Systematical Investigations on Disinfection Effectiveness of Far-UVC (222 nm) irradiation: From Laboratory Study to Field Tests

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Abstract
The spread of pathogenic microorganisms in public spaces poses a great threat to human health. Far-UVC irradiation is regarded as an efficient method for inactivating most pathogenic microorganisms. Nevertheless, most of the studies on it have been done in laboratory, and there is still little knowledge about the disinfection effectiveness of far-UVC irradiation in real life. Here, systematic investigations were conducted to shed light on the disinfection effectiveness of far-UVC irradiation with laboratory studies and field tests in a real operating public lift cabin. The results of the laboratory study demonstrated that far-UVC irradiation can markedly promote the inactivation of the selected 7 types of microorganisms (including bacteria, viruses and fungus species) on steel surface compared to that on the glass surface, due to the synergistic effect of direct and reflected far-UVC light. This improvement was identified in the field test by employing the far-UVC device for disinfecting the surfaces of the lift cabin which are mostly made of stainless steel. Furthermore, the long-term field test of about 4 months also suggested that both environmental temperature and relative humidity (RH) affect the far-UVC disinfection effectiveness, where the best inactivation efficiency (99.9%) on the surface of lift button and handrail was achieved in the environmental temperature range of 23.5-25.5°C and the RH range of 60-70% at a low UVC dose of 5.2 mJ/cm². In addition, >99.9% of airborne bacteria were inactivated in a chamber at a far-UVC dose of 15 mJ/cm², showing a better performance of far-UVC for air disinfection compared to other technologies. This study systematically investigates the performance of far-UVC irradiation for surface and air disinfection in an actual environment, which provides helpful guidance for controlling the spread of pathogenic microorganisms in public spaces, especially in the ongoing COVID-19 pandemic.

Keywords: far-UVC, surface contamination, airborne bacteria, disinfection, public space

1. Introduction

Pathogenic microorganisms pose an extraordinary challenge to public health worldwide [1,2]. Particularly, in recent years, the outbreak of coronavirus disease in 2019 (COVID-19) caused more than 250 million infections and 5 million deaths worldwide [3]. This has profoundly affected our daily life and economy. Public places are regarded as an important medium for the spread of pathogenic microorganisms, where microorganisms as individual cells or bioaerosol particles are conveniently transmitted through the ambient air or are attached to the human body via direct contact with contaminated surfaces [4,5,6]. Lift cabin, as a common space for transporting passengers in buildings, is perhaps one of the public places most susceptible to microbial contamination, especially its buttons and handrails. This is because people (with various hygiene practices) having frequent contact with the lift buttons or handrails can contribute to the colonization of microorganisms, leading to a high level of microbial contamination [7]. Recent studies indeed confirmed that lift button was one of the surface sites with the highest positive rate (43%) for microbial contamination [6]. Currently, there are totally more than 17 million lifts around the world with a rapidly increasing trend. However, the disinfection of lift environment was not given due attention until the outbreak of COVID-19 [5,8].

Various guidelines have been issued for the disinfection of the surfaces of lifts cabin during the operation period [9,10]. Most of the disinfection methods are currently limited to wiping the lift buttons and handrails with a solution containing 70% isopropyl alcohol, soapy water or other chemical disinfectants like photocatalyst coating. Although these methods can reduce microbial surface contamination, their applications may be limited. For example, cleaning wipes may lead to nasty cross-contamination while cleansing workers normally move from one lift or escalator to another with mops and brooms without re-cleansing the wipes [11]. Photocatalyst coating needs to be re-coated frequently and it needs a suitable light source with sufficient intensity to trigger the photocatalytic reaction [12].

Filtered far-UVC as a type of UV light with monochromatic source at 222 nm was proposed as an efficient disinfection technology for killing most of the microorganisms in the air or on any type of surfaces, such as glass, stainless steel or plastics [13,14,15]. Compared to other disinfection methods, far-UVC disinfection has several advantages, such as rapid effectiveness, absence of chemical residual, and easy operation [16]. Moreover, far-UVC is safer for human exposure than other common UVC light sources such as UV-254 nm. Note that conventional UV-254 nm light sources are harmful to human skins and eyes under direct exposure, which can even have carcinogenic or cataractogenic effect [17]. In contrast, far-UVC cannot penetrate the human skin epidermis or the outer layer of the eyes, showing a low-level risk to humans exposed to it [18,19,20]. A recent published guideline by the American Conference of Governmental Industrial Hygienists (ACGIH, 2020) further suggested that exposure to far-UVC irradiation below the UV doses of 161 mJ/cm² and 479 mJ/cm² is safe for the eyes and skin, respectively [21]. These limits are significantly higher than that of UV-254 nm with 7 mJ/cm². This shows that it would be much safer for human beings exposed to far-UVC. One of the important reasons is that far-UVC at 222 nm has a high protein absorption coefficient. This makes it to be strongly absorbed by the proteins in the outer layer (stratum corneum) and is drastically attenuated before reaching the living cells [20,22]. Nevertheless, because most of the environmental bacteria and viruses are very small particles in nano scale, far-UVC light can still efficiently reach their inside structure and inactivate them by directly damaging their DNA or RNA [23]. In this regard, far-UVC irradiation was supposed to be a suitable disinfection technology for public places to limit the spread of pathogenic microorganisms [23,24]. However, comprehensive investigation of the disinfection effectiveness of far-UVC in public places is still rare in the literature.

Therefore, the aim of this study was to shed light on the disinfection effectiveness of far-UVC irradiation from laboratory study to field test. Several experiments were conducted: (1) to investigate the disinfection effectiveness of far-UVC irradiation on different surfaces, two materials with distinctly different properties towards far-UVC light were used in the laboratory study. One of the materials is a transparent glass with high UVC absorption or diffusion, while the other is a stainless steel with high reflection of far-UVC light; (2) to comprehensively understand the disinfection effectiveness of far-UVC, different pathogenic microorganisms were selected, including bacteria, viruses and fungus; (3) to investigate the disinfection effectiveness of far-UVC device under real public space, an operating lift cabin was used for the field test. The bacteria levels on the lift buttons and handrail surfaces of the lift cabin were monitored with and without exposure to far-UVC. Furthermore, the disinfection effectiveness of airborne bacteria in the air was studied in an enclosed chamber similar to the lift environment. Finally, the comprehensive understanding of far-UVC disinfection and the necessary safety consideration are proposed for the deployment of far-UVC devices in public spaces.

2. Materials and Methods

2.1. Materials

Far-UVC (222 nm) lamp: a krypton-chloride (Kr-Cl) gas mixture excimer lamp with filtering that allows emission of 222 nm UV light is used in this study (USHIO model, Care 222, U3, 12W, Ushio Inc., Tokyo, Japan).

Microorganisms. Different types of microorganisms are used for the investigation of surface disinfection performance of far-UVC (222 nm) irradiation in this study: bacteria (Escherichia coli ATCC25922 (E. coli), extended Spectrum Beta-Lactamase-producing E. coli (ESBL), Streptococcus faecalis (S. faecalis), and Methicillin-resistant Staphylococcus aureus (MRSA)), seasonal influenza A viruses (H1N1 and H3N2), and fungus (Candida albicans (C. albicans)). Both E. coli and ESBL are gram-negative bacteria, and are more commonly found in the environment [25]. Especially, ESBL have been
recognized as a major multidrug-resistant bacteria implicated in serious hospital and community [26]. Both \(S.\) \textit{faecalis} and MRSA are gram-positive bacteria. \(S.\) \textit{faecalis} is commonly found in soil, water, and environments in association with humans [27]. MRSA is often found in the community, and generally causes several skin infections which are difficult to treat due to its resistance to several antibiotics [28]. H1N1 and H3N2 are two typical types of seasonal influenza A viruses, which are easily transmissible among humans and cause yearly epidemics [29]. \(C.\) \textit{albicans} is a most common fungus, and is frequently used as a model organism for fungal pathogens [30]. As all of the above bacteria, viruses and fungus with different genome organizations are usually found in our daily life, they were selected as typical representatives for the inactivation of microorganisms.

2.2. Methods

**Laboratory test.** To evaluate the disinfection effectiveness of the far-UVC light irradiation, microorganisms deposited on the glass surface and the stainless-steel surfaces were irradiated with the far-UVC light. The total viable bacteria number density was \(3 \times 10^6 - 6 \times 10^7\) CFU/cm\(^2\). The distance between the light source and the microorganisms was fixed at a distance of 300 mm and a fluence rate of 80 \(\mu\)W/cm\(^2\). To reduce the leakage of far-UVC light to the surrounding, the lamp and the samples under testing were contained in a chamber (As shown in Figure 1 a) during the experiments. Triplicate samples were placed in petri dishes covered with lids, in order to prevent microbial contamination before irradiation. Then, these samples were exposed to far-UVC light at seven fixed intervals (i.e., 0, 0.5, 1, 3, 5, 7 and 10 min), which corresponded to UVC doses of 0, 2.4, 4.8, 14.4, 24, 33.6 and 48 mJ/cm\(^2\). Finally, all the samples after being exposed to far-UVC were collected sacrificially; so no subsample was collected in one far-UVC exposure test.

**Field tests.** A passenger lift was used for the field test as shown in Figure 1b. The far-UVC disinfection system was installed close to the lift ceiling, with a mounting frame that can change angle of inclination to ensure that both the lift buttons and handrails (selected as two targeted surfaces) were under far-UVC light irradiation. Emittance flux (fluence rate, \(\mu\)W/cm\(^2\)) and wavelength (nm) of the device were calibrated by a handheld dosimeter. The emittance flux is determined to be 4.0 \(\mu\)W/cm\(^2\) at a distance of 1000 mm between the far-UVC device and the targeted surfaces. Firstly, simulated surface-contamination on the lift button was conducted to evaluate the disinfection performance of far-UVC. To prevent any other microbial contamination, the lift button was disinfected by wiping with 70% isopropyl alcohol before the test. Then, certain concentrations (about \(1 \times 10^5\) CFU/cm\(^2\)) of \(E.\) \textit{coli} and \(S.\) \textit{faecalis} were inoculated onto the selected surface to create the surface-contamination conditions, respectively. The exposure time was determined according to the laboratory test results. It was set to be 15 min for each experiment, which corresponded to a UVC dose of 5.2 mJ/cm\(^2\). Surface samples were obtained through swabbing method, in which swabs were rubbed slowly and thoroughly over the target surface after being exposed to far-UVC. In addition, sampling templates were used to ensure locations and sampling areas are consistent (as shown in Figure S1). The samples collected were then sealed inside the sampling tube and preserved in a cold box before they were examined in the laboratory within 24 hours. Note that counter samples were collected on the other sides of the lift buttons and handrails without far-UVC light irradiation (verified by the dosimeter).

Furthermore, a long-term field test of about 4 months (detail schedule is shown in Table S1) was conducted under real environment in the lift cabin. In this experiment, both lift buttons and handrails were selected as the target surfaces exposed to far-UVC. Swap samples were collected from both targeted surfaces after their exposure to far-UVC for 15 min. The method of collection was consistent with the simulated surface-contamination test. Temperature and humidity during the sampling tests were recorded, respectively. For safe operation, all experiments were carried out when the lift was unoccupied during the sampling period. In addition, the presence of far-UVC light in the lift cabin is indicated by a UVC test card, as shown in Figure S2.

![Figure 1.](image_url)
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**Air sample tests.** A chamber with a total volume of 10 m³ (L: 2600 mm, W: 1550 mm, H: 2480 mm) is used for the air sampling test (As shown in Figure 1c). In this experiment, far-UVC device is installed at the top of the chamber. A bacterial strain (*S. epidermidis*) is injected into the test chamber using a nebulizer. To accurately assess the effectiveness of the disinfection system in reducing airborne bacteria count, there was no air ventilation inside the chamber; rather two mixing fans were used to thoroughly mix the air and dosed bacteria inside the chamber. Air samples were taken at the center of the chamber, 1.2 m above the floor via a specified sampler. Initially, blank tests were conducted to determine the initial concentration of airborne bacteria (in CFU/m³). Subsequent samples were taken with the lamp switched on at a fixed interred time of 45 min.

3. Results and Discussions

3.1. Disinfection Performance of Far-UVC

To evaluate the effectiveness of far-UVC irradiation for surface disinfection, different microorganisms were inoculated on the glass surface or the steel surface, respectively. They were further irradiated with far-UVC light at various exposure times. The inactivation efficiencies of the different microorganisms on the glass surface and steel surface are listed in Table 1a and b, respectively, while their parallel experimental results are shown in Figure S3 – Figure S9. As can be seen, all bacteria, including *E. coli*, ESBL, *S. faecalis* and MRSA are inactivated by more than 90% (1 log reduction) at 30 s of irradiation (representing an UVC of 2.4 mJ/cm²) on both glass surface and steel surface. The viruses were also highly inactivated; more than 90% of H1N1 and H3N2 could be killed with an UVC dose of 4.8 mJ/cm² within 1 min on both types of surfaces. The above results suggest that the exposure of bacteria and viruses to far-UVC is more effective for them to be reduced to 1 log, as supported by previous studies [14,24]. However, *C. albicans* was less effectively inactivated by far-UVC, that it could not be reduced to 1 log, even when the exposure time was extended to 3 min with UV dose of 14.4 mJ/cm². This could be because *C. albicans* as a fungal species has higher ability to resist UV than bacteria and viruses [31,32].

**Table 1a. The inactivation efficiency of different microorganisms on the glass surface**

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>UV dose (mJ/cm²)</th>
<th>E. Coli (%)</th>
<th>ESBL (%)</th>
<th>S. Faecalis (%)</th>
<th>MRSA (%)</th>
<th>C. albicans (%)</th>
<th>H1N1 (%)</th>
<th>H3N2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2.4</td>
<td>96.71</td>
<td>96.60</td>
<td>95.50</td>
<td>93.84</td>
<td>62.79</td>
<td>94.63</td>
<td>68.38</td>
</tr>
<tr>
<td>1</td>
<td>4.8</td>
<td>99.05</td>
<td>98.05</td>
<td>97.43</td>
<td>95.15</td>
<td>69.86</td>
<td>94.95</td>
<td>82.22</td>
</tr>
<tr>
<td>3</td>
<td>14.4</td>
<td>99.91</td>
<td>99.78</td>
<td>98.49</td>
<td>97.64</td>
<td>80.74</td>
<td>98.43</td>
<td>94.38</td>
</tr>
<tr>
<td>5</td>
<td>24.0</td>
<td>99.99</td>
<td>99.98</td>
<td>99.54</td>
<td>99.61</td>
<td>93.29</td>
<td>98.43</td>
<td>98.59</td>
</tr>
<tr>
<td>7</td>
<td>33.6</td>
<td>&gt;99.99</td>
<td>99.99</td>
<td>99.91</td>
<td>99.87</td>
<td>95.29</td>
<td>99.22</td>
<td>99.11</td>
</tr>
</tbody>
</table>

**Table 1b. The inactivation efficiency of different microorganisms on the steel surface**

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>UV dose (mJ/cm²)</th>
<th>E. Coli (%)</th>
<th>ESBL (%)</th>
<th>S. Faecalis (%)</th>
<th>MRSA (%)</th>
<th>C. albicans (%)</th>
<th>H1N1 (%)</th>
<th>H3N2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>2.4</td>
<td>99.06</td>
<td>98.24</td>
<td>95.95</td>
<td>95.41</td>
<td>67.79</td>
<td>91.88</td>
<td>90.00</td>
</tr>
<tr>
<td>1</td>
<td>4.8</td>
<td>99.93</td>
<td>99.95</td>
<td>98.66</td>
<td>97.43</td>
<td>73.74</td>
<td>98.75</td>
<td>96.37</td>
</tr>
</tbody>
</table>

Figure 2. The required UVC dose for 2 log reductions of different microorganisms on the steel surface and glass surface by far-UVC exposure.
Figure 2 further compares the required UVC doses for 2 log reductions of different microorganisms on both glass and the steel surfaces. The required UVC doses for the inactivation of each bacterial species on the glass surface are 4.8 mJ/cm² (E. coli), 14.4 mJ/cm² (ESBL), 24.0 mJ/cm² (S. faecalis), and 24.0 mJ/cm² (MRSA), respectively, while they are 2.4 mJ/cm² (E. coli), 4.8 mJ/cm² (ESBL), 14.4 mJ/cm² (S. faecalis), and 14.4 mJ/cm² (MRSA) on the steel surface. It can be observed that far-UVC was more efficient for the inactivation of bacteria on the steel surface than on the glass surface. For the inactivation of viruses, the 2 log reductions of H1N1 and H3N2 on the glass surface were achieved with an UVC dose of 33.6 mJ/cm²; they were significantly higher than that on the steel surface with UVC doses of 14.4 mJ/cm² and 24 mJ/cm², respectively. A similar trend was found in the inactivation of C. albicans: there were 2 log reductions of C. albicans on the glass surface with UVC dose of 72.0 mJ/cm², higher than that on the steel surface with UVC dose of 33.6 mJ/cm². Therefore, all the selected microorganisms on the steel surface were greatly inactivated by their exposure to far-UVC compared to those on the glass surface.

To confirm the enhanced efficiency of far-UVC in inactivating the microorganisms on the surface steel, the inactivation kinetics was calculated based on the Chick–Watson model.

\[
\log_{10} I = \log_{10} \left( \frac{C}{C_0} \right) = -kD
\]

where \( \log_{10} I \) is the inactivation reduction in \( \log_{10} \)-scale, \( C_0 \) is the initial concentration of microorganisms (CFUs), \( C \) is the concentration of microorganisms after exposure to far-UVC (CFUs), \( k \) is the pseudo-first-order inactivation rate constant (cm²/mJ), and \( D \) is the UV fluence of far-UVC (mJ/cm²).

Figure 3 a and Figure 3b show the inactivation kinetics of the different microorganisms on the glass surface and steel surface, respectively. The pseudo-first-order inactivation rate constants based on the response of UVC dose to \( \log_{10} \)-scale inactivation, as well as their corresponding \( R^2 \) values are listed in Table 2. It can be observed that the rate constants for all the bacteria are higher than those of the viruses and fungal species both on the glass surface and steel surface. These results further confirmed that far-UVC has excellent performance for bacteria inactivation, as reported in previous studies [20]. Meanwhile, the rate constants for E. coli, ESBL, MRSA and S. faecalis on the glass surface are 0.140 cm²/mJ, 0.122 cm²/mJ, 0.094 cm²/mJ, and 0.090 cm²/mJ, respectively; they increased to 0.240 cm²/mJ, 0.227 cm²/mJ, 0.126 cm²/mJ and 0.133 cm²/mJ on the steel surface. Notably, the rate constants of E. coli and ESBL were significantly higher than that of MRSA and S. faecalis on glass surface or steel surface. This shows that both E. coli and ESBL are more easily inactivated by far-UVC irradiation. This phenomenon might be due to the fact that E. coli and ESBL being gram-negative bacteria are very sensitive to UVC than MRSA and S. faecalis which are gram-positive bacteria [33,34]. Furthermore, the inactivation rate constants of H3N2, H1N1 and C. albicans on the steel surface showed an increased trend compared to that on the glass surface. All these results strongly confirmed that far-UVC irradiation is more efficient for the inactivation of the microorganisms on the steel surface than those on the glass surface. One of the reasonable explanations is that the steel surface has high UVC reflection, and the reflected UVC light can further inactivate microorganisms. This leads to an enhanced effectiveness of the inactivation of microorganisms on the steel surface.

Table 2. Pseudo-first-order inactivation rate constants based on the response of UV dose to \( \log_{10} \)-scale inactivation for different microorganisms and their corresponding \( R^2 \) values

<table>
<thead>
<tr>
<th>Microorganisms</th>
<th>Glass surface ( k ) (cm²/mJ)</th>
<th>Steel surface ( k ) (cm²/mJ)</th>
<th>( R^2 ) Glass</th>
<th>( R^2 ) Steel</th>
</tr>
</thead>
<tbody>
<tr>
<td>E. Coli</td>
<td>0.140</td>
<td>0.240</td>
<td>0.97</td>
<td>0.87</td>
</tr>
<tr>
<td>ESBL</td>
<td>0.122</td>
<td>0.227</td>
<td>0.98</td>
<td>0.88</td>
</tr>
<tr>
<td>MRSA</td>
<td>0.094</td>
<td>0.126</td>
<td>0.98</td>
<td>0.93</td>
</tr>
<tr>
<td>S. faecalis</td>
<td>0.090</td>
<td>0.133</td>
<td>0.99</td>
<td>0.92</td>
</tr>
<tr>
<td>C. albicans</td>
<td>0.062</td>
<td>0.062</td>
<td>0.99</td>
<td>0.90</td>
</tr>
<tr>
<td>H1N1</td>
<td>0.060</td>
<td>0.097</td>
<td>0.97</td>
<td>0.88</td>
</tr>
<tr>
<td>H3N2</td>
<td>0.061</td>
<td>0.104</td>
<td>0.91</td>
<td>0.96</td>
</tr>
</tbody>
</table>
To confirm whether the enhanced effectiveness was attributed to the reflected far-UVC light, an experiment was conducted to detect the intensity of reflected far-UVC light on the steel surface and glass surface, respectively. As shown in Figure 4a, the reflected far-UVC light from the glass surface or the steel surface at different angles (e.g., 30°, 45°, 60°) with different distances (e.g., 10 cm, 20 cm, 30 cm) were detected by the dosimeter, respectively. For each angle, the intensity of the reflected far-UVC light in the different distances has a good linear relationship with $R^2 > 99\%$ (Figure 4b), and the linear regressing equations are shown in Table S2. The intensities of the reflected far-UVC on the glass surface or steel surface can be calculated by their corresponding linear regressing equations, respectively (Figure 4c). The intensities of the reflected far-UVC light on the steel surfaces were 47.3 μW/cm², 41.5 μW/cm² and 35.2 μW/cm² for 30°, 45° and 60° angles, respectively. Note that the intensity of the direct far-UVC light on the steel surfaces was 80.0 μW/cm². This result indicates that an enhanced intensity of far-UVC radiation was produced on the steel surface due to the combination of direct and reflected far-UVC light. However, this phenomenon was not observed on the glass surface, where the intensity of the reflected far-UVC light was insignificant in all selected angles.

Based on the above analysis, it is proposed that there is an enhanced inactivation of the microorganisms on the steel surface (shown in Figure 4d). As a transparent solid, the glass surface can efficiently absorb or diffuse most of the direct far-UVC light, yielding an insignificant intensity of reflected far-UVC light. Therefore, in this case, the inactivation of microorganisms on the glass surface was mainly attributed to the direct far-UVC irradiation. In contrast, the steel surface showed a high performance for reflecting far-UVC light. This behavior can produce enhanced far-UVC irradiation on the steel surface due to the synergistic effect of direct far-UVC light and reflected far-UVC light. As a result, the far-UVC irradiation was markedly effective in inactivating the microorganisms on the steel surface.

### 3.2. Disinfection Performance in Lift Environment

Based on the above investigations, it is reasonable to employ far-UVC irradiation for disinfecting the surface of lift cabins, since most of the lift cabins are made of stainless steel. Firstly, simulated contamination tests were conducted in a passenger lift to evaluate the disinfection effectiveness of far-UVC irradiation in actual environment. To simulate the surface contamination, a lift button was selected as the target surface. Then, *E. coli* and *S. faecalis* cultures of known concentrations were inoculated onto this surface, respectively. As shown in Figure S10, both *E. coli* (99.6%) and *S. faecalis* (99.4%) on the lift button could be efficiently inactivated by far-UVC irradiation with a UVC dose of 5.2 mJ/cm². This result suggests that far-UVC irradiation has high efficiency in inactivating the contaminated surface in the actual environment compared to that of the laboratory tests. However, the required UVC dose for 2 log reductions was slightly higher than that conducted in the laboratory test (*E. coli*: 2.4 mJ/cm²; *S. faecalis*: 4.8 mJ/cm²). This may be due to the fact that the inactivation performance was influenced by the ambient environment. For instance, environmental temperature and relative humidity (RH) were reported to be important factors that influence the inactivation of microorganisms by far-UVC [35,36,37].
Therefore, a long-term field test (about 4 months) was conducted to investigate the influence of environmental temperature and RH on the disinfection effectiveness of far-UVC in this passenger lift. The bacterial concentration on the lift button and handrail, as well as environmental temperature and RH were monitored throughout the sampling period. Figure 5 shows the variation of bacterial concentration on the lift button and handrail before they were exposed to far-UVC irradiation. It can be observed that the bacterial concentration on the lift button is generally higher than that on the handrail during the sampling time. This could be because humans have more frequent contact with the lift button than the handrail daily, leading to the high-level contamination of the surface of the lift button. It was also found that the variation of bacterial concentration significantly followed the variation of environmental temperature in the sampling period. In the first period (25-Mar.-2021 to 29-Apr.-2021), the bacterial colony was at a low level with an average environmental temperature of 24.5°C. However, the bacterial colony shows an increasing trend in the second period (29-Apr.-2021 to 1-Jul.-2021), with an average environmental temperature increasing to 25.8°C and 27.6°C, respectively. Interestingly, the inactivation efficiency also followed the variation of environmental temperature during each sampling period (Figure S11). For instance, the average inactivation efficiencies during the 1st period are 97% and 99.9% for the button and handrail, respectively; while they become 56% and 54%, respectively during the next two sampling periods. Based on the above analysis, the variation of inactivation efficiency was suspected to be related to the ambient temperature.

### 3.3. Effect of Environmental Temperature

Further analysis was therefore carried out to investigate the contribution of environmental temperature to inactivation efficiency. Figures 6 a and b show the variation of inactivation efficiency of far-UVC irradiation for lift button and handrail within the environmental temperature range of 23.5-28.5°C, respectively. The best inactivation efficiency (99.9%) for lift button and handrail was observed at the environmental temperature of 23.8°C and 24.3°C, respectively. Furthermore, it is interesting to find that most of the inactivation efficiencies (>98.5%) for both lift button and handrail were observed in the range of 23.5-25.5°C. However, the disinfection performance for both lift button and handrail displayed a significant decrease within the temperature range of 25.5-28.5°C, where most of the inactivation efficiencies were in the range of 50-70%. This result implies that the increase of environmental temperature has an inhibition effect on the inactivation of bacteria. This can be further confirmed by the linear regression fits (denoted as red line) of the inactivation efficiency against environmental temperature (Figures 6 c and d), which shows that the inactivation efficiency for both the lift button and the handrail are significantly influenced by environmental temperature (Lift button: R² = 0.413, P < 0.001; Handrail: R² = 0.342, P < 0.001). Previous research also indicated a decreased inactivation performance of UV exposure with increased temperature, but the reason is poorly understood.

Generally, low environmental temperature would decrease the cell membrane fluidity and slow down the microbial enzymatic activity; while high environmental temperature over a critical point would lead to the denaturation and inactivation of proteins [21,38]. Figures 6 c and d further illustrate the relationship between bacterial colonies and environmental temperature before irradiation for lift button and handrail, respectively. The linear regression fits (denoted as blue line) of bacterial colonies with temperature show there is a strong correlation between the bacterial colony with temperature for both the lift button and handrail (lift button: R² = 0.243, P < 0.002; handrail: R² = 0.314, P < 0.001). This result suggests that the increase in environmental temperature from 23.5-28.5°C could enhance the activities of the bacteria. Zhong et al. also found that increase in the temperature from -3.5°C to 28.4°C could enhance the enzymatic activity of the microorganisms, which resulted in the increase of the microorganisms’ concentration [39]. Based on the above analysis, it is reasonable to consider that the increase of environmental temperature can promote the viability of bacteria, leading to decreased inactivation efficiency of far-UVC exposure.
Figure 6. The variation of inactivation efficiency of far-UVC irradiation in the environmental temperature range of 23.5°C to 28.5°C for (a) lift button and (b) handrail, respectively; Relation between inactivation efficiency (red line) and bacteria colonies (blue line) and temperature for (c) lift button and (d) handrail

Figure 7. The variation of inactivation efficiency in RH range of 60% to 85% for (a) lift button and (b) handrail; Relation between inactivation efficiency (red line) and bacteria colonies (blue line) and RH for (c) lift button and (d) handrail
3.4. Effect of Relative Humidity

Apart from the temperature, the variation of RH in the range of 60-85% also has a significant influence on the disinfection efficiency during the sampling period. As shown in Figures 7 a and b, the inactivation of bacteria for both the lift button and handrail was high (>99%) in the RH range of 60-70%. However, it decreased significantly by more than 30% when the RH increased above 70%. Furthermore, the linear regression fits show there is a good correlation between the inactivation effectiveness and RH for both the lift button and handrail (lift button: R² = 0.271, P < 0.005; handrail: R² = 0.314, P < 0.001). The above results suggest that high RH (>70%) has a negative impact on the inactivation effectiveness.

Previous studies reported that high RH levels had a complicated effect on disinfection by UV irradiation [40]. On one hand, high RH levels can lead to an unstable performance of UV-inactivation. This is because water sorption onto cell membrane or UV light scattering of hygroscopic particles helps to prevent UV-induced DNA damage as RH increases [35]. On the other hand, high RH levels can enhance bacterial activity and thus lead to a decrease of UV-inactivation performance [41]. However, in this study, no significant positive correlation between RH and bacterial activity was observed in both the lift button and the handrail as indicated by the linear regression fits (Figure 7 c and d). Therefore, the decrease of the inactivation effectiveness in high RH was mainly attributed to the water sorption onto cell membrane or UVC light scattering of hygroscopic particles.

3.5. Air Sample Tests

To comprehensively evaluate the far-UVC performance in the lift environment, the inactivation of airborne bacteria (e.g., S. epidermidis) in the air was conducted in a chamber installed with a far-UVC lamp on the ceiling. It is well known that S. epidermidis as the human epithelial microflora is usually found in indoor air but is hardly inactivated due to its strong resistance [42,43]. Previous studies suggested that S. epidermidis in the air can be killed by thermal method, ozone oxidation, or plasma disinfection [38,44]. Although the above methods can efficiently inactivate S. epidermidis, they are unsuitably operated on occupied public spaces because they are very risky to human beings. However, for far-UVC exposure in the lift environment demonstrated that far-UVC is very efficient in inactivating the pathogenic microorganisms deposited on the lift button and handrail with an UVC dose as low as 5.2 mJ/cm² in the actual environment. However, the inactivation efficiency was influenced by the ambient environment. As confirmed through a long-term field test, both environmental temperature and RH affected the inactivation efficiency with different mechanisms. The best inactivation efficiency (>99%) on the surface of lift button and handrail was achieved in an environmental temperature range of 23.5-25.5°C and RH range of 60-70% with a low UVC dose of 5.2 mJ/cm².

Furthermore, the inactivation of airborne bacteria by far-UVC irradiation also displayed excellent inactivation performance as compared to other disinfection technologies.

Although far-UVC irradiation is very efficient in the inactivation of microorganisms, its application in public spaces should be taken into more consideration. It has been known that direct exposure to UVC light (especially to 254 nm) can cause a potential health hazard, both to skin and eyes. Currently, a guideline on the UV dosage limit is widely accepted that far-UVC exposure towards human beings (skin or eyes) should not exceed 25 mJ/cm² within a period of 8 hours (ACGIH 201838). According to this limit, this study further discussed the potential application of far-UVC for air and surface disinfection in specific public spaces, such as passenger lift cabin, and advised were provided for consideration (Text S1 and Figure S13). Nevertheless, there is no official standard regarding the safety operation of far-UVC in public space so far. Therefore, whether far-UVC disinfection can be widely used in common public spaces still requires more experiments and safety assessments. Lastly, it is essential that all applied Far-UVC product be properly designed and operated in compliance with the applicable safety requirements of relevant local regulations and international standards or specified by relevant local authorities under specific circumstances for particular types of products.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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References


**Supplementary Information**

**Text S1.** Potential application of far UVC in lift cabin.

Here, we further discussed the potential application of far-UVC irradiation in a public passenger lift. In the present Far-UVC system, there are two operation modes for far-UVC irradiation.

One is the continuous irradiation mode. Under this operation mode and assuming an irradiation intensity of 5 µW/cm² which is the same as our experimental setting, the maximum time for people in the lift would be 83 min according to the guideline of ACGIH 2018. According to the experimental results in this study and the guideline of ACGIH 2018, the high performance for disinfection required that E should be better around 5.2 mJ/cm² or above, while the UV radiation limit towards individual required that E should not exceed 25 mJ/cm². Therefore, to ensure the high disinfection performance as well as the safety toward individuals, the range of E should be as follows.

\[ 5.2 \leq E \leq 25 \]  

(3)

Substituting the parameters:

\[ 5.2 \leq 5 \times t_1 \times \frac{28800}{t_1 + t_2} \leq 25 \]  

(4)

Simplifying the equation:

\[ 0.036 \leq \frac{t_1}{t_1 + t_2} \leq 0.174 \]  

(5)
Figure S13 further shows the relationship between $t_1$ and $t_2$. It can be observed that the optimized $t_1$ is located at the range of 5-15 seconds and $t_2$ is located at the range of 24-71 seconds. For instance, a typical lift operated in a commercial building of 6 floors requires 60-70 seconds from the ground to the top floor. Therefore, if $t_1$ and $t_2$ are set at 10 seconds and 50 seconds, respectively, the corresponding $E$ is 24 mJ/cm$^2$ that satisfies the above conditions. In this case, people can safely use the lift irrespective of the usage frequency in 8 hours. However, it should note that other factors, such as the distance of the lift operation, the operation speed, and the number of lift users may affect the selection of $t_1$ and $t_2$ but it is anticipated that feasible setting can be obtained.

In addition, highly photosensitive individuals may have adverse effect on exposing to the far UVC irradiation. These individuals should take more attention to the far UVC irradiation in the lift environment and may need the advice from medical professionals.

Table S1. Sampling schedule of the long-term field test

<table>
<thead>
<tr>
<th>Month</th>
<th>Days</th>
<th>Dates</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>May '21</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5</td>
<td>6</td>
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</tr>
<tr>
<td></td>
<td>31</td>
<td>32</td>
<td>33</td>
</tr>
</tbody>
</table>

Table S2. Linear regression equations for the calculation of the reflected UVC intensity. Note: $x$ is the distance between reflected surface and the dosimeter, cm; $y$ is the reflected UVC intensity, $\mu$W/cm$^2$

<table>
<thead>
<tr>
<th>Angle (°)</th>
<th>Glass surface</th>
<th>R$^2$</th>
<th>Steel surface</th>
<th>R$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>$y = -0.17x + 5.9$</td>
<td>0.994</td>
<td>$y = -1.36x + 47.3$</td>
<td>0.996</td>
</tr>
<tr>
<td>45</td>
<td>$y = -0.21x + 7.6$</td>
<td>0.993</td>
<td>$y = -1.19x + 41.5$</td>
<td>0.998</td>
</tr>
<tr>
<td>60</td>
<td>$y = -0.24x + 8.0$</td>
<td>0.998</td>
<td>$y = -1.00x + 35.2$</td>
<td>0.999</td>
</tr>
</tbody>
</table>

Table S3. The inactivation efficiency of S. epidermidis in the air by far-UVC irradiation

<table>
<thead>
<tr>
<th>Initial concentration (CFU/m$^3$)</th>
<th>Inactivation efficiency (%)</th>
<th>Average UV dose (mJ/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5 \times 10^3$</td>
<td>100</td>
<td>13.5</td>
</tr>
<tr>
<td>$1 \times 10^4$</td>
<td>99.87</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table S4. Inactivation of S. epidermidis by far-UVC irradiation comparison of recently reported disinfection methods

<table>
<thead>
<tr>
<th>Methods</th>
<th>Efficiency (%)</th>
<th>Parameters</th>
<th>Advantages/ Disadvantages</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold plasma</td>
<td>20-70%</td>
<td>Bacteria concentration: $1.1 \times 10^6$ CFU/m$^3$; Energy consumption: 4 W;</td>
<td>Fast disinfection performance; Generation of O$_3$ byproduct; Required posttreatment</td>
<td>[46]</td>
</tr>
<tr>
<td>Silver nanoparticles filter</td>
<td>58-99%</td>
<td>Bacteria concentration: $1.1 \times 10^6$ CFU/m$^3$; Time: 9 min</td>
<td>No energy consumption; Influence by the particle size and environmental conditions</td>
<td>[47]</td>
</tr>
<tr>
<td>UV-Thermal system</td>
<td>87%</td>
<td>Bacteria concentration: $1.0 \times 10^6$ CFU/m$^3$; Temperature: 200 °C; UV light source: 254 nm; Time: 1 min</td>
<td>Fast disinfection performance; High energy consumption;</td>
<td>[48]</td>
</tr>
<tr>
<td>UVC-LED</td>
<td>~90%</td>
<td>Bacteria concentration: $1.1 \times 10^5$ CFU/m$^3$; UV light source: 254 nm; UVC power: &gt;200 mW; Time: 13 min</td>
<td>Room temperature</td>
<td>[49]</td>
</tr>
<tr>
<td>Far-UVC radiation</td>
<td>&gt;99.8%</td>
<td>Bacteria concentration: $1 \times 10^6$ CFU/m$^3$; Far-UVC power: 12 W; UV light source: 222 nm; Time: 45 min</td>
<td>Room temperature; This work</td>
<td></td>
</tr>
</tbody>
</table>
Figure S1. Surface swabbing of button panel (a) and handrail (b) by using the sampling templates, respectively.

Figure S2. Far-UVC test card attached on the lift cabin.

Figure S3. Inactivation performance of E. coli on (a) glass surface and (b) steel surface, respectively, and their corresponding log_10 reduction on (c) glass and (d) steel surface.
Figure S4. Inactivation performance of ESBL on (a) glass surface and (b) steel surface, respectively, and their corresponding log_{10} reduction on (c) glass and (d) steel surface.

Figure S5. Inactivation performance of MRSA on (a) glass surface and (b) steel surface, respectively, and their corresponding log_{10} reduction on (c) glass and (d) steel surface.
Figure S6. The inactivation performance of S. faecalis on (a) glass surface and (b) steel surface, respectively, and their corresponding log_{10} reduction on (c) glass and (d) steel surface.

Figure S7. The inactivation performance of C. albicans on (a) glass surface and (b) steel surface, respectively, and their corresponding log_{10} reduction on (c) glass and (d) steel surface.
Figure S8. The inactivation performance of H1N1 on (a) glass surface and (b) steel surface, respectively, and their corresponding log_{10} reduction on (c) glass and (d) steel surface.

Figure S9. The inactivation performance of H3N2 on (a) glass surface and (b) steel surface, respectively, and their corresponding log_{10} reduction on (c) glass and (d) steel surface.
Figure S10. Comparison of the inactivation of E. coli and S. faecalis between the laboratory test and field test.

Figure S11. Inactivation efficiency of bacteria on the surface of the lift button (red circle) and the handrail (blue square) by far-UVC exposure during sampling tests from Mar. 25 to Jul. 29, 2021.
Figure S12. Inactivation kinetics of *S. epidermidis* by far-UVC irradiation

\[ y = e^{-0.242x} \]
\[ R^2 = 0.9943 \]

Figure S13. Relationship between \( t_1 \) and \( t_2 \) for the far-UVC operation cycle