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# Reflection of UVC wavelengths from common materials during surface UV disinfection: Assessment of human UV exposure and ozone generation

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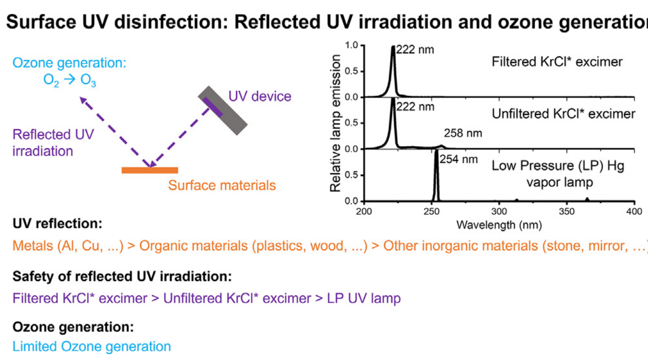
## HIGHLIGHTS

- Common materials can reflect UV, among which metals have greater reflection.
- Filtered KrCl* excimer is safe and effective for surface disinfection.
- Reflected UV for unfiltered KrCl* excimer and Hg lamp exhibit greater health risks.
- Ozone generation by UV lamps is unlikely to cause health risks.

## GRAPHICAL ABSTRACT

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## ABSTRACT

The COVID-19 pandemic has promoted interest in using devices emitting ultraviolet-C (UVC) irradiation (200–280 nm) for surface disinfection to reduce pathogen transmission, especially in occupied public spaces. While UVC devices have been shown to be highly effective against various pathogens, there are safety concerns when using conventional UVC devices for surface disinfection, including human exposure of reflected UVC irradiation and ozone generation. Emerging Far UVC devices (emitting at 200–230 nm), like the krypton chloride (KrCl*) excimer, have the potential to be safely applied in occupied spaces due to their minimal adverse effects on skin and eyes. In this study, UV reflection of 21 common materials was documented and compared using a filtered KrCl* excimer (installed with a bandpass filter at 222 nm), an unfiltered KrCl* excimer, and a conventional low-pressure mercury vapor lamp. The safety of Far UVC devices was evaluated based on the irradiance and spectrum of reflected UV irradiation and ozone generation measured at various locations around the device. Our results show that most common materials can reflect UV irradiation, among which some metals tend to have greater reflection. The Far UVC devices, especially the filtered KrCl* excimer, should be safe to be applied in occupied spaces for effective surface disinfection, with limited ozone generation and no health risk from reflected UV irradiation. However more caution is needed when using unfiltered KrCl* devices and conventional UV 254 nm light. This study provides urgently needed data on UV reflection of common materials and guidance for safety assessments of UVC devices for surface disinfection in occupied spaces.

## 1. Introduction

There is an increasing need for effective and safe approaches for disinfecting surfaces in high-risk areas like healthcare facilities and public transportation systems, especially since the COVID-19 pandemic, considering coronaviruses and other pathogens may stay viable on surfaces up to

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several days and cause infection (van Doremalen et al., 2020; Kramer et al., 2006; Kramer and Assadian, 2014). Germicidal ultraviolet (UV) devices emitting UVC irradiation between 200 and 280 nm have been widely applied for surface disinfection in various configurations, including UV cabinets, portable area robot-like disinfection units, and overhead or lower room systems (Byrne et al., 2015; Kowalski, 2009). Compared to conventional approaches of using products containing chemicals, soap, or detergent, UVC surface disinfection has several advantages, including high effectiveness, no chemicals and off-gassing, and limited to no material corrosion (Lawal et al., 2018; Rockett, 2019).

Safety of UVC devices needs to be evaluated before applying them in occupied spaces. Conventional UVC devices, such as low-pressure (LP) mercury vapor lamps emitting at 254 nm, are known to be hazardous to exposed to human skin and eyes, causing erythema and photokeratitis (Harrison and Young, 2002; Sengillo et al., 2021; Tenkate, 1998; Zaffina et al., 2012). Although direct human exposure of UV irradiation from the UVC devices should be avoided during surface disinfection, reflected UV irradiation from surfaces may still pose health risks, especially from highly reflective surfaces when using devices such as UV wands and handheld devices. Compared to conventional UVC devices, emerging Far UVC devices emitting at 200–230 nm, like krypton chloride (KrCl*) excimer, could serve as a safer and better surface disinfection solution in occupied spaces. Previous studies suggested that irradiation from Far UVC devices are much safer for human exposure due to poor penetration into human cells (Buonanno et al., 2020, Buonanno et al., 2017; Kaidzu et al., 2021), while still providing effective disinfection of various pathogens (Ma et al., 2022). In addition to skin exposure concerns, Far UVC devices may generate ozone via photochemical reaction and electric discharges, causing cough, throat irritation, and shortness of breath (Claus, 2021).

In this study, the UV reflection (i.e., the fraction of UV irradiance that is reflected from a surface to the incident irradiance) of surfaces made of 21 commonly used materials, including metals and plastics, was documented using filtered and unfiltered KrCl* lamps and a conventional LP UV lamp. To assess the safety of Far UVC devices for surface disinfection in occupied spaces, the spectrum and irradiance of reflected UV irradiation from surfaces were measured at various locations around individual KrCl* and LP UV devices. These results were compared with the American Conference of Governmental Industrial Hygienists (ACGIH®) Threshold Limit Values (TLVs®) (ACGIH, 2022) for human skin and eye exposures and the daily maximum exposure time for the UV devices that would ensure safety from acute adverse health effects was recommended. Finally, the ozone concentrations around the UV devices during application were evaluated.

## 2. Materials and methods

### 2.1. UV reflection of common surfaces

UV reflection of common surfaces was measured using an apparatus adopted from Blatchley, 1997 as configured in Fig. 1 (Blatchley, 1997). Three UV devices were used in this study, including a handheld filtered KrCl* excimer lamp emitting at 222 nm (BeamClean™ from Freestyle Partners, LLC, and its affiliate, FSP Innovations, LLC, MI, USA), a handheld unfiltered KrCl* excimer lamp emitting primarily at 222 nm with additional radiation up to 270 nm (BeamClean™ from Freestyle Partners, LLC, and its affiliate, FSP Innovations, LLC, MI, USA), and a LP mercury lamp emitting at 254 nm (18 W UVC Surface Sanitizer, GermAwayUV, Inc., FL, USA). Detailed UV device specifications are listed in Table S1. The dimensions of the handheld filtered and unfiltered KrCl* excimers are shown in Fig. S1. Relative emission spectra (normalized to the maximum value across 200 nm to 400 nm; solid lines in Fig. 2) for these UV lamps were measured using a calibrated Maya 2000 Pro spectrometer (Ocean Insight, Dunedin, FL, USA). Surface sheets (12 in. × 12 in.) made of 21 different commonly used materials were evaluated in this study, including metals [aluminum, aluminum foil tape, anodized aluminum, copper, nickel, silver, and stainless steel with different finishes (#2B, #4, and #8)], organic materials (acrylic, cardboard, Formica laminate, office paper, polycarbonate, polyester, Tyvek® board, and wood), and other inorganic materials (marble, mirror, stone, and tile). Detailed information of all tested materials is summarized in Table S2.

The reflected irradiance ($I_r$) from the surface sheets was measured by setting the center of the UV lamp at 10.75 in. above and 10.75 in. right to the center of a surface sheet at a 45° angle facing the sheet (Fig. 1-A). A calibrated radiometer (ILT- 2400 w/ SED 240; International Light Technologies, Inc., Peabody, MA, USA) was set at the same height as the UV lamp but 10.75 in. left to the center of a surface sheet at a 45° angle facing the sheet (Fig. 1-A). The detection limits of the radiometer at 222 nm and 254 nm were $1.68 \times 10^{-5}$ mW/cm$^2$ and $1.81 \times 10^{-5}$ mW/cm$^2$, respectively. A cardboard divider (12 in. × 12 in. × 1 in.) was placed vertically at 7.25 in. above the center of the surface sheet (i.e., 3.5 in. below the radiometer) to block diffuse UV irradiation from the UV lamp to the radiometer (Fig. 1-A). Complete blocking of direct UV signal was confirmed as no UV signal was detected by the radiometer without the surface sheet in place. Incident irradiance ($I_0$) from the UV device at the same beam traveling distance of 30.4 in. (i.e., $2 \times 10.75 \times \sqrt{2}$ inches; Fig. 1-A) was measured by positioning the radiometer 21.5 in. below and 21.5 in. left to the center of the UV lamp at a 45° angle facing the UV lamp (Fig. 1-B). Five

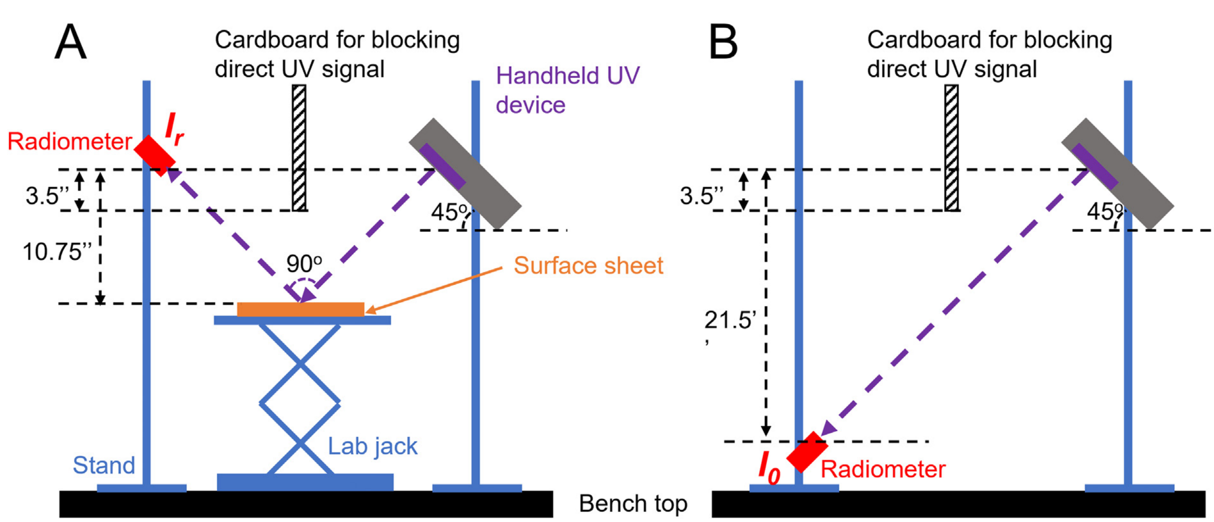


**Fig. 1.** Experimental setups for the measurements of UV reflection of common surfaces. The reflection was presented as the fraction of the reflected irradiance from a surface ($I_r$; measured as shown in Fig. A) to the incident irradiance ($I_0$; measured as shown in Fig. B) at the same beam traveling distance of 30.4 in. (i.e., $2 \times 10.75 \times \sqrt{2}$ inches).

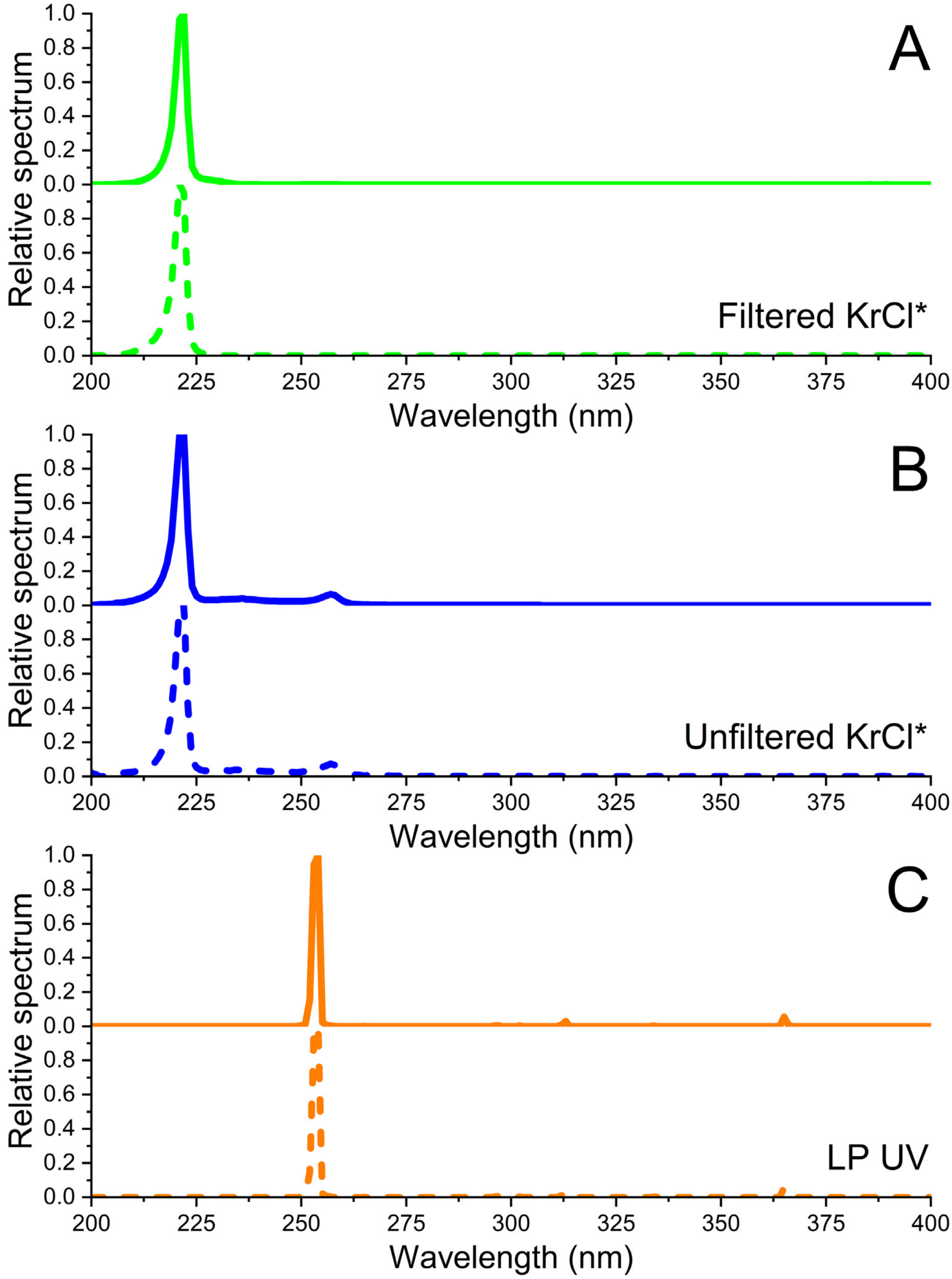


**Fig. 2.** Relative spectra of lamp emission (solid lines) and reflected irradiation (dashed lines) from anodized aluminum for the filtered KrCl* excimer (A), unfiltered KrCl* excimer (B) and LP UV lamp (C). All spectral emission measurements made using a calibrated spectrometer.

measurements of reflected and incident irradiance were taken for each surface material. The UV reflection of surfaces was presented as the fraction of the reflected irradiance measured at a defined point and distance in space away from the material to the incident irradiance measured at an equivalent beam traveling distance using Eq. (1):

$$\text{UV reflection value} = \frac{I_r}{I_0} \times 100\% \tag{1}$$

### 2.2. Reflected UV spectrum and irradiance from surfaces

To assess the surface disinfection efficacy and safety of the handheld filtered and unfiltered KrCl* excimer devices, UV irradiance from the device and the subsequent reflected UV spectrum and irradiance from common surfaces were measured. The LP mercury lamp was not selected for these measurements because this device is not designed to be applied around humans without proper protective equipment due to its adverse effects on human skin and eyes (Harrison and Young, 2002; Sengillo et al., 2021; Tenkate, 1998; Zaffina et al., 2012) and subsequent low TLVs (ACGIH, 2022). The UV irradiance reflected from the handheld devices was measured over an area of 6 in. in radius when held at a distance of 1 in. from a surface, which is the recommended distance for surface disinfection application according to the device manufacturer's instructions (Fig. 3-A). Measurements were collected directly below the center of the excimer lamp and at radii of 1, 2, 3, 4, and 6 in. from the center of the measurement area for every 45° up from 0° (front of the device; Fig. S1) to 360°. The average irradiance ($I_r$) at a radius ($r$) of 0 to 6 in. for every 0.05 in. is estimated from the measurements using the 'interpolation' function in OriginPro 2022. The average irradiance ($I_R$) within a radius ($R$) is calculated using Eq. (2):

$$I_R = \frac{\int_0^R (I_r \times 2\pi r)\, dr}{\pi R^2} \cong \frac{\sum_0^R I_r \times 2\pi r \times 0.05}{\pi R^2} \tag{2}$$

The reflected UV spectrum and irradiance was assessed by setting the handheld UV devices horizontally at 1 in. above five common surfaces, including anodized aluminum, stainless steel (#8), polycarbonate, marble, and mirror. The reflected UV spectrum was measured by placing the spectrometer in front of the UV device at a heigh of 0.5 in. above the bottom of the device to avoid the spectrometer collecting any direct UV signal from the device (Fig. 3-B). The reflected UV irradiance measurements were collected at heights ($H$) of 1, 6, 12, and 24 in. above the bottom of the excimer lamp and radii ($R_r$) of 6 and 12 in. from the center of the lamp for every 45° from 0° (front of the device) to 360° ($\theta$ in Fig. 3-C). At each location, the measurements were collected by placing the radiometer at angles of 0° (horizontally facing the device), 45 °, and 90° (vertically facing the surface sheet) and the highest value was recorded ($\alpha$ in Fig. 3-C).

### 2.3. Ozone generation and concentration.

The ozone generation by filtered and unfiltered KrCl* excimer lamps was determined by measuring the ozone concentration in a closed cardboard box [10 in. × 9 in. × 11 in., volume ($V$) = $1.62 \times 10^{-2}$ $m^3$; Fig. 4] with the excimer lamps. A fan was placed in the box to ensure the air was well-mixed. For each measurement, the excimer lamp was turned on for 1 min (i.e., the maximum time for a continuous operation per the device manufacturer's instructions) and then turned off for at least 5 min to ensure that ozone concentration went back to the background level (Mean ± S.D. = 1.6 ± 1.5 ppb) before the next measurement. The ozone concentration at 6 in. directly below the lamps was monitored continuously over the entire course of a measurement using an ozone meter (GO3, 2B Technologies, Inc., Boulder, CO, USA), and the maximum ozone concentration was recorded ($C_{Max.\ ozone}$ in ppb; 1 ppb = 2.14 μg/$m^3$ ozone). Five measurements were collected for each excimer lamp and the ozone generation (i.e., ozone generated per minute of excimer lamp operation in μg/min) was calculated using Eq. (3).

$$\text{Ozone generation} = \frac{(C_{Nax.ozone} - 1.6\ \text{ppb}) \times 2.14 \frac{\mu g/m^3}{\text{ppb}} \times V}{1\ \text{minute}} \tag{3}$$

The ozone concentrations at heights of 1, 6, 12, and 24 in. above the bottom of the filtered and unfiltered KrCl* excimer lamps were also documented in an indoor environment (area = 67.5 $m^2$, height = 3 m, air exchange = 6.95 per hour, background ozone concentration = 38.8 ± 2.0 ppb) to estimate the possible human respiratory exposure while using the handheld excimer lamps. All measurements were taken using the same method as described above. Triplicate measurements were collected at each height for each excimer lamp. The ozone concentration contributed by the excimer lamps was calculated by excluding the background ozone concentration.

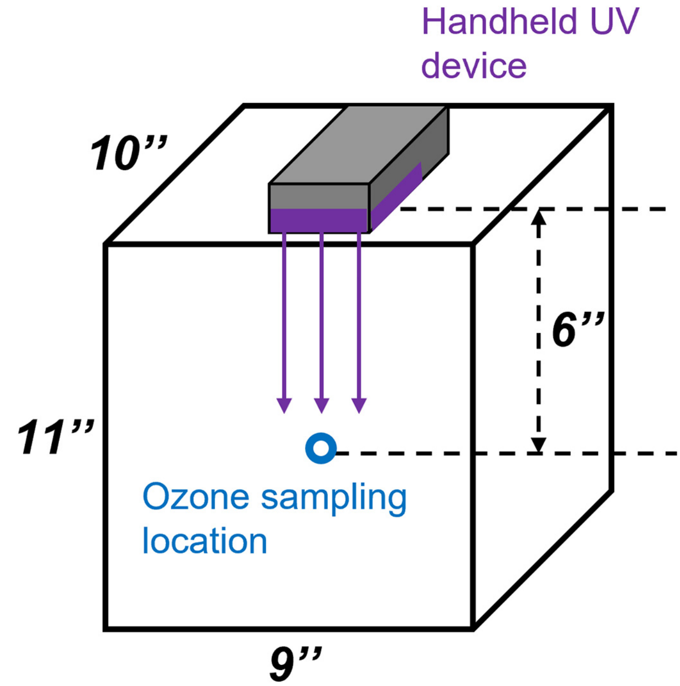


**Fig. 4.** Experimental setup for measurements of ozone generation by the filtered and unfiltered KrCl* excimer lamps.

### 2.4. Hazardous effectiveness assessment of reflected UV irradiation

Considering the handheld KrCl* excimer devices are designed to be applied by and around humans, the daily maximum exposure time allowable within the ACGIH recommendation limit ($T_{exp}$) for the reflected UV irradiation from surfaces was calculated according to the method by Henderson et al. (2022). Briefly, the weighted spectral hazardous effectiveness ($RE$; Relative to a monochromatic UV source emitting at 270 nm, at which UV irradiation has the highest hazardous effectiveness) for human skin and eye under reflected irradiation was calculated using Eq. (4).

$$RE = \frac{\sum_{i=200}^{i=400} (RI_i \times RE_i)}{\sum_{i=200}^{i=400} RI_i} \tag{4}$$

where $RI_i$ is the relative irradiance of the reflected irradiation at wavelength i nm, which is assumed to be the same as the device emission relative

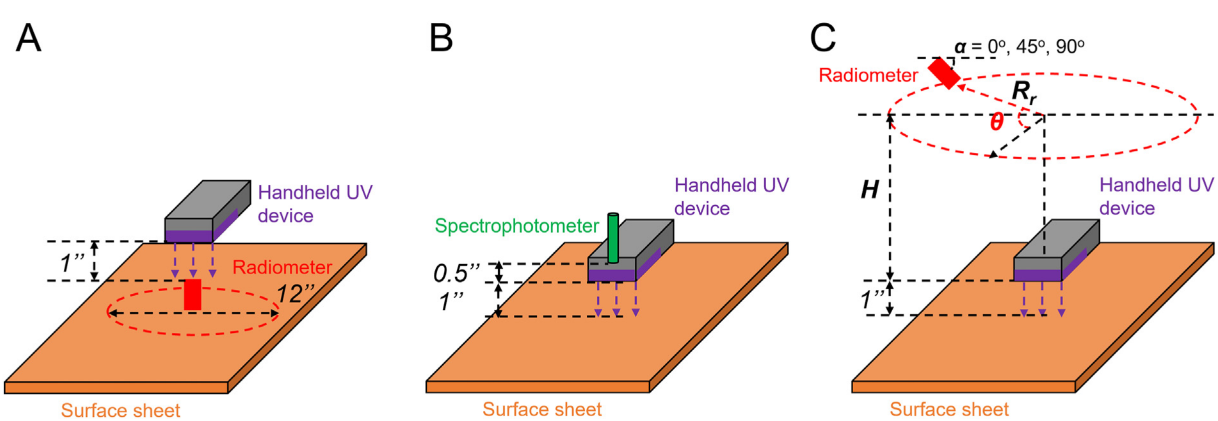


**Fig. 3.** Experimental setups for measurements of UV irradiance from the handheld filtered and unfiltered KrCl* excimer devices (A), and the reflected UV spectrum (B) and irradiance (C) at various locations around the handheld UV device.

irradiance (Fig. 2), $RE_i$ is the relative spectral hazardous effectiveness for skin or eye exposures at wavelength $i$ nm according to ACGIH, 2022 (Fig. S2). Then, $T_{exp}$ for a UV device was calculated using Eq. (5).

$$T_{exp} = \frac{TLV}{I_r} = \frac{TLV_{270}}{RE \times I_r} \tag{5}$$

$TLV$ is the threshold limit value of daily exposure UV dose (in mJ/cm$^2$) for the KrCl* excimer devices and $TLV_{270}$ is 3 mJ/cm$^2$ (the threshold limit value at 270 nm in ACGIH, 2022).

### 2.5. Data analysis

Paired $t$-tests were performed to determine whether there was a statistically significant difference in (1) the UV reflection between tested surfaces, and (2) the ozone concentrations for different UV devices. Two sample t-test was also conducted to determine whether there was a statistically significant difference in the ozone generation rate by the filtered and unfiltered KrCl* excimer lamps. All contour plots were made using OriginPro 2022.

## 3. Results and discussion

### 3.1. UV reflection of common surfaces

The UV reflection values of surface sheets made of 21 different common materials upon irradiation by the filtered and unfiltered KrCl* excimer lamps and the LP UV lamp are shown in Fig. 5. Minor differences in UV reflection values were observed between the UV devices. Among 21 tested materials, 14 materials exhibited the lowest level of UV reflection values using the filtered KrCl* excimer lamp, which was on average 3.6 % and 3.3 % lower than the values using the unfiltered KrCl* excimer lamp and the LP UV lamp, respectively. No significant difference in the UV reflection values was observed for the unfiltered KrCl* excimer lamp and the LP UV lamp across materials (Paired $t$-test: $P = 0.7$). While most tested materials (20 out of 21 materials, except for stone) can reflect some level of UV irradiation, significant differences in UV reflection values were observed between materials. In general, metals exhibited higher reflection values than organic materials and other inorganic materials, ranging from 12 % (stainless steel #4 for the filtered KrCl* excimer) to 67 % (aluminum foil tape for the unfiltered filtered KrCl* excimer). Greater metallic reflection of UV and visible lights was also observed in previous studies (Blatchley, 1997; Claus and Cooksey, 2022; Goncalves, 2020), except for one organic material, polytetrafluoroethylene (PTFE), which is highly reflective of UV irradiation and is often used as a reference standard for reflectance measurements (Claus and Cooksey, 2022; Stojalowski and Fairfoull, 2021). For the same metal, the UV reflection may be modified by surface coating and polishing. Anodized aluminum exhibited much greater UV reflection values compared to a common aluminum plate (i.e., 61–62 % vs. 22–33 % for all UV devices; Fig. 5), which agrees with previous observations by Claus and Cooksey (2022). Significantly greater UV reflection values were observed for stainless steel with mirror finish (#8) than with mill finish (#2B; Fig. 5). It is important to note that while the reflection values measured in this study were mainly representative of the specular reflection (i.e., mirror-like reflection), surfaces with greater roughness may have more diffuse reflection (i.e., reflection scattered at many angles), which leads to lower reflection intensity when measured at a point in space. Considering the purpose of this study is to understand the amount of UV irradiation reflected to points around the UV source that a person may be located, the safety consideration for UV exposure should be specific to a point in space from the UV device and surfaces and may include any type of reflected irradiation. Thus, we also investigated the reflected UV irradiance from surfaces at different coordinate locations around the device.

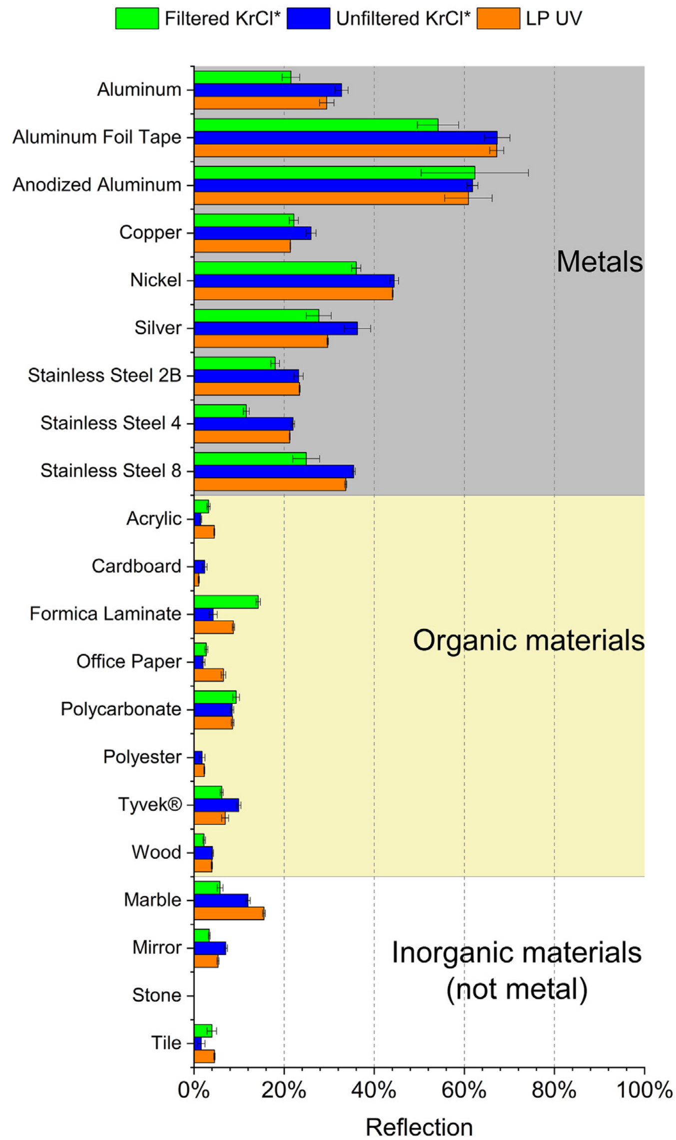


**Fig. 5.** Reflection (i.e., the fraction of reflected UV irradiance to the incident irradiance) of common surfaces upon irradiation by the filtered KrCl* excimer, unfiltered KrCl* excimer and LP UV lamp.

### 3.2. Reflected UV spectrum and irradiance mapping from selected common surfaces

The UV irradiance distribution over an area of 12 in. in diameter at a distance of 1 in. from the filtered and unfiltered KrCl* excimer devices is shown in Fig. 6. Most irradiance was observed within a 2 in. in radius, with the average irradiance of 1.68 and 2.14 mW/cm$^2$ for the filtered and unfiltered KrCl* excimer devices, respectively (Table 1). According to our previous study on UV inactivation kinetics of SARS-CoV-2 (pseudo-first-order inactivation rate constant at $\log_{10}$-sacle: 1.42 and 1.53 cm$^2$/mJ for filtered and unfiltered KrCl* excimer (Ma et al., 2021)), these irradiance levels can achieve 4 log (99.99 %) reduction of SARS-CoV-2 within 1.67 and 1.22 s, respectively.

Five materials that represent all tested material types (i.e., metal, organic material, and non-metal inorganic material) and cover a wide range of UV reflection values (3.4 % to 62.3 %; Fig. 5) were selected for assessment of reflected UV spectrum and reflected irradiance mapping, including anodized aluminum, stainless steel #8 (mirror finish), polycarbonate, marble, and mirror. The reflected UV spectrum was only documented for anodized aluminum (Fig. 2) because the reflected irradiation for other materials were too weak for the spectrophotometer to detect. Similar spectra were observed for the UV emission irradiation from the device and the

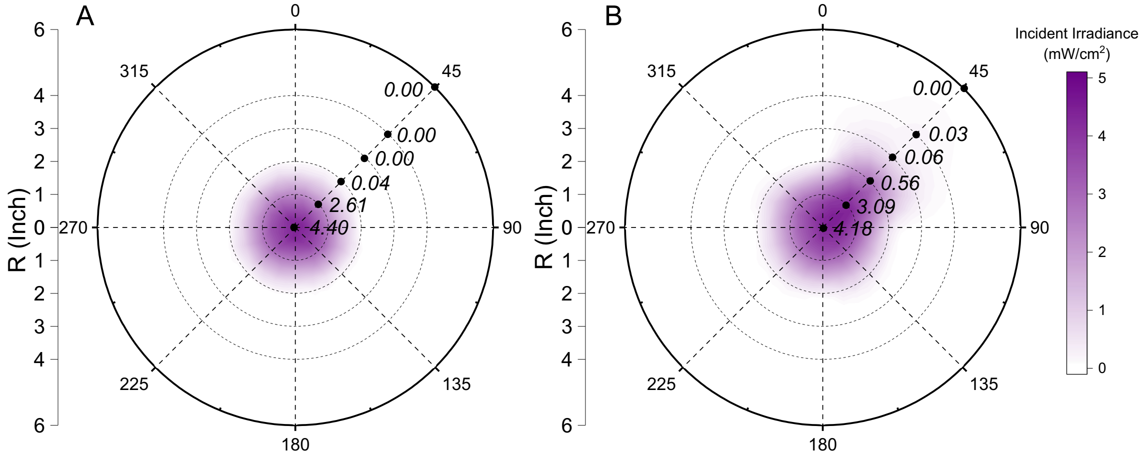


**Fig. 6.** UV irradiance distribution over an area of 12 in. in diameter at a distance of 1 in. from the handheld filtered (A) and unfiltered (B) KrCl* excimer. The average irradiance ($I_r$ in mW/cm$^2$) at radii of 0, 1, 2, 3, 4, and 6 in. from both devices are labeled in the plot.

**Table 1**
Average irradiance over an area of 1, 2, 3, 4, and 6 in. in radius at a distance of 1 in. from the filtered and unfiltered KrCl* excimer devices.

| Radius (inch) | Average irradiance (mW/cm$^2$) | |
|---|---|---|
| | Filtered KrCl* | Unfiltered KrCl* |
| 1 | 3.33 | 3.60 |
| 2 | 1.68 | 2.14 |
| 3 | 0.76 | 1.11 |
| 4 | 0.42 | 0.64 |
| 6 | 0.19 | 0.29 |

reflected UV irradiation from the anodized aluminum [i.e., differences in relative irradiance ($RI_i$; Fig. 2) between emission irradiation and reflected irradiation across 200 nm to 400 nm varied by <0.04]. This was expected because the UV reflection value of anodized aluminum is relatively consistent across UVC wavelengths as indicated by our results that only minor difference in UV reflection values was observed for the KrCl* excimer and the LP UV lamp (Fig. 5). Other materials, such as Formica laminate and marble, may marginally alter the UV spectrum during reflection as these materials exhibited minor differences in UV reflection values across wavelengths (222 nm from the filtered KrCl* vs. 254 nm from the LP UV lamp; Fig. 5),

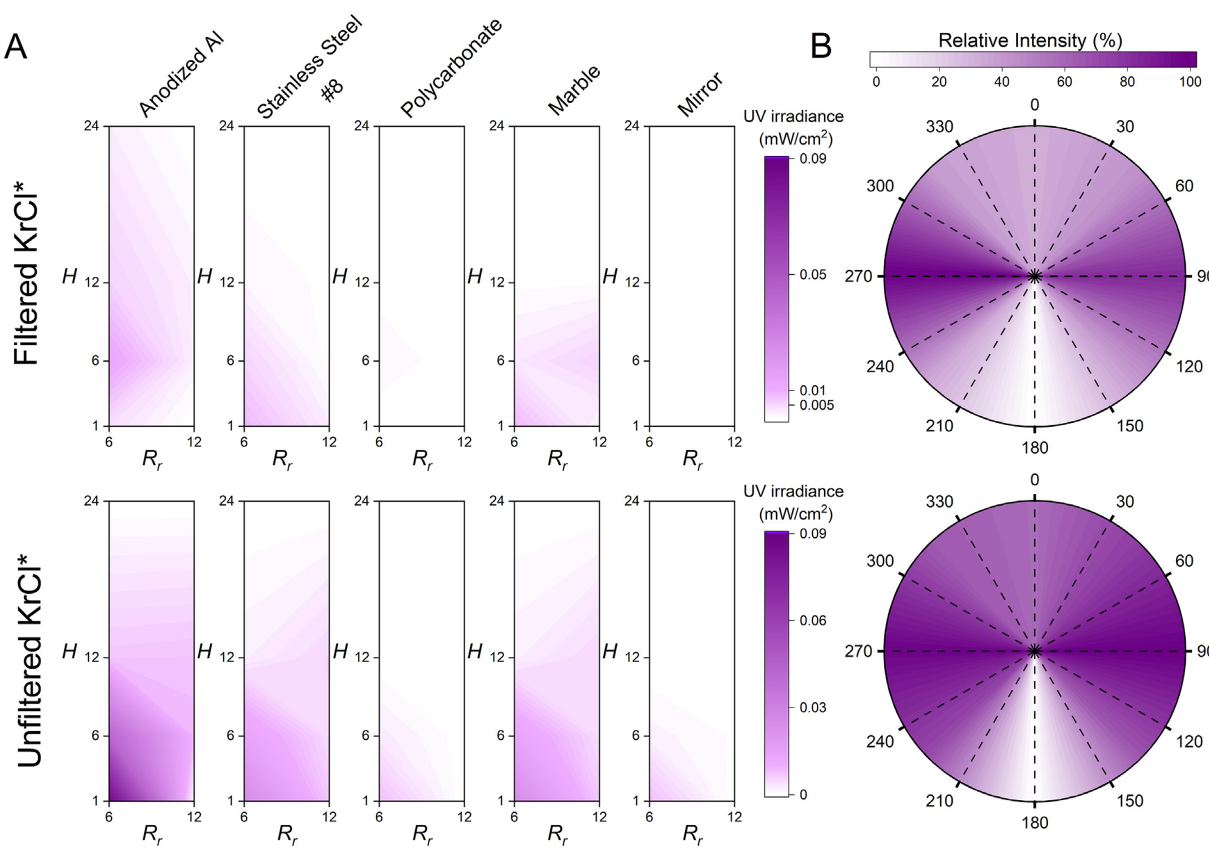


**Fig. 7.** (A) Maximum reflected irradiance measured at different heights ($H$) above the bottom of the lamp and horizontal distances ($R_r$) from the center of the lamps in the handheld filtered (upper panel) and unfiltered (bottom panel) KrCl* excimer devices. (B) The average relative reflected irradiance at different positions (0° is the front side of the handheld excimer devices) around the device from all tested surfaces.

**Table 2**
The relative hazardous effectiveness (*RE*; relative to 270 nm) and threshold limit value (*TLV*) for UV exposures of human eye and skin for reflected UV irradiation from surfaces under the filtered and unfiltered KrCl* handheld devices and the LP UV lamp.

| | *RE* | | *TLV* (mJ/cm$^2$) | |
|---|---|---|---|---|
| | Eye | Skin | Eye | Skin |
| Filtered KrCl* excimer | 0.021 | 0.007 | 143.9 | 407.5 |
| Unfiltered KrCl* excimer | 0.091 | 0.041 | 33.0 | 73.4 |
| LP UV lamp | 0.491 | 0.300 | 6.1 | 10.0 |

which, if relevant, should be investigated in the future. To simplify the discussion in this study, the reflected UV irradiation spectra for all materials were assumed to be the same as the UV device emission spectra.

The reflected UV irradiance was measured at various locations around the handheld KrCl* excimer devices (Fig. 7). The highest UV irradiance was always measured when the radiometer was placed at an angle of 45° from normal ($\alpha$ in Fig. 3-C). The reflective irradiance from different materials was ranked as: Anodized Aluminum > Stainless Steel #8 > Marble > Polycarbonate > Mirror, following the same rank of the material's reflection values (Fig. 5). For the same material, the reflected UV irradiance was higher for the unfiltered KrCl* excimer than the filtered KrCl* excimer, due to the higher UV irradiance (Fig. 6 and Table 1) and marginally higher reflection value (Fig. 5) for the unfiltered KrCl* excimer. The reflected UV irradiance varied with the distance from the UV devices. In general, the reflected irradiance decreased with $H$ (height above the bottom of the lamp) and $R_r$ (horizontal distances from the center of the lamps). For most tested surfaces, the maximum irradiance was observed at $H$ of 1 or 6 in. and $R_r$ of 6 in., ranging from $2.1 \times 10^{-4}$ to $1.2 \times 10^{-2}$ mW/cm$^2$ for the filtered KrCl* excimer and $8.1 \times 10^{-3}$ to $8.6 \times 10^{-2}$ mW/cm$^2$ for the unfiltered KrCl* excimer (Fig. 7-A). The reflected UV irradiance also changed with the position around the UV devices (Fig. 7-B). The highest reflected irradiance was always observed at the side of the device ($\theta = 90°$ and 270°) and no reflected irradiance was observed behind the device ($\theta = 180°$; Fig. 7-B). This is likely due to shape of the device chassis (Fig. S1), which blocks the reflected irradiation at the back of the device while letting reflected irradiation out from the side of the device.

The relative hazardous effectiveness (*RE*) and threshold limit value (*TLV*) for UV exposures of human eyes and skin was calculated for reflected UV irradiation from the filtered and unfiltered KrCl* handheld devices and the LP UV lamp (Table 2). The daily maximum exposure time allowable within the ACGIH recommendation limit ($T_{exp}$) at various distances from the KrCl* handheld devices was calculated (Fig. 8), based on the maximum reflected irradiance measured at the respective locations (Fig. 7-A). The LP UV lamp has the greatest relative hazardous effectiveness (*RE*), which are 5.4 and 7.3 times higher than the unfiltered KrCl* excimer and 23.4 and 42.9 times higher than the filtered KrCl* excimer for eye and skin exposures, respectively. The reflected irradiation from surfaces under the filtered KrCl* excimer is much safter than the unfiltered KrCl* excimer, with lower relative hazardous effectiveness (*RE* in Table 2) and higher TLVs for both eye and skin exposures. This is due to the differences in their emission spectrum. Approximately 8.5 % of the irradiation from the unfiltered KrCl* excimer is between 250 nm to 270 nm (Fig. 2), which are wavelengths that are more hazardous than the primary emitting wavelength of the filtered KrCl* excimer at 222 nm (Fig. S2). As a result, much longer daily maximum exposure time allowable within the ACGIH recommendation limit ($T_{exp}$) was observed for the filtered KrCl* excimer, with the lowest $T_{exp}$ of 3.3 h (anodized aluminum, $H = 6$ in., $R = 6$ in., eye exposure) and $T_{exp}$ >24 h for most surfaces at greater distances (i.e., $H > 6$ in. and $R > 6$ in.). These results suggest that the filtered KrCl* excimer is unlikely to cause adverse health risks from reflected UV irradiation from common surfaces when used as directed. Relatively long $T_{exp}$ (i.e., > 6 h) was also observed when the unfiltered KrCl* excimer was applied to surfaces with low reflection value, such as polycarbonate and mirror, especially at greater distances ($H$ and $R > 6$ in.; Fig. 8). But the $T_{exp}$ values were generally lower than 3 h for the highly reflective surfaces like anodized aluminum, with the lowest $T_{exp}$ of 6.4 min for eye exposure and 14.2 min for skin exposure (anodized aluminum, $H = 1$ in., $R = 6$ in.; Fig. 8).

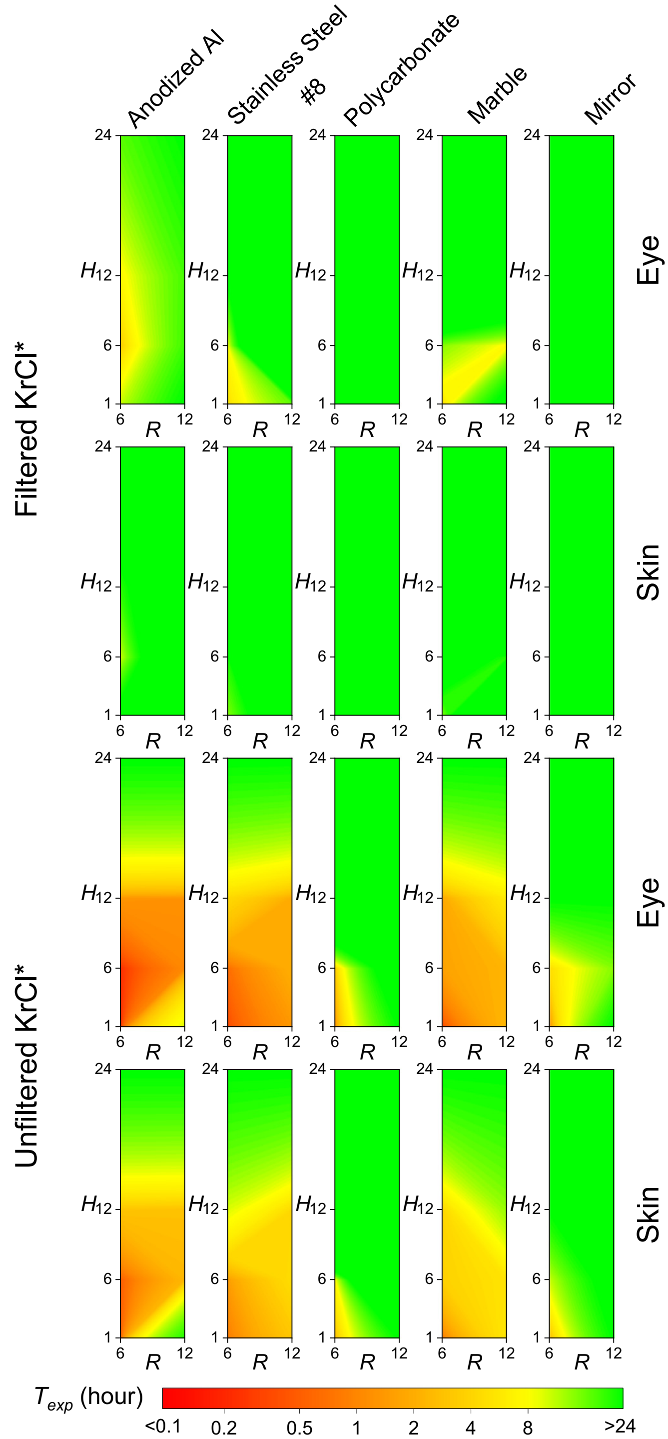


**Fig. 8.** The daily maximum exposure time of reflected UV irradiation allowable within the ACGIH recommendation limit ($T_{exp}$) for human eye and skin at various distances from the filtered and unfiltered KrCl* excimer devices.

### 3.3. Ozone generation

Significantly lower ozone generation ($P = 1.3 \times 10^{-7}$; Two sample *t*-test) was observed for the filtered KrCl* excimer lamp (1.6 ± 0.1 μg/min; Table 3) compared to the unfiltered KrCl excimer lamp (3.0 ± 0.2 μg/min). This is

**Table 3**
Ozone generation by the filtered and unfiltered KrCl* excimer devices and ozone concentrations measured at heights of 1, 6, 12, and 24 in. above the bottom of the excimer devices in an indoor environment.

| | Filtered KrCl* excimer | Unfiltered KrCl* excimer |
|---|---|---|
| Ozone generation measurements in closed box. | | |
| Max. ozone concentration (ppb) | 46.7 ± 1.9 | 86.8 ± 4.5 |
| Ozone generation (μg/min) | 1.6 ± 0.1 | 3.0 ± 0.2 |
| Ozone concentration measurements in indoor environment. | | |
| Height (inch) | Ozone concentration (ppb) | |
| 1 | −0.8 ± 2.6 | 2.3 ± 2.3 |
| 6 | 2.7 ± 1.3 | 1.4 ± 0.7 |
| 12 | 1.8 ± 1.4 | 1.5 ± 1.8 |
| 24 | −0.3 ± 1.2 | 0.6 ± 1.2 |

expected because the filtered KrCl* excimer lamp had less UVC irradiance (Fig. 6) due to the optical filter installed. The ozone concentrations at heights of 1, 6, 12, and 24 in. above the bottom of the filtered and unfiltered KrCl* excimer devices in an indoor environment are listed in Table 3. There was no significant difference in the ozone concentrations for the filtered and unfiltered KrCl* excimer across heights ($P = 0.58$; Paired t-test). The ozone concentrations from the KrCl* excimer devices were lower than 3 ppb for all the locations measured, which is much lower than ACGIH TLV of 100 ppb (ACGIH, 2022) and the FDA limit for extended exposure (50 ppb; CFR Title 21). These results suggests that although the handheld KrCl* excimer devices generate ozone during operation, they do not significantly contribute to the ozone accumulation in an indoor environment. Ozone generation is not a concern for LP UV lamps as previous study by Claus (2021) showed that typical soft glass LP UV lamps cannot generate ozone.

In summary, this study provides urgently needed data on UV reflection of commonly used materials and a comprehensive approach for safety assessment of UVC devices for surface disinfection in occupied spaces, considering both the UV exposure to reflected irradiation and ozone generation. Our results show that most common material can reflect UV irradiation, and the reflected UV irradiance decreases with the distance from the surfaces. The hazardous effectiveness of reflected UV irradiation and ozone generation by the filtered KrCl* excimer are within the ACGIH exposure recommendation limits, even when applied to the most highly reflective surfaces for a long period of time (> 8 h), suggesting the filtered KrCl* excimer should be safe to be applied in occupied spaces. The hazardous effectiveness of reflected UV irradiation for the unfiltered KrCl* excimer may still be within the ACGIH recommendation limits when applied to surfaces with low reflection values, but precautions need to be considered when applied to highly reflective surfaces for a longer period; such as wearing UV blocking goggles and covering exposed skin. More caution is needed for any use of the LP UV lamp due to its much greater hazardous effects and low TLV.

## CRediT authorship contribution statement

Ben Ma: methodology, formal analysis, visualization, investigation, writing – original draft; Sam Burke-Bevis and Luke Tiefel: analysis, investigation. Jennifer Rosen and Ben Feeney: conceptualization, funding acquisition, review and editing; Karl Linden: conceptualization, project administration, writing – review and editing.

## Data availability

Data will be made available on request.

## Declaration of competing interest

Karl Linden reports financial support was provided by Freestyle Partners LLC.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.161848.

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