Effects of Germicidal Far-UVC on Indoor Air Quality in an Office Setting

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Abstract

The application of 222 nm light from KrCl excimer lamps (GUV222 or Far-UVC) is a promising approach to reduce the indoor transmission of airborne pathogens, including the SARS-CoV-2 virus. GUV222 inactivates airborne pathogens and is believed to be relatively safe for human skin and eye exposure. However, UV light initiates photochemical reactions which may negatively impact indoor air quality. We conducted a series of experiments to assess the formation of ozone (O_3) and secondary organic aerosols (SOA) induced by commercial far-UVC devices in an office environment with an air exchange rate of 1.3 h^{-1}. We studied scenarios with a single far-UVC lamp, corresponding to the manufacturer's recommendations, and with four far-UVC lamps, which exceeded both the manufacturer's and regulatory recommendations. The single far-UVC lamp did not significantly impact O_3 or fine particulate matter levels. Consistent with previous studies in the literature, the higher far-UVC fluences lead to increases in O_3 of 5 to 10 ppb above background, and minor increases in particulate matter. The use of far-UVC at intensities consistent with regulatory / manufacturer's recommendations, and in conjunction with normal ventilation, may reduce airborne pathogen levels while minimizing the formation of air pollutants.

Introduction

The dominant pathway of transmission for respiratory viruses, including SARS-CoV-2, influenza, and respiratory syncytial virus, is airborne (aerosol) transmission.[1,2] In this scenario, an infected person emits respiratory aerosols containing pathogens which may be inhaled by others, leading to infection. Indoor gatherings, especially in crowded and poorly ventilated settings, pose a higher risk of transmission. Engineering solutions, including adequate ventilation and air filtration, can reduce transmission risk.[3,4]

Germicidal ultraviolet (GUV) light has been proposed as another promising tool for reducing the risk of airborne virus transmission indoors. UV light is well-known to inactivate or kill

bacteria and viruses on surfaces and in aerosols,[5-11] but drawbacks include the potentially harmful impacts of UV rays on human skin and eyes. The use of light in the far-UVC range (200-235 nm) minimizes these negative impacts. Far-UVC is effective at inactivating or killing microorganisms, including bacteria, viruses, and fungi.[12-17] Research indicates that 222 nm light from KrCl excimer lamps (far-UVC) has minimal adverse effects on the skin and eyes, attributable to a limited ability for the radiation to penetrate deeply into biological materials.[12,18-20] Due to its ability to inactivate airborne pathogens and relative safety, far-UVC has been recommended for use indoors to inactivate pathogens, including SARS-CoV-2.[11]

Besides direct damage to skin and eyes, another potential drawback of GUV is negative impacts on indoor air quality due to photochemistry. Oxygen photodissociates in the presence of high energy light (wavelengths shorter than 242 nm):

$$O_2 + h\nu \rightarrow O + O \qquad \text{(R1)}$$

The atomic oxygen generated reacts with O_2 to yield ozone (O_3).

$$O + O_2 + M \rightarrow O_3 + M \qquad \text{(R2)}$$

Acute and long-term exposure to elevated levels of O_3, a respiratory irritant and strong oxidant, is harmful to human health.[21] O_3 also contributes to fine particulate matter levels by oxidizing volatile organic compounds (VOCs) to form semivolatile or water-soluble products, a process known as secondary organic aerosol (SOA) formation. Terpene compounds associated with scent products in indoor environments, such as limonene, are particularly reactive towards O_3 and have high SOA formation potential.[22]

While ozone formation chemistry has been studied extensively for broad spectrum solar light in the outdoor context,[23,24] the effects of far-UVC indoors are less well-known. Recent numerical modeling[25,26] and laboratory[26-30] studies show that 222 nm far-UVC can increase ozone levels[25-30] and SOA formation.[25,26,30] The laboratory studies were mostly performed in reactor systems with low or no ventilation. These systems differ in important ways from an indoor office environment, which is ventilated and has various reactive surfaces which act as sinks for ozone.[27,31] Peng and coworkers observed O_3 production and decay from the use of far-UVC (2.0 $\mu W\ cm^{-2}$) in a small, low-ventilation (0.62-0.96 h^{-1}) office setting. They found steady-state production of around 6.5 ppb O_3, with an inferred O_3 deposition rate of 0.5-2.3 h^{-1}.

Here, we report the impact of commercial far-UVC lamps with a range of intensities on ozone and submicron aerosol particle levels in an indoor office environment.

Methods

Room Setup. The study was conducted in a small conference room (4.62m × 2.74m, 3.30m ceiling height) in a 19-story academic building at Columbia University's Morningside Heights

campus in New York, NY, USA from March 2023 to January 2024. The building, constructed in 1961, has a centralized mechanical heating, ventilation, and air conditioning system. The room has no window, and the door was closed during experiments. The air exchange rate in the room was measured using the CO_2 tracer method[32] with portable CO_2 sensors (Aranet4) to be 1.3 h^{-1}. The conference room is carpeted and equipped with a conference table, a small wooden desk, and chairs. It also has room lighting and a wall-mounted computer monitor. Within the experimental duration none of the electronics were turned on.

Far-UVC Source. During the study, the room was equipped with either one or four commercial fixtures to generate far-UVC radiation. Tests with a single fixture used a Lumenlabs Lumenizer 300 (Lumenlabs, Shanghai, China) and tests with four fixtures used Lumenlabs Zone devices. Each of these fixtures contains three optically filtered KrCl bulbs with a peak emission wavelength of 222 nm. The optical output of a Lumenizer fixture is 55 mW and the optical output of a single Zone fixture is 190 mW. Lamps were placed on the floor and oriented towards the ceiling for all tests; this placement is unconventional and not recommended for an installation but allowed for temporary deployment for these tests. A model of the small conference room including the far-UVC fixtures was generated using Visual Lighting software with the GUV package (Acuity Brands, Atlanta, GA). The modeled average fluence rate with the single Lumenizer fixture in the room was 0.29 $\mu W\ cm^{-2}$ while the four Zone fixtures produced an average room fluence rate of 5.2 $\mu W\ cm^{-2}$. The model was also used to compute the average and maximum horizontal irradiance at 1.8 m down from the ceiling for each installation. Since the lamp arrangement is flipped in the room from a typical ceiling installation, measuring 1.8 down from the ceiling represents the measurement at 1.8 above floor height which is typically used to evaluate installations for safety exposure limits as recommended in the ANSI/IES RP-27.1–22 standard. The model for the single lamp installation yielded an average irradiance of 0.2 $\mu W\ cm^{-2}$ and a maximum irradiance of 0.9 $\mu W\ cm^{-2}$ at 1.8 m height. The model for the four lamp installation yielded an average irradiance of 4.1 $\mu W\ cm^{-2}$ and a maximum irradiance of 9.0 $\mu W\ cm^{-2}$ at 1.8 m height. For context, the 8-hour Threshold Limit Values recommended by ACGIH for the eye and skin for 222 nm exposure are 160 $mJ\ cm^{-2}$ and 480 $mJ\ cm^{-2}$, which equate to average irradiance values of 5.5 $\mu W\ cm^{-2}$ and 16.6 $\mu W\ cm^{-2}$, respectively.[33] The 8-hour Exposure Limit recommended by the ICNIRP for 222 nm exposure is 23 $mJ\ cm^{-2}$, which equates to an average irradiance of 0.8 $\mu W\ cm^{-2}$.[34] The 4-lamp experiments were meant to show the ozone and SOA production under higher intensity conditions that exceed the manufacturers recommended number of lamps given the volume of the room.

Ozone and particle measurements. Ozone monitors (2B Technologies, Model 202 Series #2544) were used for ozone measurement inside the conference room and outside in a lounge area where the far-UVC lamps were not present, to obtain a background signal. The concentration

was recorded for approximately 8 hours during the daytime at 10-second intervals, measured in units of ppb, and an hourly average reading was computed.

The particle size distribution in the 11.1nm-1.1µm size range was monitored during experiments using a scanning mobility particle sizer (SMPS) (Grimm Technologies). The SMPS scan frequency was 7 minutes. Some experiments were performed with only ozone or SMPS measurement.

Experimental design. The two ozone monitors and/or the SMPS were turned on at the start of the experiments. Background signal was obtained. After the background period, the far-UVC source (1 or 4 lamps) was turned on in the conference room and no change was made to the lounge. Ozone and SMPS data were collected with the far-UVC source and no other changes. Each experiment (1 or 4 lamps) was repeated three or more times.

Results

Experiments performed with a single far-UVC lamp did not show a significant impact on ozone or fine particulate levels above background levels in the conference room. When higher lamp intensity was used, minor increases in ozone (up to 10 ppb above background) and particulate matter were observed.

Ozone. The hourly averaged measured ozone level in the conference room and in the outside lounge for a typical single-lamp experiment is shown in Figure 1. Background ozone level in the office suite (conference room and lounge area) drifted between 2-20 ppb during the course of the experiments, which lasted up to 10 daytime hours, reaching a peak during midday. This trend suggests that the changes were driven by outdoor ozone concentrations.[33] After 2 hours, a single far-UVC lamp was turned on in the closed conference room. The ozone levels in the conference room continued to track the concentrations in the lounge area, and in fact were slightly lower, likely due to higher rates of ozone deposition in the small furnished room. The ozone measurements in the conference room and lounge area had a strong linear correlation throughout the 10-hour experiment (R^2 = 0.963).

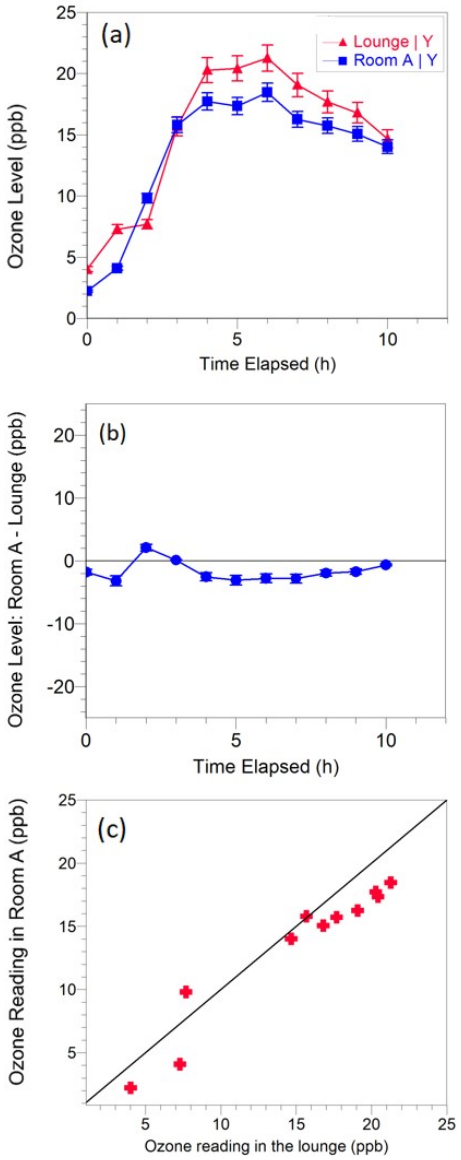

Figure 1 O_3 data for a typical single-lamp experiment. The far-UVC lamp was turned on after 2 hours (The shaded region represents lamp-off period). (a) Hourly averaged ozone readings in the conference room and outside in the lounge. (b) Difference plot indicating the difference in ozone level inside the conference room and in the lounge. (c) Correlation between ozone level in the conference room and the lounge.

The ozone level for a typical higher intensity experiment is shown in Figure 2. Background ozone levels again drifted throughout the 10-hour experiment, with a mid-day maximum (Figure 2(a)). However, when the four far-UVC lamps were turned on at the beginning of hour 3, the ozone level in room A increased to roughly 5-10 ppb above the background (Figure 2(b)). Average results for O_3 production in single-lamp and higher intensity experiments are shown in Table 1.

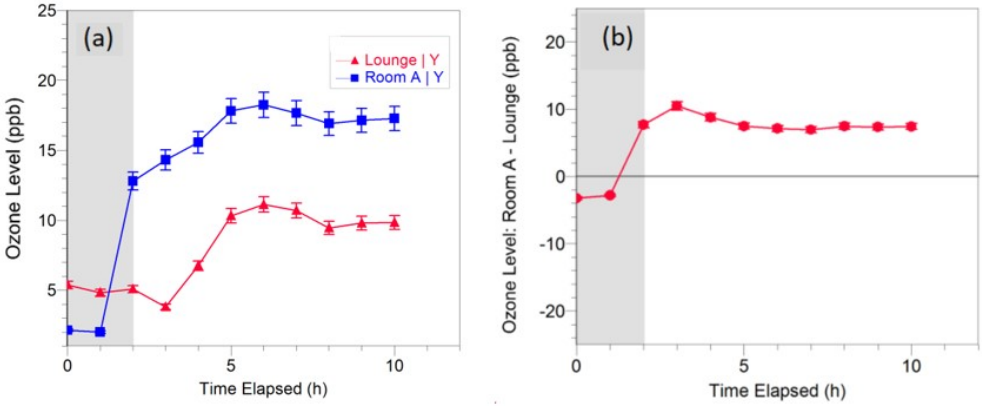

Figure 2. High intensity experiment. far-UVC lamps were turned on after 2 hours (shaded area represents the lamp-off time interval). (a) Ozone level reading in both room A and outside in the lounge (b) Difference plot indicating the difference in ozone level inside the conference room and in the lounge.

Table 1. Average O_3 production results, (Room A – Lounge) difference, for lamp on and lamp off conditions, for the single lamp and 4 lamp experiments.

Experiment	**Room A-Lounge O_3, Lamp off (ppb)**	**Room A-Lounge O_3, Lamp on (ppb)**
1 lamp	-3.36 ±0.38	-0.62 ±0.03
4 lamp	-2.56 ±0.33	6.98 ±0.24

Particle Concentration and Size Distribution. The evolution of particle number and mass concentrations in room A for a single far-UVC lamp is illustrated in Figure 3a and 3b. Background data were collected for the initial 35 minutes of the experiment. Subsequently, far-UVC was activated and remained on for 35 minutes, during which particle concentrations continued to be monitored. The comparison of particle counts within the entire 70-minute experimental period reveals consistent particle concentrations, with no discernible variation observed when the far-UVC lamp was activated (Figure 3a). Similarly, particle mass did not change monotonically

over the course of the experiment (Figure 3b). Particulate matter in Room A typically exhibited a lognormal size distribution with a peak particle size of around 60 nm. The particle size distribution did not change significantly when the far-UVC lamp was turned on (Figure 3c).

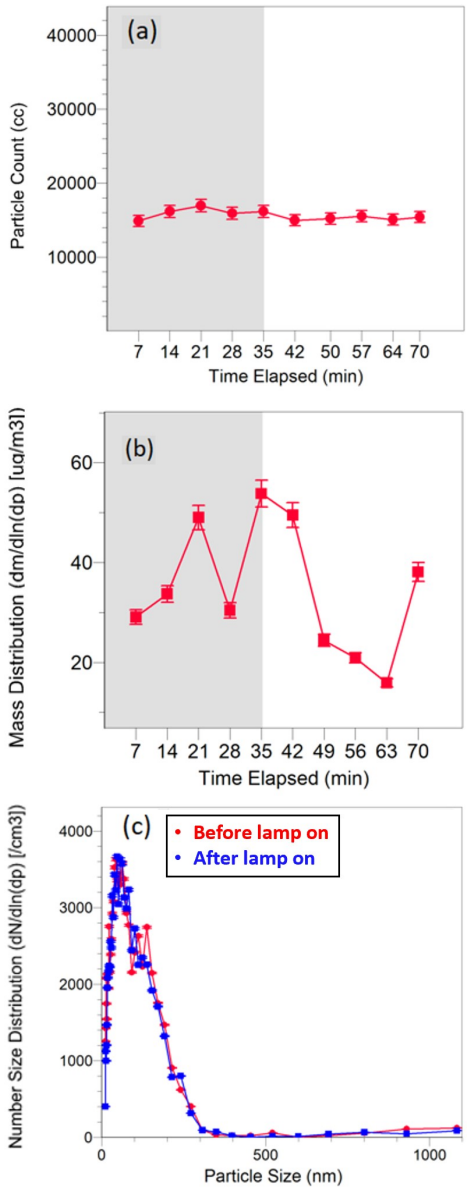

Figure 3 Evolution of (a) particle count and (b) particle mass during a typical single-lamp experiment. Lamp was turned on after 35 minutes. Particle size distribution is shown in 3(c).

Averaging data from four single-lamp experiments, we find that the particle number count changes by 142 ± 546 particles cm^{-3} and particle mass changes by -1 ± 9 μg m^{-3}. Error bars were calculated by propagation of error from the raw experimental data followed by weighted linear least squares averaging. Statistics from only one dataset are available for the high intensity experiment; the observed change was 354 ± 218 particles cm^{-3} and 2.3 ± 43.5 μg m^{-3}.

The data shows an average change of 0.3% ± 3.6% in number count for the single lamp experiments and 16% ± 10 % for the higher intensity experiments. We note significant variability in the background particle mass, particularly for experiments conducted in Summer 2023.

Discussion

The far-UVC average fluence used for the lower-intensity (single lamp) experiments in this study was 0.29 μW cm^{-2}. According to the manufacturer, one lamp is recommended for disinfection of a room the size of Room A. The modelled average fluence and irradiance values are consistent with conditions observed by Eadie et al. in a chamber study to reduce airborne pathogens (*S. aureus*) by 92% or more.[16] Under these conditions, we did not measure significant changes in ozone level or particulate matter in Room A, despite the relatively low ventilation conditions in the room.

The high intensity experiments employed more far-UVC irradiance than required for disinfection of a room the size of Room A. The increase in ozone of up to 10 ppb above background during these experiments is consistent with the observations of Kalliomäki and coworkers, who used 1.7-1.8 μW cm^{-2} far-UVC in a poorly ventilated hotel quarantine facility room,[34] and Peng and coworkers[27] who used a similar level of far-UVC (2.0 μW cm^{-2}) in a small office with low ventilation. Steady state production of 8.6 ppb of O_3 above baseline was also predicted by simulations of Barber et al. for 5 μW cm^{-2} in a room with 1 h^{-1} ACH, assuming an O_3 deposition rate of 3 h^{-1}.[26] Also consistent with our observations, Kalliomäki did not observe a clear correlation between far-UVC use and submicron particle concentrations with SMPS measurements.[34]

Conclusion

We have observed the effects of far-UVC on indoor ozone and particulate matter under conditions of real-world application in an office setting with low ventilation. We find that a far-UVC system installed in concordance with the manufacturer's recommendation does not negatively impact indoor air quality through generation of O_3 or PM under the conditions of our experiment. Far-UVC may be a valuable component of a multilayer approach to reduce the risk of transmission of respiratory viruses, used in combination with ventilation and other interventions including air filtration, masks and vaccination. The smallest possible irradiance should be used for the application in order to minimize ozone generation and any possible effects on skin or eyes. Better ventilation (>3.0 h^{-1}) than we observed in Room A would reduce steady state ozone buildup and is recommended for improved indoor air quality in general.[4]

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