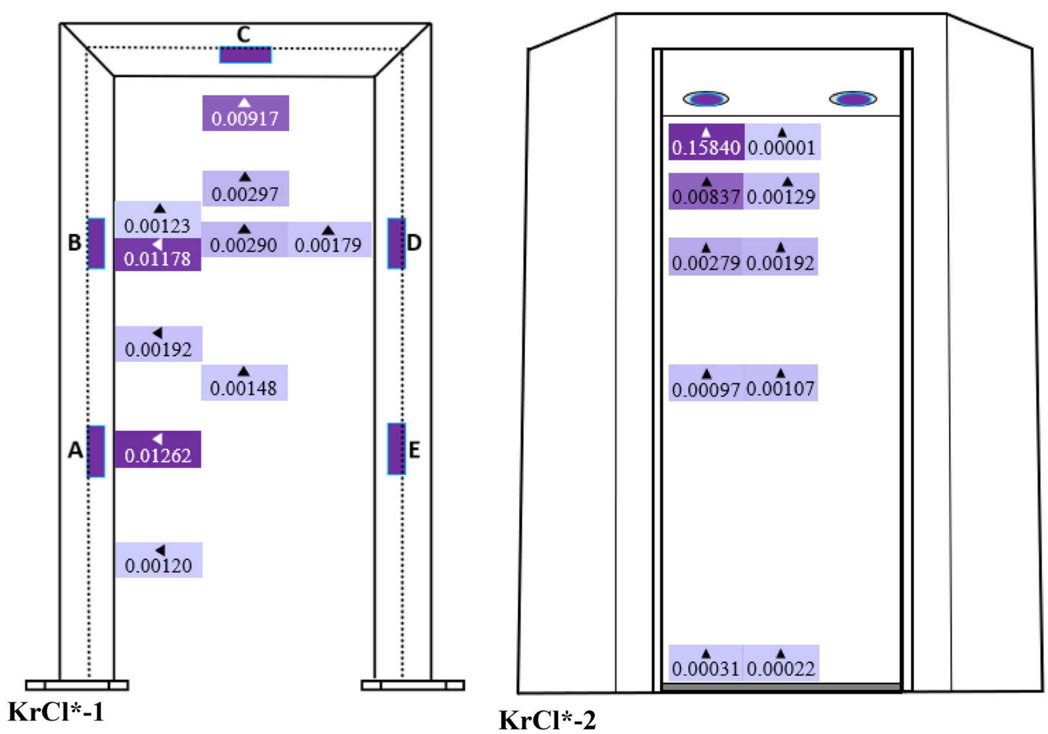

Figure 4. Schematic diagram of KrCl* excimer lamp devices showing UV irradiance (in mW/cm^2) and general radiometer detector locations. The radiometer detector locations are listed in Table 3. KrCl* excimer lamp shown in purple and arrows represent the direction which the detector was facing.

within the system, the velocity in the duct and dwell time near the lamps, if not optimized, can impact the overall effectiveness of the UV system. To determine the complete efficacy of this system, more detailed modeling and calculations would be needed.

According to inactivation rate values from previous studies testing SARS-CoV-2 and its surrogates (Table 1), KrCl* excimers exhibited better performance per mJ/cm^2 delivered than LP UV devices, requiring an average of 0.7 mJ/cm^2 for 1 log-reduction, but emit at much lower irradiance levels than most LP UV lamps investigated in this study. Based on the 222 nm efficacy and the measured irradiance values, it is estimated that an average of 5 min (0.9–9.9 min) in the UV Sanitizing Entry gate is needed to achieve 1 log-reduction of SARS-CoV-2, depending on the exposure location (Table 3).

UV fluences for a 4-min exposure for an elevator customer's facial area (average human facial height of 5′1″ [154.9 cm] is used here) are 0.49 mJ/cm^2 right below a bulb and 0.45 mJ/cm^2 right below two bulbs overlapping on center. Such fluences are estimated to inactivate 79.5% and 77.0% SARS-CoV-2 on average over the 4 min.

Safety

Using the 2021 TLV values, the weighted spectral effectiveness (RS_{device} in Equation 6) for the UV Sanitizing Entry Gate and the UV Elevator Lights are 0.234 and

0.213, respectively, and with the 2022 TLVs, these values are 0.152 and 0.128, respectively. The allowable TLVs for these two devices are 12.8 mJ/cm^2 and 14.1 mJ/cm^2, respectively (19.7 mJ/cm^2 and 23.5 mJ/cm^2 using the 2022 TLVs). Calculations were performed for employees working within the vicinity of these devices throughout their work shift and employees exposed intentionally through the typical operation of the UV devices (e.g., passing through the entry gate, elevator users positioned directly under the elevator lights).

UV sanitizing entry gate—nearby employee exposure

The maximum daily exposure time without acute adverse health effects for a healthy worker operating the UV Sanitizing Entry Gate (T_{exp}) are 453.9 min and 698.9 min (using the 2021 and 2022 TLVs, respectively; Table 4) when an irradiance estimate of 0.00047 mW/cm^2 at 182 cm from the source of UV bulb A and B (Table 2; assuming the operator is directly exposed by bulb A and B) is used. It should be noted that the excimer lamps emit primarily 222 nm light (Figure 2 KrCl*-1 & KrCl*-1) with approximately one-third of the radiant energy emitted at wavelengths greater than 228 nm (Table 2). While this may be problematic in cases where these wavelengths are unknowingly emitted (i.e., where it is assumed a filtered source is used), in our calculations here, these are all accounted for in the weighted TLV calculated for these sources (Supplementary material, Figure S1).

UV sanitizing entry gate—user exposure

The maximum daily exposure time without acute adverse health effect based on TLVs in the UV Sanitizing Entry Gate is 16.9 min and 26.1 min (using the 2021 and 2022 TLVs, respectively; Table 4) when a maximum UVC irradiance of 0.0126 mW/cm^2 is used (Table 2). This time is much longer than the operational exposure time for this entry gate experienced by users or nearby employees.

UV elevator lights—elevator operator exposure

The maximum daily exposure time without acute adverse health effects for a person operating the elevator would be over 13 hr or 21 hr (using 2021 and 2022 TLVs, respectively; Table 4) when the irradiance reading of 0.0003 mW/cm^2 at a height of 152.4 cm is used (Table 2). Again, these exposures are primarily driven by irradiance at higher wavelengths (228–262 nm; Figure 2) due to higher hazardous effectiveness at these wavelengths (Supplementary material, Figure S1). With properly filtered lamps, emitting solely at 222 nm, the allowable exposure time would be higher.

UV elevator lights—user exposure

UV fluence was calculated for a Space Needle employee elevator user and compared to the device's TLV. Assuming an average height of the facial area of an elevator user of 5′1″ (154.9 cm), UV fluences for a 4 min exposure are 0.49 mJ/cm^2 right below a bulb and 0.45 mJ/cm^2 right below two bulbs overlap center (Table 4). These values are 29 and 31 times lower than the device TLV in 2021, and 47 and 52 times lower than the device TLV in 2022.

Discussion

All LP mercury-vapor UV devices' (i.e., LP-1, LP-3, LP-4) measured emission spectra had UVC radiation primarily at 254 nm as advertised and expected. KrCl* excimer devices (i.e., KrCl*-1 and KrCl*-2) emitted far UVC at 222 nm but also emitted longer, more hazardous wavelengths at a lower intensity. These wavelengths are germicidal but also pose potential risks of skin and eye damage upon human exposure. Identification of wavelengths outside of the advertised wavelengths is an important quality check, as safety professionals evaluating UV radiation sources often do not have access to emission spectra measuring devices and must rely on the manufacturer's specified wavelengths. These additional wavelengths, outside of the advertised ranges, may impact risk evaluations and efforts should be made to further minimize any wavelengths outside of the targeted ranges.

UVC fluence levels from the LP devices were adequate to inactivate SARS-CoV-2 when comparing inactivation rates to the measured irradiance values and estimated exposure time. Far UVC sources emitted irradiance at levels lower than are needed for effective disinfection of SARS-CoV-2 with the typical exposure times humans spend within the devices, but in theory, can achieve effective disinfection of non-moving surfaces over longer periods. Additional research is needed to validate the efficacy of these types of devices against specific microorganisms, under varying conditions (e.g., virus on surface *vs.* aerosol) with viral and environmental characteristics that may challenge the transmission of UV irradiation.

Estimated employee UV fluence exposures for the Sanitizing Entry Gate are below both the 2021 and 2022 ACGIH TLVs if employees are positioned 182 cm away from entry gate lamps that are facing

Table 4. Summary of KrCl* devices maximum exposure.

Device & exposure group	UVC Irradiance (mW/cm^2)	Distance (cm)	Acceptable Duration (min)[a]	Device TLV (mJ/cm^2)[a]
KrCl*-1: UV sanitizing entry gate				12.8/19.7
Employee—Users	0.01262[b]	25.4	16.9/26.0	
Employees working near	0.00047[c]	182.9	453.9/698.6	
KrCl*-2: UV elevator lights[d]				14.1/23.5
Employee—Users (directly below one bulb)	0.00203		115.8/192.9	
Employee—Users (directly below two bulbs overlap center)	0.00188		125.0/208.3	
Elevator Operators (near operator control panel—not directly below bulbs)	0.00031		758.1/1263.4	

[a]The values of acceptable duration and device TLV were calculated using ACGIH TLV 2021 and 2022 and presented as "the 2021 value/the 2022 value."
[b]Maximum irradiance measurement used.
[c]E-11 in Table 2.
[d]Irradiance at a height of 1.6 m (i.e., the estimated average height of a Space Needle employee) calculated using Equation 4 (Table 3). Irradiance at a height of 152.4 cm were used for Elevator Operator location because the irradiance at 1.6 m cannot be calculated using Equation 4 without the direct distance between the operator location and the lamp.

them. Estimated employee UV fluence exposure for Elevator Operators exposed to UV Elevator Lights are below the ACGIH TLVs under the Space Needle's reported rotating work shifts. Notably, these estimates do not account for employees being exposed to multiple UV devices over their work shift (e.g., employee riding in the elevator throughout their day, passing through UV Sanitizing Entry Gate(s) and working within the vicinity of the UV sources). As mentioned, for UV radiation, the ACGIH TLVs apply to "healthy" workers and do not apply to workers considered to be photosensitive or individuals concomitantly exposed to photo-sensitizing agents. Compared to the 2021 TLV, the 2022 version separates general exposures and exposures when the eyes are shielded; increasing the device TLVs 1.5 and 1.7 times for the UV sanitizing entry gate and UV elevator lights, respectively.

This field study evaluated UV fluence based on the measured irradiance when the radiometer was aimed directly at the UV source to conservatively evaluate these installed devices. For optical exposure, this approach may be an overestimate of actual employee exposure since it is unlikely an elevator user would be looking directly at the UV device mounted on the elevator ceiling for the full estimated duration of their elevator ride. Ozone generation may also occur with the application of UVC devices. This field study did not evaluate ozone formation for the installed devices and potential ozone generation should be assessed for the Space Needle's installed devices in areas without proper ventilation.

Recent published studies evaluating the human health effects from far UVC are promising, however as noted above, UV radiation associations and committees have expressed concern and cautioned their usage early in the pandemic and at the time of this field study. More recently and since the execution of this field study, the IUVA came out with a subsequent State of the Science report on Far UVC in May 2021 with updated data on the efficacy of SARS-CoV-2 disinfection from exposure to Far UVC and more information on human exposure thresholds based on the most recent published data. The report presented evidence supporting far UVC radiation as less damaging to mammalian tissues than longer UVC radiation based on literature reviews, taskforce expert opinions, and photobiological principles. This white paper stated regulators and standard agencies are evaluating the safety of far UVC technology and relaxing UVC exposure restriction have been proposed, as described by the ACGIH "Notice of Intended Change." The report also concludes:

> In summary, while research should continue into both the safety and efficacy of Far UV-C, the material in the Report suggests that there is sufficient evidence for immediate consideration of this technology during this world-wide health crisis. Far UV-C offers promising technology to reduce surface and airborne disease transmission in occupied spaces, including COVID-19 and other viral disease, when it is properly designed, engineered, and applied. (Blatchley et al. 2021)

This evolving information based on the latest research studies indicates far UVC in occupied spaces, where human exposure is anticipated, is likely to be further explored. Safety and health professionals should anticipate further application as a potential control method if studies continue to validate the efficacy and safety of these types of devices. Given the exposures noted in this study and based on current TLV guidance, the use of the far UVC devices at the Space Needle does not appear to put "healthy" workers, as defined by the ACGIH TLV, in danger, however, some of the devices may not provide the desired disinfection benefit if operated as intended.

Future work should be focused on the general public's exposure to UVC devices. The exposure guidelines of the ACGIH TLVs are based on "healthy" workers and are intended for use to help in the control of potential workplace health hazards and for no other use (ACGIH 2021, 2022). The ICNIRP (2004), a nonprofit scientific organization that guides health hazards of non-ionizing radiation exposure, published "Guidelines on Limits of Exposure to Ultraviolet Radiation of Wavelengths between 180 nm and 400 nm (Incoherent Optical Radiation)." This document presents UV radiation exposure limits similar to the ACGIH TLVs and states the exposure limits are intended for the working population but also indicates the established limits could apply to the general public with some precaution. Additional research and health and safety guidance to standardize risk assessment of UVC devices in a public setting is needed.

Conclusion

In response to the COVID-19 pandemic, the Space Needle worked diligently to enhance the safety for their employees and guests. Their procurement and installation of commercially available UVGI devices and early response by some within the UV radiation community warranted an evaluation of UV radiation hazards and efficacy. The evaluation confirmed advertised wavelengths for some devices but also identified wavelengths outside of the advertised bands. Measured irradiance suggests LP devices are likely effective against SARS-CoV-2, but the KrCl* excimer devices are expected to have limited efficacy at the very low irradiance levels as deployed. Further investigation is needed to assess the specific efficacy of each device under a range of scenarios. Exposure calculations for employees working within the vicinity of these devices throughout their work shift and exposed intentionally through the typical operation of the UV devices indicate exposures are less than the 2021 and 2022 versions of ACGIH TLVs Time-Weighted Average; the published guideline levels under which nearly all workers may be repeatedly exposed 8 hr a day, 40 hr per week for a working lifetime with no acute adverse health effects such as erythema or photokeratitis. Although not all exposure scenarios were assessed, caution should be applied to those employees qualifying under the ACGIH TLV limitations. More recent far UVC guidance published by an IUVA task force serves as an indication that expanded application of far UVC devices should be expected. Additional research and clearer occupational health and safety guidance to standardize risk assessment of UVGI devices in occupational and public settings are needed.

An accounting of the experience of the Space Needle with implementing various UV devices is presented as supplemental information to this manuscript.

Conflict of interest

Karl Linden is a member of the board of International Ultraviolet Association, Inc.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

References

ACGIH®. 2021. TLVs and BEIs based on the documentation of the threshold limit values for chemical substances and physical agents & biological exposure indices. Cincinnati (OH): ACGIH Signature Publications.

ACGIH®. 2022. TLVs and BEIs based on the documentation of the threshold limit values for chemical substances and physical agents & biological exposure indices. Cincinnati (OH): ACGIH Signature Publications.

Biasin M, Bianco A, Pareschi G, Cavalleri A, Cavatorta C, Fenizia F, Galli P, Lessio L, Lualdi M, Redaelli E, et al. 2021. UV-C irradiation is highly effective in inactivating and inhibiting SARS-CoV-2 replication. Sci Rep. 11:6260. doi:10.1038/s41598-021-85425-w

Blatchley E, III, Brenner D, Claus H, Cowan T, Linden K, Liu Y, Mao T, Park S, Piper P, Simons R, et al. 2021. Far UV-C radiation: current state-of knowledge. Chevy Chase (MD): IUVA; [accessed 2021 Dec]. https://iuva.org/.

Bolton JR, Linden KG. 2003. Standardization of methods for fluence (UV dose) determination in bench-scale UV experiments. J Environ Eng. 129(3):209–215. doi:10.1061/(ASCE)0733-9372(2003)129:3(209).

Buonanno M, Welch D, Shuryak I, Brenner DJ. 2020. Far-UVC light (222 Nm) efficiently and safely inactivates airborne human coronaviruses. Sci Rep. 10(1):1–8. doi:10.1038/s41598-020-67211-2

Illuminating Engineering Society (IES) Photobiology Committee. 2020. IES Committee Report 2-20-V1: germicidal ultraviolet (GUV)-frequently asked questions. New York (NY): IES; [accessed 2022 Jul]. https://www.ies.org/standards/committee-reports/.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). 2004. ICNIRP guidelines on limits of exposure to ultraviolet radiation of wavelengths between

180 nm and 400 nm (Incoherent Optical Radiation). Munich (Germany): ICNIRP; [accessed 2022 Jul]. https://www.icnirp.org/cms/upload/publications/ICNIRPUV2004.pdf.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). 2020. UVC lamps and SARS-COV-2. Munich (Germany): ICNIRP; [accessed 2021 Dec]. https://www.icnirp.org/en/activities/news/news-article/sars-cov-2-and-uvc-lamps.html.

International Ultraviolet Association Inc (IUVA). 2020. Discouraging the use of UV light on the human body. Chevy Chase (MD): IUVA; [accessed 2021 Dec]. https://iuva.org/uv-light-on-human-body.

Kitagawa H, Nomura T, Nazmul T, Omori K, Shigemoto N, Sakaguchi T, Ohge H. 2021. Effectiveness of 222-nm ultraviolet light on disinfecting SARS-CoV-2 surface contamination. Am J Infect Control. 49(3):299–301. DOI: 10.1016/j.ajic.2020.08.022.

Lawrence Berkeley National Laboratory (LBNL). 2018. Ultraviolet radiation. Berkeley (CA). [accessed 2022 Jun 6]. https://ehs.lbl.gov/resource/documents/radiation-protection/non-ionizing-radiation/ultraviolet-radiation/.

Ma B, Gundy PM, Gerba CP, Sobsey MD, Linden KG. 2021. UV inactivation of SARS-CoV-2 across the UVC spectrum: KrCl* Excimer, mercury-vapor, 1 and LED sources. Appl Environ Microbal. 87: e01532–21. doi:10.1128/AEM.01532-21

Ma B, Linden YS, Gundy PM, Gerba CP, Sobsey MD, Linden KG. 2021. Inactivation of coronaviruses and phage Phi6 from irradiation across UVC wavelengths. Environ Sci Technol Lett. 8(5):425–430. doi:10.1021/acs.estlett.1c00178

Narita K, Asano K, Morimoto Y, Igarashi T, Nakane A. 2018. Chronic irradiation with 222-nm UVC light induces neither DNA damage nor epidermal lesions in mouse skin, even at high doses. PLoS One. 13(7):e0201259. doi:10.1371/journal.pone.0201259

Robinson RT, Mahfooz N, Rosas-Mejia O, Liu Y, Hull NM. 2021. SARS-CoV-2 disinfection in aqueous solution by UV 222 from a krypton chlorine excilamp. medRxiv. 2021, 2021.02.19.21252101.

Rockey NC, Henderson JB, Chin K, Raskin L, Wigginton KR. 2021. Predictive modeling of virus inactivation by UV. Environ Sci Technol. 55(5):3322–3332. doi:10.1021/acs.est.0c07814

Simons R, Blatchley E, III, Linden K. 2020. Far UV-C in the 200-225 nm range, and its potential for disinfection applications. Chevy Chase (MD): IUVA; [accessed 2021 Dec]. https://iuva.org/resources/covid-19/Far%20UV-C%20in%20the%20200%20_%20225%20nm%20range,%20and%20its%20potential%20for%20disinfection%20applications.pdf.