Far UVC light for reducing airborne transmission of bacteria and viruses

Final report for NHS Scotland Assure

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1 Executive Summary

This study has carried out experimental measurements in a room scale chamber and computational fluid dynamics modelling to evaluate the performance of filtered Krypton-Chloride (KrCl) lamps (known as Far-UVC technology) in reducing the concentration of microorganisms in air and on surfaces in indoor settings. The study considers a range of microorganisms and ventilation conditions. Key findings from the study are:

- Far-UVC effectively inactivates airborne microorganisms in a room under controlled experimental conditions and under a range of ventilation rates.
- Far-UVC appears to result in inactivation of microorganisms on surfaces in the room at different ventilation rates.
- Far-UVC is very likely to inactivate airborne pathogens that are relevant to healthcare settings.
- The results from our preliminary work (Eadie et al. 2022) are robust to changes in ventilation pattern and sample location.
- The experimentally measured effectiveness increases with the number of lamps used and hence the quantity of Far-UVC in the room.
- A situation where the Far-UVC field is evenly distributed across a room demonstrates less variability than having the UVC source at a single location
- The optimum number of lamps with diffuser per unit volume could be as low as a single 15 W lamp per 8 m^3; our computer modelling suggests 4 lamps may have produced results very similar to the 5 lamps used within the chamber study. This would need to be explored with further experiments.
- The aim would be to optimise inactivation of pathogen for the lowest possible electrical power consumption. Our results provide guidance with current lamp wall plug efficiency, which is approximately 0.5% - 1%, i.e. a 15 W lamp produces somewhere between 0.075 - 0.15 W of Far-UVC.
- We have not measured health effects in this study, however our other ongoing work and international evidence has not identified any acute effects from filtered KrCl lamps on either skin or eyes. Evidence from cell and animal

studies suggests that long-term Far-UVC exposure is unlikely to cause non-melanoma skin cancer.

- We have not directly considered usability and acceptability in this study, however our experience across ongoing studies suggests that the following are important to consider in further research and evaluation:
    - communication/consultation with staff and patients to gauge their understanding of Far-UVC and the potential benefits and any risks
    - Evaluation of product design and robustness to identify which lamps would be suitable for healthcare installation
    - Consideration of which spaces would be most suitable for installation. Although Far-UVC is considerably safer than other wavelengths of UV light, it would be important to consider who would be exposed for how long and whether there are any groups who could be more vulnerable/concerned by the use of Far-UVC
- Our study has shown that Far-UVC has a great deal of potential, however these are in controlled scenarios. There remain several research questions which would inform deployment:
    - We have considered two microorganisms in the timescale of this study, however it would be important to test against a wider range including fungi
    - Our experiments are carried out using aerosolisation of the microorganisms in distilled water, which does not fully represent the size range or composition of human respiratory aerosols. Absorption by proteins in human respiratory aerosols may affect the efficacy of Far-UVC.
    - We have not measured any impacts of the Far-UVC on indoor air chemistry and potential for the creation of any harmful by-products. International evidence suggests that this risk is very low, however it would be advantageous for further research to evaluate this possibility.

2 Introduction

Krypton-Chloride excimer lamps, known as Far-UVC, is a recently developed technology that uses ultraviolet (UV) light to inactivate microorganisms in indoor spaces. The approach aims to predominantly reduce concentrations of microorganisms in air and hence reduce transmission of respiratory pathogens, but there may also be some benefits in terms of surface contamination. Evidence from studies prior to this project, including our chamber experiments, suggests that Far-UVC is effective at inactivating microorganisms including the SARS-CoV-2 virus.

Far-UVC uses UV light with a wavelength of 222nm that is germicidal. Unlike other UVC wavelengths, evidence suggests that Far-UVC is much safer for human exposure with no evidence from studies that it harms skin or eyes when used within current guidance exposure values. Far-UVC therefore has significant potential to mitigate transmission of infection, particularly in spaces which are poorly ventilated.

This report details experimental studies carried out in a room-scale bioaerosol chamber and computational modelling using a CFD approach to evaluate the performance of Far-UVC for a number of relevant microorganisms under different ventilation conditions. We consider the impact of Far-UVC on both air and surface microbial contamination. The report uses our results together with data from other studies worldwide to outline the potential for application in healthcare and further research needs.

3 Experimental Methodology

The experimental study was designed to investigate a number of factors, including:

- Comparison of ventilation rates to understand the performance under different airflow conditions.
- Comparison of ventilation regimes to understand the performance under different air patterns.
- Spatial effectiveness of the Far-UVC system including sampling at locations close to the aerosol source to determine whether the devices can have any impact on close-range transmission.
- Variation in inactivation with different microbial species.

3.1 Aerobiology chamber and FAR-UVC lamps

Experiments were conducted in the controlled aerobiology chamber at the University of Leeds; the dimensions used were similar to a single-bed room at the hospital (32.25 m^3): 4.26m (L) x 3.36m (W) x 2.26m (H). The ventilation was HEPA filtered at the supply and the extract to provide contaminant-free inlet air and ensure safe discharge (**Figure 1**).

The room is designed to safely conduct controlled aerosol experiments. All experiments were carried out with no occupants in the room and with the ventilation operating under negative pressure for safety. The chamber is capable of ventilation rates between 1.5 and 12 Air Changes per Hour (ACH).

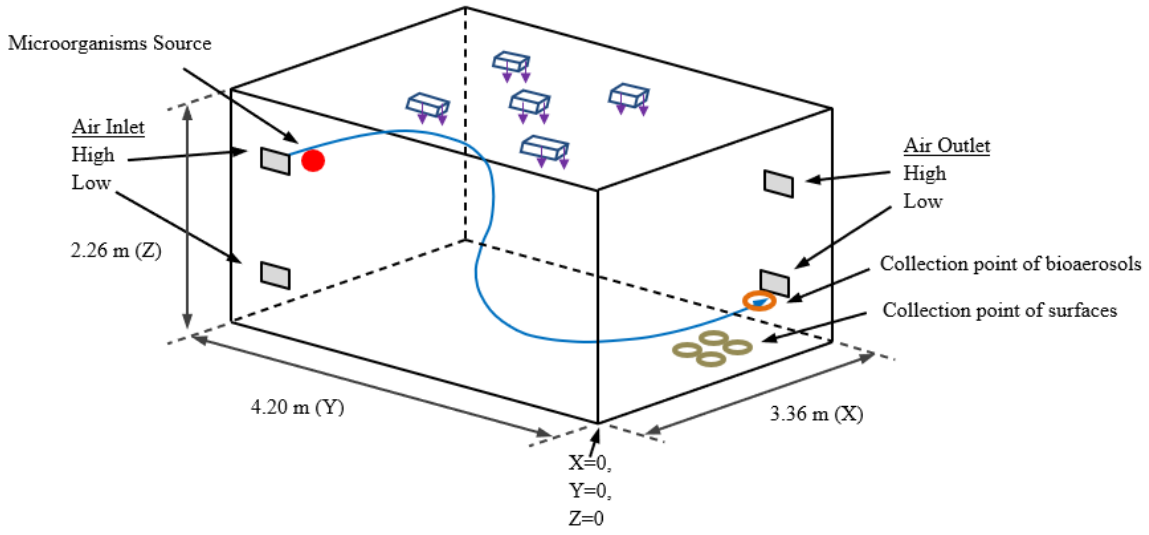

Figure 1: The aerobiological chamber dimensions and ventilation regime.

Prior to the microbial experiments, five Krypton Chloride excimer lamps were mounted close to the ceiling of the chamber in a quincunx formation. Filters were added so that the lamp intensity could be adjusted and diffusers were added to increase the volume of the room being irradiated. Experiments were carried out with one or five lamps operating. These Far-UVC devices are commercially available and have been donated to us by a company. We tested them with the lamps modified so they operate continuously at different power levels; this will allow us to test the technology rather than the product. This resulted in a room average UVC irradiance as reported in Eadie et al 2022 (see **Table 1**)

Table 1: Average irradiance and calculated 8-hour exposure dose for three different exposure conditions at two heights from the ground. The bold, italicised 8-hour exposure values are above the ICNIRP 222-nm exposure limit of 23 $mJcm^{-2}$. No exposures exceeded the 2022 ACGIH threshold limit value for skin of 478 $mJcm^{-2}$ at 222 nm.

	No. of lamps	Peak Values				Average Values			
		Height = 1.7 m		Height = 1 m		Height = 1.7 m		Height = 1 m	
		Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)	Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)	Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)	Irradiance (μWcm^{-2})	8-hour dose ($mJcm^{-2}$)
High	1	14.4	***415***	1.93	***56***	0.57	16.5	0.45	12.9
	5	14.4	***415***	3.42	***98***	2.73	***78***	2.01	***58***
Medium	1	0.92	***26.5***	0.13	3.7	0.03	0.87	0.03	0.82
	5	0.92	***26.5***	0.22	6.3	0.14	4.1	0.13	3.67
Low	1	0.09	2.65	0.01	0.37	0.003	0.09	0.003	0.08
	5	0.09	2.65	0.02	0.63	0.01	0.41	0.01	0.37

3.2 Preparation of culture broth, agar plates

A laboratory strain of *Staphylococcus aureus* (ATCC 6538) and *pseudomonas aeruginosa* (NCIMB 10848) culture was prepared by transferring a loopful of bacteria into a 100ml of sterilised nutrient broth (Oxoid Ltd, UK). This culture broth was then incubated at 37°C for 48 hours.

Tryptone Soya Agar (TSA) Oxoid Ltd, UK, was used to prepare Petri dishes plates 90 mm and 55 mm. An amount of 40g of TSA was added to one litre in the Masterclave 09 (Don Whitley Scientific). The agar mixtures were stirred for 15 minutes, and then they were heated to 121°C for 15 minutes. The agar was then cooled and left at a constant temperature of 45°C. An automated pourer stacker (Don Whitley Scientific) was used to pour the agar broth into sterile Petri dishes (37 ml/ Ø 90mm plate); this volume was recommended by (Mcdonagh et al., 2013). The TSA plates of Ø 55mm used in AMPAS were prepared using pouring methods. The manufacturer's instructions (Oxoid Ltd, UK) were followed to prepare the agar for 500ml of the medium in Duran bottles. The mixture was hand shaken to make sure it was thoroughly mixed; then, the agar was autoclaved at 121 °C for 15 minutes and later left to cool at 60 °C before pouring 20ml into the Ø 55mm Petri dishes under aseptic conditions. All the TSA plates of Ø 90mm and Ø 55mm agars were left to cool and become solid and then stored at room temperature to be used whenever required.

To find the concentration of the strain in the culture broth, it was diluted five folds (10^{-5} concentration) using serial dilutions with 9ml distilled water that was autoclaved at 121 °C for 15 minutes and left to cool before being used. 0.1ml of the fifth bottle was pipetted and dispensed on the TSA, then incubated at 37°C for 24h for counting. The concentration of the strain in the culture broth was (~1 x10^{8} cfu/ml).

3.3 Generation of the aerosolised microorganisms

The Collison 6-jet nebuliser (BGI, USA) was used to generate the aerosolised microorganisms in the range of 0.3-10 µm diameter (King et al., 2013). This nebuliser was operating at 12 L.min^{-1} and was located outside the chamber (**Figure 2**).

Figure 2: The suspension fluid in the Collison nebuliser.

These aerosolised microorganisms are released at one of three locations at coordinates (X,Y, Z) as shown in **Figure 1.**

- L_{G1}: Through a tube and near the high-level supply of fresh air (0.5 m, 3.55 m, 1.7 m).
- L_{G2}: Through a tube and near the middle Far-UVC lamp (0.68 m, 2.1 m, 1.7 m).
- L_{G3}: Through a hole in the wall directly to the centre of the long wall of the chamber (0 m, 2.1 m, 1.2 m).

The location of the source points (L_{G1}) has been used previously and was selected for the majority of experiments as it was not located directly under a Far-UVC source (Eadie et al., 2022). Location L_{G2} was chosen to be 2 m away from the collection point and Far-UVC was in the middle. Location L_{G3} was used to release *Pseudomonas aeruginosa* as it was challenging to create sufficient aerosol in the room (extremely low generation) and this location prevented losses in tubing that are present with other release locations.

The suspension fluid inside the Collison nebuliser vessel was created by adding 1ml from the culture broth, then adding it to 99 ml distilled water to achieve a concentration of (~1 $x10^6$ cfu/ml).

3.4 Air sampling

The bioaerosols were collected onto TSA using the 6-stage Anderson air sampler that was operated at a flow-rate of 28 $l.min^{-1}$ for one to ten minutes depending on the concentration inside the chamber to reach a raw colony count between 50-150 per plate as recommended (Cantium Scientific Limited, 2015). A correction table (Appendix B - 400 Hole Count) was used to apply positive hole correction for the air samples to correct for potential over-counting under higher bioaerosol concentrations (Cantium Scientific Limited, 2015). These six stages represent the lungs and allow different ranges of particles' size to go through (7, 4.7, 3.3, 2.1, 1.1 and 0.65 µm diameter). We used one plate for sampling from stage number 6 (0.65 µm diameter) because it represents more than 95% of the data, according to our observation. The sampler was located externally to the chamber in the ante-room, and air samples were taken using tubes via a sampling port at one of these three locations at coordinates (X,Y, Z) as shown in **Figure 1.**

- L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).
- L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).
- L_{A3}: Through a tube and near the middle Far-UVC lamp (2.68 m, 2.1 m, 1.7 m).

The location of the collection points (L_{A1} and L_{A2}) has been shown previously to be representative of the average bioaerosol concentration of the whole chamber. Location L_{A3} was chosen to present a social distance of 2 m away from the source of infection (L_{G3}) with the Far-UVC lamp in between L_{G3} and LA_3.

3.5 Surface Sampling

The deposited microorganisms were collected using a custom Automated Multiplate Passive Air Sampling (AMPAS) device (Hiwar et al., 2020). The device comprises a series of 6 Petri dishes arranged in a circle, covered by a rotating tray controlled by a stepper motor (**Figure 3**). The device is programmed to expose each agar plate to the microorganisms in the air at pre-determined times and for pre-programmed periods before covering them, without human intervention, to ensure they are no longer exposed to air. Four AMPAS devices were put close together in front of the outlet grid **Figure 1**.

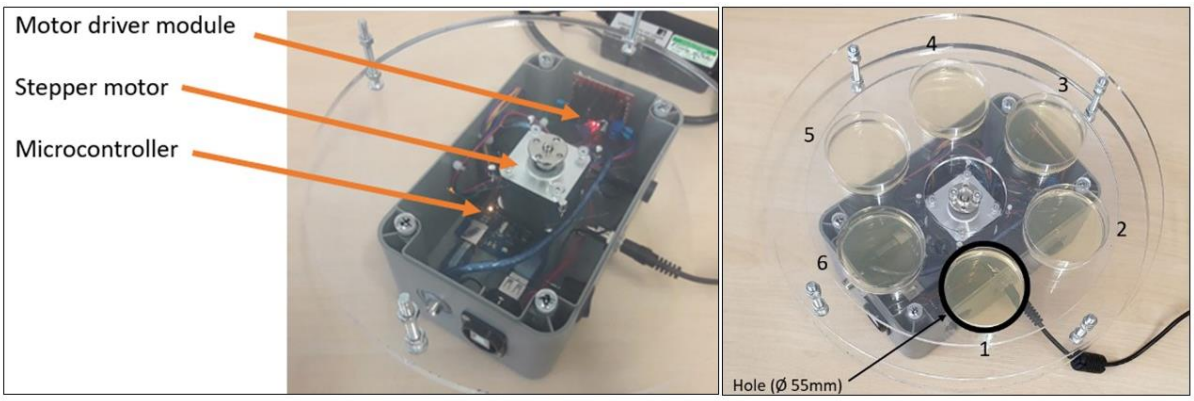

Figure 3: AMPAS device and components.

3.6 Experiments setting

All experiments were carried out under the steady-state conditions and under a slight negative pressure (0.5 bar) using between 1 and 5 ceiling-mounted Far-UVC lamps (Eadie et al., 2022). Prior to performing the microbial tests, we measured ventilation rates in the chamber using a Balometer. *Staphylococcus aureus* (gram-positive)/spherical shaped) was used in all experiments, while *Pseudomonas aeruginosa* (gram-negative)/rod shaped) was only used for the comparison of different species.

In each experiment, the nebuliser and ventilation operated continuously; this replicates a realistic scenario in a hospital setting where an infectious person is continuously releasing a pathogen over a long period of time. A continuous release of aerosolised microorganisms was introduced to the chamber for 210 minutes. The first 60 minutes were employed to let the room achieve steady-state conditions, then 50 minutes were used to perform sampling ten times (Far-UVC device off). The device(s) were then turned on and left for 20 minutes before taking ten more samples (Far-UVC device on) for 50 minutes. For air sampling, the duration time of sampling was 1-5 minutes (according to the type of experiment), and for surface sampling, it was in 10-minute cycles and was repeated five times (ten plates with Far-UVC device off and ten plates with Far-UVC device on). Following sampling, the nebuliser and Far-UVC devices were switched off, and the room ventilation rate was increased to 12 ACH for 30 minutes to flush any remaining airborne microorganisms from the room (**Figure 4**). Following the experiment, the plates were incubated at 37 °C for 24 hours.

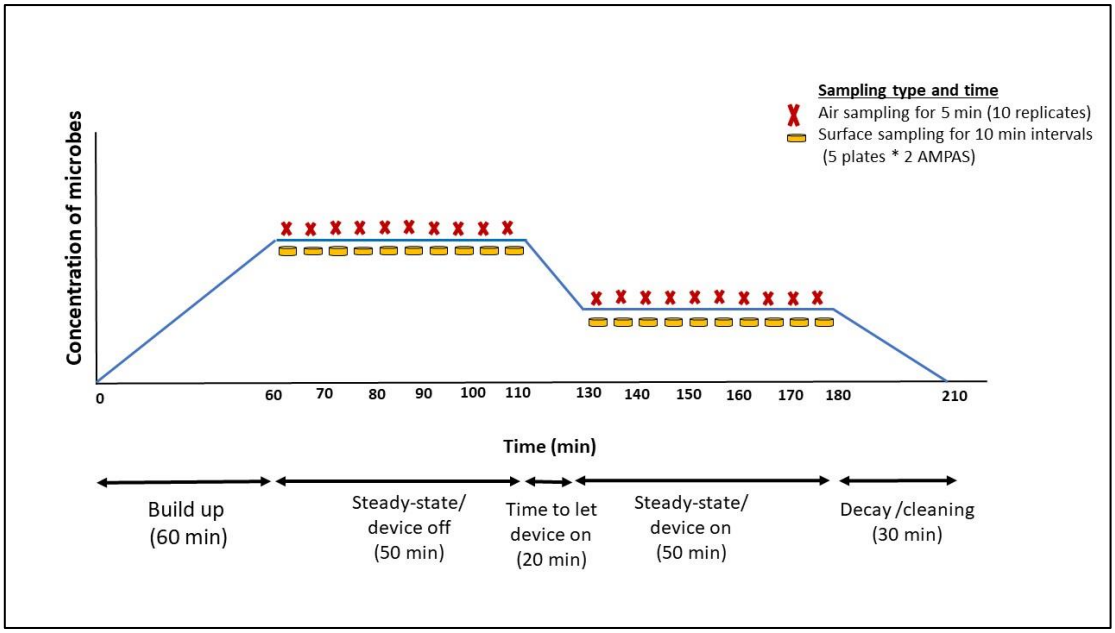

Figure 4: The microbial concentration with different sampling types and times.

Ventilation rate comparison was carried out at an airflow rate of 0.013 m^3s^{-1}, 0.027 m^3s^{-1}, 0.054 m^3s^{-1} and 0.081 m^3s^{-1} equivalent to 1.5, 3, 6 and 9 air-changes-per-hour (ACH), respectively, with the ventilation regime (high grid inlet- low grid outlet). The location of generation sources was $L_{G1,}$ and the collection point of air sampling was L_{A1}.

Ventilation regime comparison was carried out at high grid inlet- low grid outlet and low grid inlet- high grid outlet at a constant ventilation rate of 3 ACH. The location of generation sources was $L_{G1,}$ and the collection points of air sampling were L_{A1} and L_{A2}.

Spatial comparison was carried out at high grid inlet- low grid outlet at 3 ACH. The location of the generation source was $L_{G2,}$ and the collection points of air sampling were L_{A1} and L_{A3}.

Microbial species comparison was carried out with *Staphylococcus aureus* and *Pseudomonas aeruginosa* at 3 ACH with high grid inlet- low grid outlet. The location of generation source was L_{G1} (*Staphylococcus aureus*) and L_{G3} (*Pseudomonas aeruginosa*), and the collection point of air sampling was L_{A1}. Experiments were also attempted using Phi-6, a bacteriophage which is widely used as a surrogate for viruses, however these were not successful as it was not possible to generate a sufficient concentration in air to reliably measure the impact of the Far-UVC lamps.

4 Experimental Results

4.1 Ventilation rate comparison

The impact of using Far-UVC light on reducing the bioaerosols load under the steady state condition has been investigated at different ventilation rates. The concentration of bioaerosols was significantly lower with the Far-UVC light on, in all the experiments (See **Table 2** and **Figure 5**).

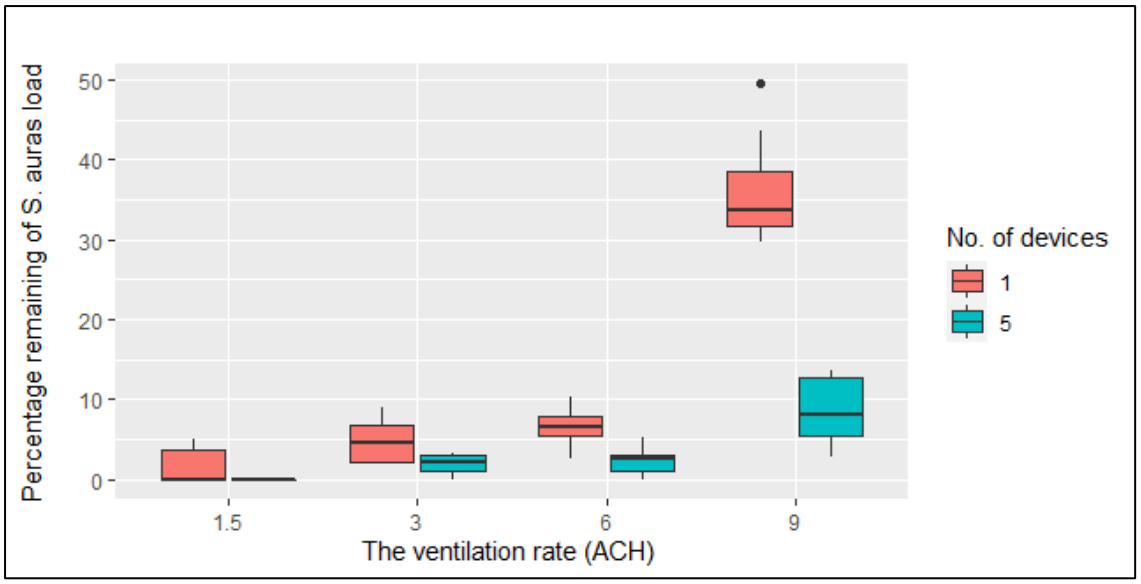

Figure 5: The performance of Far-UVC (222 nm) irradiation in reducing the concentration of *S. aureus* in the air under the steady state condition at different ventilation rates.

Table 2 and **Figure 5** illustrate that the Far-UVC devices have a significant impact on steady state reduction of microorganisms across a wide range of ventilation rates in the chamber. As expected, the relative benefit of the Far-UVC is greater at a lower ventilation rate and with a greater number of devices. At a high ventilation rate, there is already significant removal of microorganisms by the ventilation air, and hence the additional benefit measured by the experiments is relatively less than at a low ventilation rate. In addition, at a higher ventilation rate, the airflow in the room is at a higher velocity and will have a lower residence time within the UVC field.

Table 2: The performance of Far-UVC light to reduce the steady state concentration of airborne microorganisms at different ventilations rates. Lamp irradiance was "High" (see **Table 1**).

No. of devices	Far-UVC light (222 nm)	Ventilation rate (ACH)	Bioaerosols load (cfu/m3), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
				Median	LOG	IQR	
1	Off	1.5	711 ± 162 (536 - 1071)				
		3	1711 ± 391 (1286 - 2393)				
		6	800 ± 180 (583 - 1000)				
		9	1800 ± 313 (1357 - 2286)				
	On	1.5	11 ± 17 (0 - 36)	100%		-	5.4%
		3	75 ± 32 (36 - 143)	95.5%	1.35	93.3% - 97.8%	2.2%
		6	58 ± 21 (24 - 95)	92.8%	1.14	91.4%-93.9%	1.3%
		9	650 ± 124 (536 - 893)	66.3%	0.47	61.4% - 68.3%	2.0%
5	Off	1.5	2456 ± 388 (1702 - 2845)				
		3	3339 ± 424 (2714 - 4000)				
		6	1167 ± 99 (1036 - 1357)				
		9	1486 ± 479 (893 - 2250)				
	On	1.5	0 ± 0 (0 - 0)	100%			0.5%
		3	64 ± 38 (0 - 107)	97.8%	1.67	97.0% - 98.9%	1.1%
		6	27 ± 14 (0 - 54)	97.4%	1.58	96.8% - 98.8%	1.0%
		9	114 ± 54 (36 - 179)	91.9%	1.09	87.2% - 94.6%	2.7%

Table 3 shows the impact of the Far-UVC on the deposition rate of microorganisms under different ventilation rates. The impact of Far-UVC on reducing the load appears to be significant. However, the concentration of deposited microorganisms was low even when the Far-UV light was off because the concentration of bioaerosols was low over the different experiments. The relationship between the concentration of microorganisms in the air and on surfaces appears to be positively correlated; at a high ventilation rate (9 ACH), the deposition rate appears to be higher than at other flow rates, which may be due to the more dynamic airflow. The low concentrations mean that these results are close to the experimental resolution and further investigation is required with a higher concentration of bioaerosols to ensure that the collection of deposited microorganisms is sufficient in order to confirm this conclusion.

Table 3: The performance of Far-UVC light to reduce the concentration of deposited microorganisms on surfaces at different ventilation rates.

No. of device	Far-UVC light (222 nm)	Ventilation rate (ACH)	Deposited microorganisms concentration (cfu/plate*), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
				Median	LOG	IQR	
1	Off	1.5	0.30 ± 0.48 (0 - 1)				
		3	1.30 ± 1.16 (0 - 3)				
		6	0.20 ± 0.42 (0 - 1)				
		9	2.00 ± 1.25 (1 - 5)				
	On	1.5	0 ± 0 (0 - 0)	100.0%	-	-	-
		3	0 ± 0 (0 - 0)	100.0%	-	-	-
		6	0 ± 0 (0 - 0)	100.0%	-	-	-
		9	0.60 ± 0.97 (0 - 3)	100.0%	-	0.00% - 50%	50.0%
5	Off	1.5	0.50 ± 0.71 (0 - 2)				
		3	3.10 ± 2.02 (1 - 8)				
		6	1.40 ± 1.07 (0 - 3)				
		9	1.30 ± 1.25 (0 - 4)				
	On	1.5	0 ± 0 (0 - 0)	100.0%	-	-	-
		3	0.30 ± 0.48 (0 - 1)	100.0%	-	0.00% - 25%	33.3%
		6	0 ± 0 (0 - 0)	100.0%	-	-	50.0%
		9	0.20 ± 0.63 (0 - 2)	100.0%	-	-	100.0%

4.2 Ventilation regime

Different ventilation regimes were used and the impact of using Far-UVC light on reducing the bioaerosols load under the steady state conditions was investigated. The concentration of bioaerosols was significantly lower with the Far-UVC light on in all the experiments (See **Table 4** and **Figure 6**).

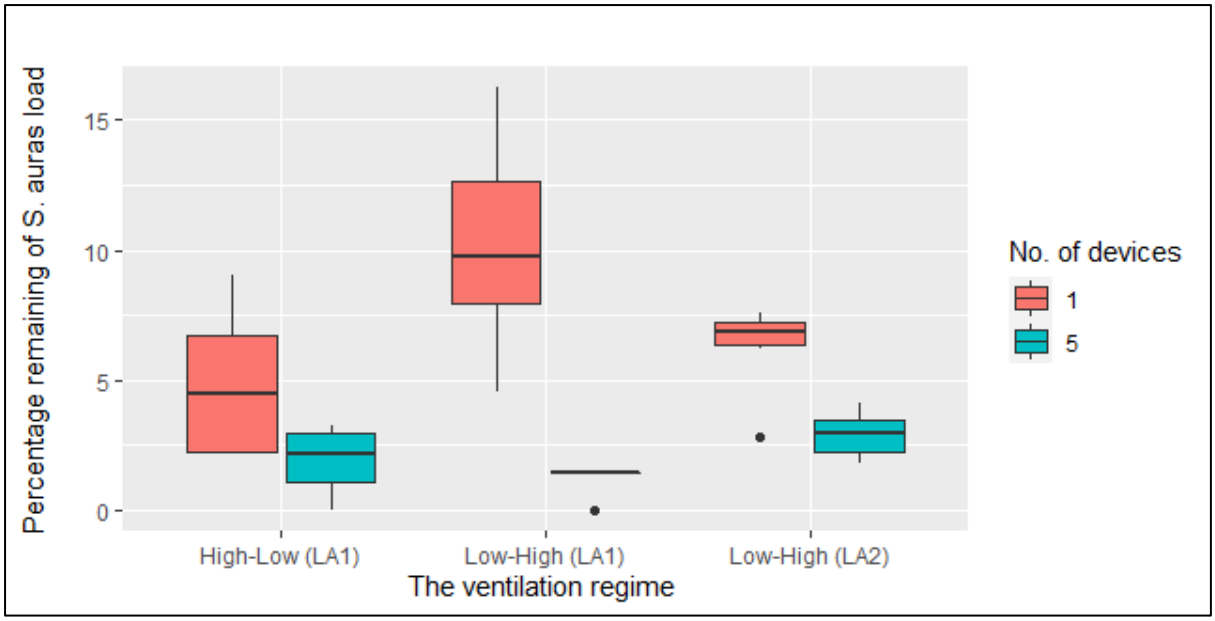

Figure 6: The performance of Far-UVC (222 nm) irradiation in reducing the concentration of *S. aureus* in the air at 3 ACH under different ventilation regimes.

As shown in **Table 4** and **Figure 6**, there is a small impact of ventilation regime and sample location on the reduction of microorganisms in the air. This is more noticeable in cases with only one lamp, where there is a greater variation in the results. The Far-UVC appears to be slightly more effective when the ventilation air is supplied from a high-level diffuser and extracted at low level, however there is not a clear pattern between ventilation regime and sample location seen in the results.

Table 4: The performance of Far-UVC light to reduce the concentration of airborne microorganisms under different ventilation regimes. Lamp irradiance was “High”.

No. of devices	Far-UVC light (222 nm)	Ventilation regime	Sampling point	% Reduction			Experiment Resolution
				Median	LOG	IQR	
1	Off	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).				
	On	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).	95.5%	1.35	93.3% - 97.8%	2.2%
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).	90.3%	1.01	87.3% - 92.0%	0.6%
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).	93.1%	1.16	92.8%-93.7%	0.3%
5	Off	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).				
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).				
	On	High-Low	L_{A1}: Near the low air extract (2.85 m, 0.65 m, 0.5 m).	97.8%	1.67	97.0% - 98.9%	1.1%
		Low-High	L_{A1}: Near the high air extract (2.85 m, 0.65 m, 0.5 m).	98.6%	1.85	-	1.4%
		Low-High	L_{A2}: Near the high air extract (2.85 m, 0.65 m, 1.7 m).	97.1%	1.53	96.5% - 97.8%	0.3%

4.3 Distance comparison

A social distance of 2 m away from the source of infection with the Far-UVC lamp located centrally between releasing and sampling points was investigated (**Figure 7**). This is compared to results with the same lamp but with the release and sample locations as in the scenarios above. Initial results to evaluate whether a Far-UVC device is effective at reducing exposure at different distances from the source suggest that even at closer proximity where the exposure time will be lower, the Far-UVC has a substantial effect (**Table 5** and **Figure 8**). However, experiments to measure the effect of proximity are challenging to set up and conduct, and more research is required to evaluate the influence of distance

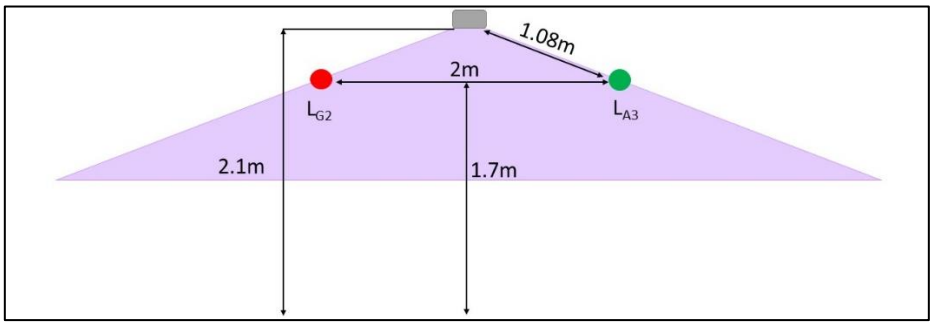

Figure 7: The short-range distances experiment setup showing source (L_{G2}), Far-UVC lamp and sample locations (L_{A3}).

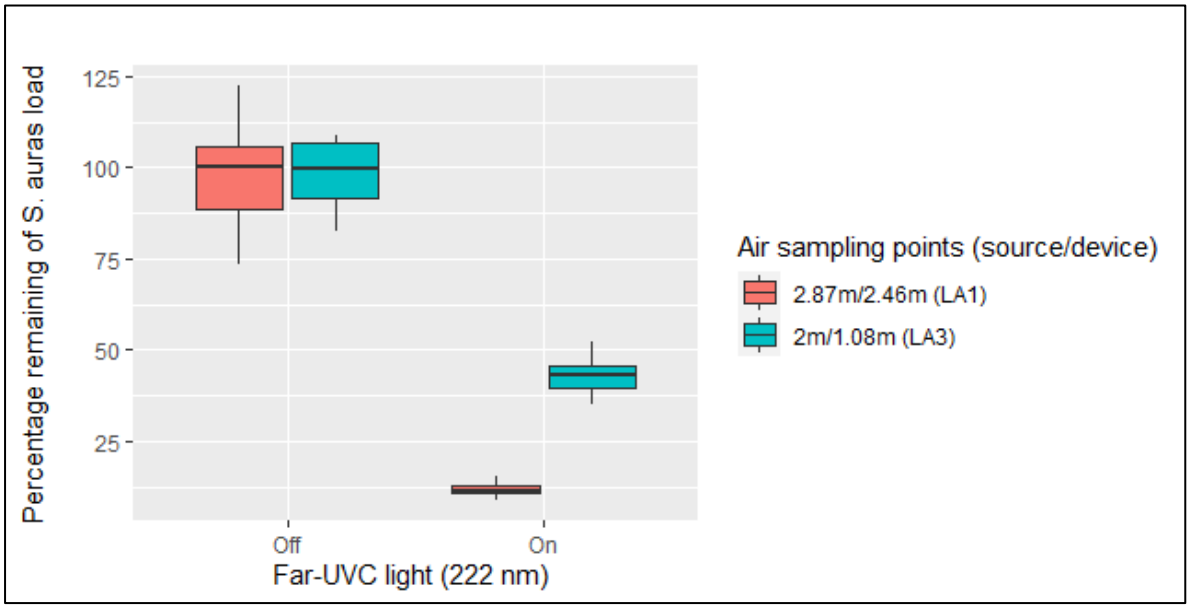

Figure 8: The performance of Far-UVC (222 nm) irradiation in reducing the concentration of *S. aureus* in the air at 3 ACH and at different distances between the source and sample location.

Table 5: The performance of one Far-UVC light device to reduce the concentration of airborne microorganisms at different distances between source and sample. Lamp irradiance was “High” (see **Table 1**).

Far-UVC light (222 nm)	Air sampling collection point	Bioaerosols load (cfu/m3), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
			Median	LOG	IQR	
Off	2m away from the source, 1.08m from the Far-UVC device (L_{A3}: Near the middle device [2.68 m, 2.1 m, 1.7 m])	2436 ± 227 (2054 - 2696)				
	2.87m away from the source, 2.46m away from the Far-UVC device (L_{A1}: Near the low air extract [2.85 m, 0.65 m, 0.5 m])	2348 ± 351 (1768 - 2946)				
On	2m away from the source, 1.08m from the Far-UVC device (L_{A3}: Near the middle device [2.68 m, 2.1 m, 1.7 m])	1045 ± 124 (857 - 1268)	57.4%	0.4	55.1% - 61.0%	0.7%
	2.87m away from the source, 2.46m away from the Far-UVC device (L_{A1}: Near the low air extract [2.85 m, 0.65 m, 0.5 m])	282 ± 44 (214 - 375)	88.5%	0.9	87.4%- 89.4.7%	0.7%

4.4 Microbial species

Two different microbial species (*Staphylococcus aureus* and *Pseudomonas aeruginosa*) were considered at 3 ACH with ventilation regime (high grid inlet- low grid outlet). The results show that for both species, the Far-UVC light had a significant impact on their inactivation (**Table 6** and **Figure 9**). It should be noted that

results for the two species need to be compared with caution as the release location was different for *Pseudomonas aeruginosa* due to experimental challenges.

Table 6: The performance of Far-UVC light to reduce the concentration of airborne microorganisms for different species. Lamp irradiance was “High” (see **Table 1**), mechanical ventilation was 3 ACH.

No. of device	Far-UVC light (222 nm)	Generation source	Species	Bioaerosols load (cfu/m3), Mean ± SD (Min-Max)	% Reduction			Experiment Resolution
					Median	LOG	IQR	
1	Off	L_{G1}: Through a tube and near the supply fresh air (0.5 m, 3.55 m, 1.7 m).	*SA*	1711 ± 391 (1286 - 2393)				
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	567 ± 48 (507 - 657)				
	On	L_{G1}: Through a tube and near the supply fresh air (0.5 m, 3.55 m, 1.7 m).	*SA*	75 ± 32 (36 - 143)	95.5%	1.3	93.3% - 97.8%	2.2%
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	31 ± 11 (14 - 50)	94.9%	1.3	93.6% - 94.9%	1.4%
5	Off	L_{G1}: Through a tube and near the	*SA*	3339 ± 424 (2714 - 4000)				

		supply fresh air (0.5 m, 3.55 m, 1.7 m).						
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	471 ± 51 (345 - 524)				
	On	L_{G1}: Through a tube and near the supply fresh air (0.5 m, 3.55 m, 1.7 m).	*SA*	64 ± 38 (0 - 107)	97.8%	1.7	97.0% - 98.9%	1.1%
		L_{G3}: Through a hole in the wall directly to the chamber (0 m, 2.1 m, 1.2 m).	*PA*	2 ± 6 (0 - 12)	100.0%	-	-	2.5%

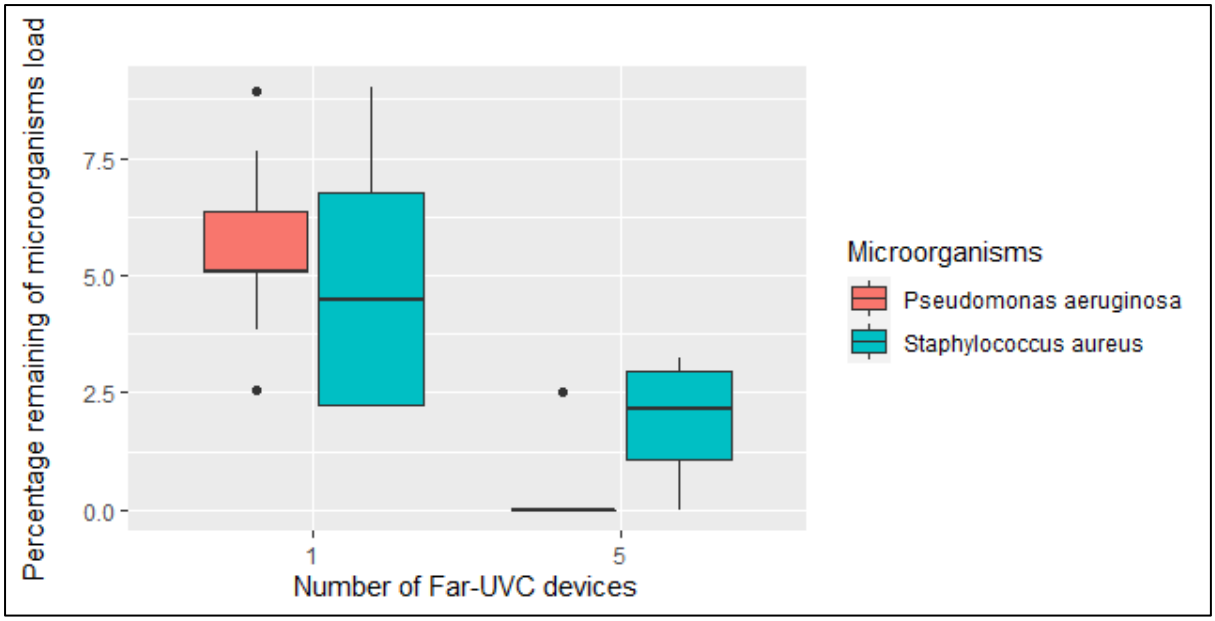

Figure 9: The performance of Far-UVC (222 nm) radiation in reducing the concentration of *S. aureus* and *P. aeruginosa* in the air at 3 ACH.

5 Computational Simulation Methodology

Complex computational simulations, designed to replicate the set-up above, were undertaken. Results of the simulations were compared to the experimental results for validation purposes and then the simulations were expanded to investigate variables which were not explored experimentally.

5.1 Steady state airflow and particle dissemination

To calculate the flow fields of the room we use the open source computational fluid dynamics (CFD) software package, OpenFOAM [OpenCFD Ltd] to calculate steady-state, incompressible solutions of the Reynolds-averaged Navier-Stokes equations.

The room dimensions are as described above, we use a uniform grid to model the room with a mesh resolution of 2cm, where the inlet and outlet are modelled as 25cm by 50cm patches. The inflow pattern modelled was taken from a previously measured velocity profile for the chamber, where we set the inflow velocity to achieve the required ACH.

As a result, we obtain a steady state airflow for different setups (**Figure 10**). Assuming that particles are held in aerosolised drops of liquid we can mimic the dispersal of bacteria or virus by using the steady state result. Particle dissemination is calculated by using Fluid Gravity Ltd's particle dissemination code to integrate the equations of motion for a particle moving through a gas, subject to drag and gravity. The simulations assume the limiting case of zero-radius particles, so the particles behave as passive tracers following the fluid flow. This is an appropriate assumption for the small aerosols used in the experimental study which largely move like a gas (Noakes et al 2009), however it is important to note that it may not be representative of larger respiratory aerosols that are more likely to deposit quickly.

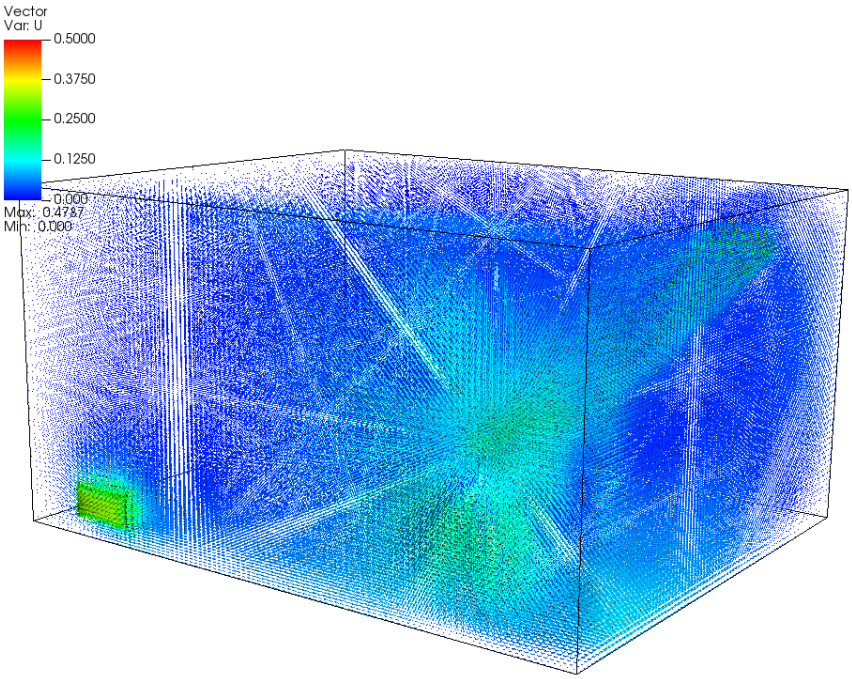

Figure 10: Airflow pattern of the chamber as produced by the CFD simulations

5.2 Far-UVC fluence rate

The three-dimensional fluence rates arising from the Far-UVC devices are computed throughout the room using a Monte Carlo radiation transfer (MCRT) code. To accurately model the pattern and fluence rate of the lamps the measured irradiance at heights of 1.7m and 1.0m from the ground are incorporated into the MCRT simulations which are scaled accordingly. Scattering and absorption are not considered within the room because the attenuation coefficient for Rayleigh scattering and absorption in air is of order 10^{-5} m^{-1} at 222nm and we assume a reflection coefficient of the chamber walls of 10% which is typical for common surfaces.

5.3 Pathogen Inactivation

To model the inactivation of any bacteria or viruses we combine the particle trajectories obtained with CFD and particle dissemination code with the Far-UVC illuminating patterns produced with the MCRT. One important assumption for this model to work is that the interaction between the Far-UVC and the pathogen is independent from the fluid dynamics.

As particles move within the flow field in the room they are exposed to a spatially varying fluence rate. We can describe the fluence rate as a function of position and time used then to compute the absorbed dose of each particle throughout its exposure to Far-UVC light in a one-time release. Assuming an exponential decay for the inactivation of the pathogen with a specific inactivation constant (k-value), we can then calculate the inactivation percentage of a given pathogen for any experimental setup. This follows the approaches used in previous studies modelling upper-room UV systems (Gilkeson and Noakes 2013). As mentioned previously, the measured results of the chamber experiment are from a continuous release of *S. aureus* that is regularly sampled every 5 minutes. The continuous release particles can be modelled using time-shifted copies of existing trajectories in the data set. For modelling *S. aureus* inactivation we use k-values of k = 3.6 cm^2mJ^{-1} and also adjust for the experimental sampling times recorded.

6 Computer Simulation Results

6.1 Model Validation

Figure 11 shows the simulations results (dashed lines) using a decay constant, k = 3.6 cm^2mJ^{-1} and experimental data for *S. aureus* (data points) plotted on a linear scale at ventilation rate of 3 ACH. Particles are continuously introduced into the chamber and the bacterial load builds up to a steady state. After two hours the lights are turned on and a new, lower steady state is attained.

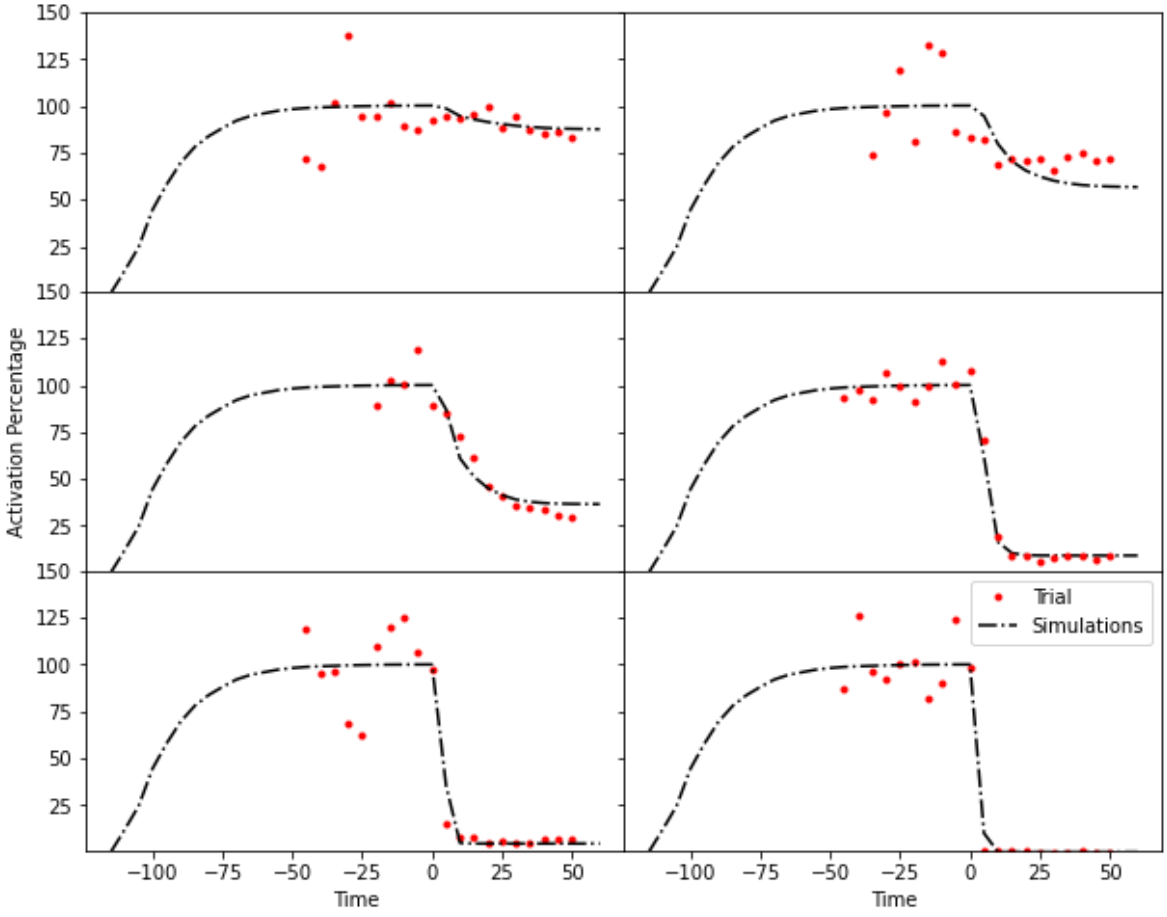

Figure 11: Simulations results compared to experimental results for 3 ACH. Left panels are for a single light and right panels for five lights, while the intensity settings of the lights are low (upper panels), medium (central panels), and high (lowest panels).

Results using k = 1.8 cm^2mJ^{-1} as estimated from the small-chamber experiments (assuming a single pass through a spatially uniform UVC radiation field) (REF) do not reproduce the measured level of bacterial inactivation within the larger bioaerosol chamber. However, a k value that is double (k = 3.6 cm^2mJ^{-1}) provides a better match between simulation and experimental result as can be seen in **Figure 11**. The increased k-values are required because the aerosolised particles take complex paths through the 3-Dimensional Far-UVC light pattern within the small and large chambers, meaning that simply assuming a single-pass through a spatially-uniform light pattern is not accurate. Previous studies of upper-room UV systems have also show that room scale inactivation constants differ from single-pass data (Beggs et al 2006).

Comparing the original experimental data with our simulations shows very good agreement between both data sets. We can observe the Far-UVC modelling can accurately account for the inactivation of *S. aureus* given different lighting patterns and intensities. Considering the costs and limitations of the experimental setup, this is an important validation of our models as it allows for the exploration of a much larger parameter space. More specifically we can explore what the ideal light setup is for a minimum inactivation of any pathogen in small aerosol given an appropriate inactivation rate constant, and therefore inform what the most cost-efficient solution is for wide implementation.

6.2 Different Pathogens

With the computer modelling validated, the simulation was repeated for human coronaviruses (HCOV) which have a higher k-value. Due to the higher sensitivity of human coronaviruses to Far-UVC (Eadie et al. 2022), the reduction in pathogen load in the room was predicted to be higher than with *S. aureus*, particularly at lower lamp intensities (**Table 7**).

Table 7: Modelled percentage reductions for different microorganisms and lamp configurations.

Lamp intensity	Number of lamps	Modelled S. aureus k = 3.6 cm^2mJ^{-1}	Modelled H. CoV k = 12.4 cm^2mJ^{-1}
Low	1	19.1%	34.4%
	5	56.6%	75.6%
Medium	1	74.3%	86.7%
	5	93.5%	96.6%
High	1	95.4%	99.1%
	5	99.8%	99.99%

6.3 Different ventilation rate

Like **Figure 11, Figure 12** shows the simulations (dashed lines) and experimental data for (data points) on a linear scale where left panels are for a single light and right panels for five lights at a high intensity setting. In this case each row shows the results for ventilation rates of 1.5 ACH, 3ACH, 6ACH and 9 ACH in descending order.

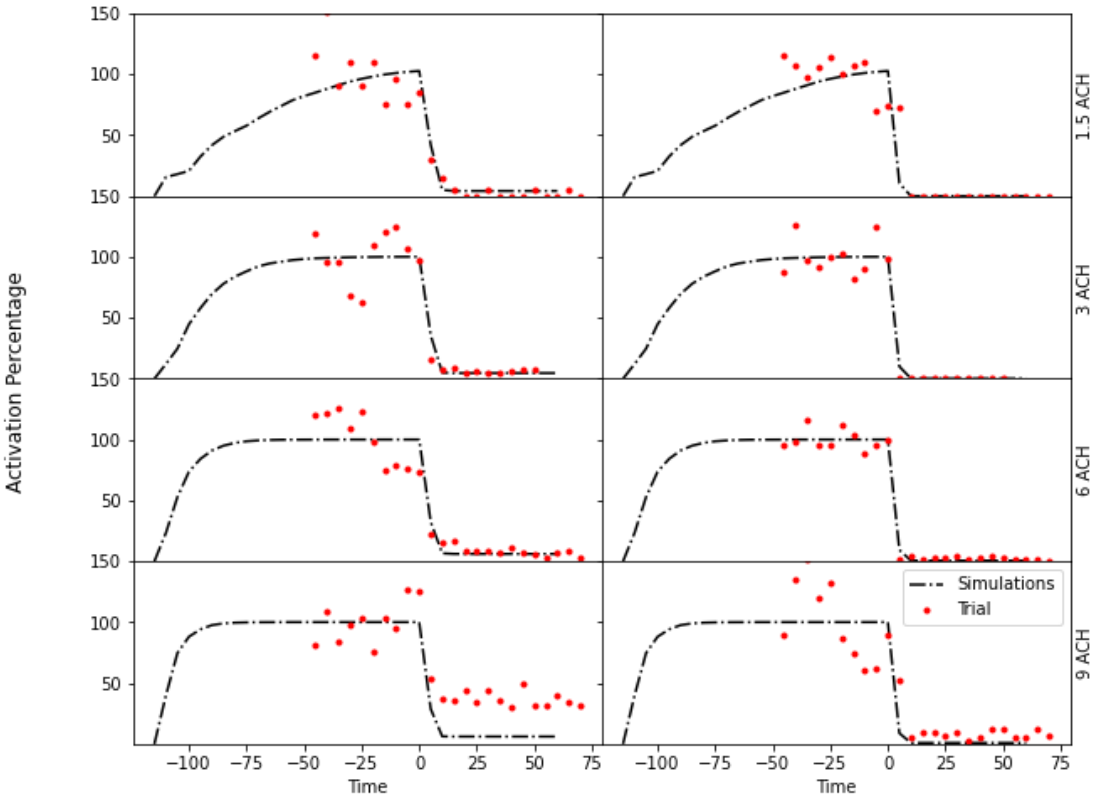

Figure 12: Model comparison with experimental data at different ACH.

6.4 Optimal Number of Lamps

Whilst the experimental work focussed on either one or five lamps, the computer modelling explored additional lamp numbers. **Figure 13** demonstrates diminishing returns, with incrementally less pathogen reduction as the number of lamps is increased. In the “Medium” scenario, equivalent to current UK exposure limits, four lamps has a percentage reduction that is within 2% of the reduction achieved by five lamps, I.e. approximately equal.

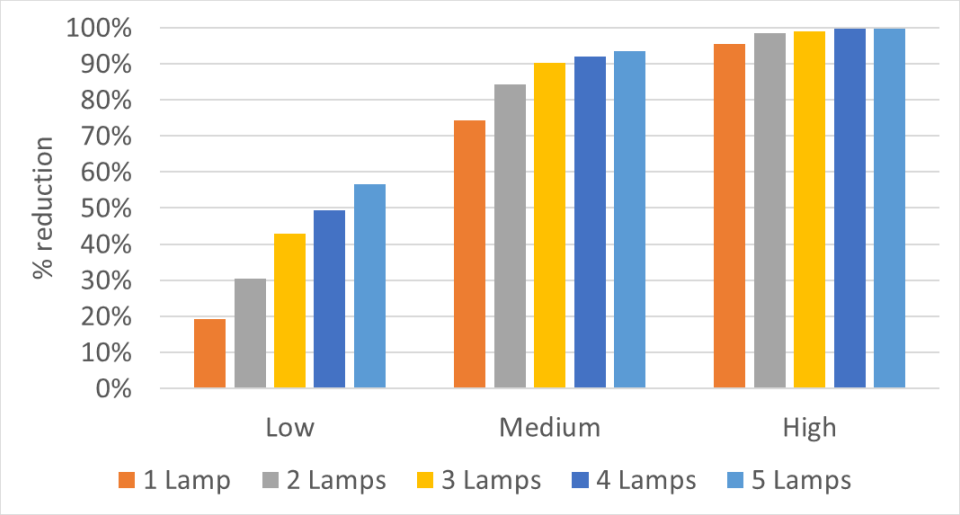

Figure 13: Percentage reduction in S. aureus, simulated by the computer modelling, for lamp numbers which were both tested (1 and 5 lamps) and not tested (2 and 4 lamps) experimentally. The modelling was performed with the Far-UVC lamp having diffused irradiation.

6.5 Lamps without a diffuser

Our previous research, modelling a classroom environment, indicated that if the Far-UVC lamps had diffusers, increased inactivation could be achieved with fewer lamps (Wood et al. 2021). In the environment of the bioaerosol chamber, there is an advantage in having diffusers on the lamps when there are fewer lamps or the lamps are of lower intensity (**Table 8**). The advantage of the diffusers decreases as the number of lamps and their intensity are increased.

Table 8: Simulated percentage reduction in S. aureus for Far-UVC lamps with, and without, diffusers. Room mechanical ventilation rate of 3 ACH.

	Low		Medium		High	
# Lamps	**Diffuser**	**No Diffuser**	**Diffuser**	**No Diffuser**	**Diffuser**	**No Diffuser**
1	19.1%	12.1%	74.3%	57.6%	95.4%	88.2%
2	30.5%	21.6%	84.3%	68.3%	98.5%	94.3%
3	42.9%	32.4%	90.2%	81.2%	99.0%	97.4%
4	49.4%	39.7%	92.1%	87.2%	99.6%	99.2%
5	56.6%	45.5%	93.5%	89.7%	99.8%	99.2%

6.6 Caveats and implementation

Results in **Figure 12** further validate the accuracy of our models showing a good correlation between simulations and experimental data at 1.5, 3 and 6 ACH. At 9 ACH our models are more efficient at the pathogen inactivation than the experimental results. It is worth noting that a comparative higher activation percentage at high ACH does not imply a higher pathogen load within the room. At higher ACH a lower overall pathogen load is to be expected, therefore the higher activation percentage indicates the relative efficiency of UVC sources at higher ACH.

Our approach to simulating the Far-UVC inactivation of *S. aureus* replicates the experimental results at relatively low ACH but overestimates the efficiency of Far-UVC at 9ACH. There are two possible explanations for the failure to accurately reproduce these results. First, our CFD models assume a steady-state airflow which is then used to describe the particle trajectories within the room. At higher ACH this might be too simplistic an approach leading to an inaccurate description of the particle trajectories and therefore its inactivation. Alternatively, the limitation might be in the simple approach to inactivation modelled as an exponential decay. Viruses and bacteria might require a more detailed inactivation function where the decay constant is dependent on exposure times; such a scenario would explain why our models overestimate the inactivation.

We have carried out several different simulations that accurately reproduce the experimental data measured. We find this provides a confident validation of our computer model and approach when used at ventilation rates equal to or lower than 6 ACH. Furthermore, this allows the exploration of a much larger parameter space beyond the technical limitations of an elaborate experimental setup.

7 Potential for Application of Far-UVC in Healthcare Settings

7.1 Equivalent Air Change Rates

Our experiments were all carried out under steady state conditions, whereby we compare the concentration of airborne microorganisms in the chamber with no Far-UVC with the concentration with the Far-UVC switched on, after allowing the room to reach steady state conditions. This is different to tests that many manufacturers use which measure the decay time with and without Far-UVC. A decay approach is more suited to when a device is used to remove contamination after an event (fallow time) and is commonly expressed as an equivalent ventilation rate, while the steady state methods in our study are used to replicate occupied spaces where the contamination of the environment can be considered to be continuous.

Although we have expressed results in terms of a % reduction under steady state conditions, this can be converted to an equivalent air change rate for the experimental set up.

Under steady state conditions with no Far-UVC and assuming the air in the chamber is well mixed, the concentration of microorganisms in air, C_{off} (cfu/m^3) is given by

$$C_{off} = \frac{q}{(N_v + N_d)V}$$

Here, q is the emission rate of microorganisms (cfu/hr), V is the volume of the room (m^3), N_v is the ventilation rate in air changes per hour (ACH), and N_d is the loss rate (1/hr) due to deposition and natural decay.

In the case where the Far-UVC is switched on, the new concentration, C_{uv} (cfu/m3) can be expressed as the combined effect of the room ventilation rate N_v plus an equivalent air change rate, N_{uv} (ACH)

$$C_{uv} = \frac{q}{(N_v + N_d + N_{uv})V}$$

In our experiments the fraction of microorganisms remaining when the Far-UVC is switched on is given by

$$\frac{C_{off}}{C_{uv}}$$

By substituting for C_{off} and C_{uv} in the above, assuming that deposition and natural decay remain the same regardless of the UV and ventilation rate, and rearranging, the equivalent ventilation rate due to the UV can be given by

$$N_{uv} = N\left(\frac{C_{off}}{C_{uv}} - 1\right)$$

Table 9 illustrates this theoretical relationship between reduction in air, the ventilation rate in the room and the calculated additional equivalent ventilation provided by the Far-UVC. Here we have indicated an approximate mapping to the experimental results in **Table 2**, where cells coloured yellow represent cases with a single lamp and cells coloured green represent cases with 5 lamps. At very low room ventilation rate (1.5 ACH), 100% reduction was seen in both cases; it is not possible to calculate an equivalent ventilation rate for this level of reduction so the orange cell indicates the calculated equivalent ventilation rate for a 99% reduction.

It should be noted that these air change rates relate to the experimental chamber which is a relatively small room. However, it can clearly be seen that very high equivalent ventilation rates are achievable with the Far-UV system. As a comparison, a typical HEPA based air cleaner with a Clean Air Delivery Rate between 150 and 300 m3/hr would deliver an equivalent additional ventilation rate of 4.7 to 9.4 ACH for the experimental chamber.

Table 9: Theoretical equivalent ventilation rate (ACH) for different room ventilation rates (ACH) and % reduction due to Far-UVC. Lamp irradiance “High” (see **Table 1**).

% Reduction	% Remaining	Nv	Nuv	Nv	Nuv	Nv	Nuv	Nv	Nuv
10	0.9	1.5	0.17	3	0.33	6	0.67	9	1.00
30	0.7	1.5	0.64	3	1.29	6	2.57	9	3.86
50	0.5	1.5	1.50	3	3.00	6	6.00	9	9.00
66	0.34	1.5	2.91	3	5.82	6	11.65	9	17.47
70	0.3	1.5	3.50	3	7.00	6	14.00	9	21.00
90	0.1	1.5	13.50	3	27.00	6	54.00	9	81.00
92	0.08	1.5	17.25	3	34.50	6	69.00	9	103.50
93	0.07	1.5	19.93	3	39.86	6	79.71	9	119.57
96	0.04	1.5	36.00	3	72.00	6	144.00	9	216.00
97	0.03	1.5	48.50	3	97.00	6	194.00	9	291.00
98	0.02	1.5	73.50	3	147.00	6	294.00	9	441.00
99	0.01	1.5	148.50	3	297.00	6	594.00	9	891.00

7.2 Electrical Power Requirements

The lamps used in the experimental and modelling studies have an electrical power consumption of 15 W. In the “Medium” scenario (see **Table 1**), which is roughly equivalent to current UK Far-UVC exposure limit legislation, an approximate **90% reduction in pathogen load could be achieved for an effective electrical power consumption of 2.3 W m^{-3} (5 lamps x 15 W / 32.25 m^3).** This is with a mechanical ventilation rate of 3 ACH, and as per **Table 7** would provide an equivalent additional ventilation rate of around 27 ACH.

The 2.3 W m^{-3} is somewhat of a worst-case scenario for several reasons:

First, in our experiments, in order to run the lamps continuously and comply with UK ultraviolet exposure limits, we had to attenuate the Far-UVC – effectively “wasting” useful UV. An alternative technique to remain within exposure limits is for the lamp to switch on and off on a duty cycle. In our experiments a duty cycle of 10% (1:9) would have been required to remain within UK exposure limits directly under a lamp. Duty cycling is the most common method utilised by Far-UVC suppliers and would result in an approximately **90% reduction in pathogen load for an average power consumption of approximately 0.23 W m^{-3}**. However this makes a few assumptions, one of the largest being that the same pathogen reduction would be achieved by duty cycle as is achieved by continuous operation. We have not investigated this experimentally as the duty cycle adds a further uncertainty into the experimental conditions, but our previous modelling based research (Wood et al. 2021) suggests it may not be the case and further investigation is required.

Secondly, we make the assumption that the exposure limit assumes a “worst-case” of an individual stood directly under the lamp for a full eight hours. However, this is not realistic and time-weighted studies have shown actual exposures to be between 20-50% of the “worst-case” scenario. Therefore, the lamp intensity could be increased whilst still complying with current exposure legislation, which will not improve the power consumption but would improve the pathogen reduction.

Thirdly the computer modelling suggests fewer lamps could achieve above 90% pathogen reduction depending on the setup used. For example, results in **Error! Reference source not found. Figure 13** show that four lamps in the “Medium” scenario provide inactivation within 2% of the five lamps. This would result in an

approximate **90% reduction in pathogen load being achieved for an effective electrical power consumption of 1.9 W m^{-3} (4 lamps x 15 W / 32.25 m^3).**

As a comparison, to achieve the same additional ventilation rate of 27 ACH using HEPA filter type units, it would be necessary to provide a total Clean Air Delivery rate of 864 m^3/hr. Power consumption for a Philips AC3033 operating at 290 m^3/hr is around 16W; three of these units (total 870 m^3/hr) would be needed to achieve a 90% reduction which would result in an electrical power load of 1.5 W per m^3 of room volume. Therefore, the energy efficiency of Far-UVC is currently comparable to a good quality HEPA device. However, the number of HEPA devices to room volume ratio that would be needed is likely to be impractical in reality due to space and noise implications.

Finally, current Far-UVC lamp technology is currently very inefficient at converting electrical power to Far-UVC, approximately 0.6% (or 0.04% if the Far-UVC is attenuated to remain within UK exposure limits). With new technology (for example LEDs), or an improvement in existing lamp efficiency, the same pathogen inactivation could be achieved for lower electrical power consumption. A typical electrical-to-optical efficiency target is 30%.

7.3 Optical Power Requirements

Each lamp emits approximately **100 mW** of Far-UVC. Fitting a logarithmic curve (y = 11.547ln(x) + 70.827, where y is percent reduction and x is power per unit volume) to the results from this chamber a 90% reduction in *S. aureus* can be achieved by **5.3 mW of Far-UVC per m^3 of room volume** (Sense check: 5.3 mW optical power at 0.04% electrical-to-optical efficiency is 13.3 W electrical power, approximately 15 W). If the computer modelling is accurate and four lamps would be roughly equivalent to five lamps then a 90% reduction in pathogen could be achieved by **4.6 mW of Far-UVC per m^3 of room volume** (% reduction = 11.897ln (power per unit volume) + 71.815)**.**

Room volume may not be the best metric to use when planning deployment. It may be more appropriate to base the deployment on the room area, as long as the peak irradiance is maintained at the UK exposure limit. In such a scenario **11.9 mW of Far-UVC per m^2 of room area (5 lamps, y = 11.547ln(z) + 61.412) or 10.4 mW (4 lamps y = 11.897ln(z) + 62.114),** where z is the power per unit area**.**

7.4 Real-world Hospital Room Examples

Using the analysis from the previous sections, **Table 10** shows calculations of hypothetical number of Far-UVC lamps with diffuser required in real hospital rooms to achieve a minimum of 90% *S. aureus* reduction. In small to medium sized rooms, 1 – 2 lamps with diffuser are required and there is no difference between calculations based on 4 (simulation) or 5 (experimental) lamps. In larger rooms the number of lamps required is less clear and would benefit from computer modelling.

Table 10: Estimated number of Far-UVC lamps required in a number of healthcare scenarios based on data from rooms at Ninewells Hospital, Dundee

	Two-person office (P8 013, Level 8, Photobiology Unit, Ninewells Hospital, Dundee).	**Outpatient consulting room (Consulting 3, Dermatology Dept. Ninewells Hospital Dundee)**	**Seminar Room (Dermatology Dept. Ninewells Hospital, Dundee)**
Length (m)	3.0	4.3	12.3
Width (m)	3.2	3.7	6.2
Area (m2)	9.6	15.9	76.3
Height (m)	2.5	2.5	2.5
Volume (m3)	24	39.8	190.7
(experiment) # of lamps (Power consumption) Area based calculation Volume based calculation (# lamps)	9.6 m^2 x 11.9 mWm^{-2} = 114.2 mW = **2 lamps (30 W)** 24 m^3 x 5.3 mWm^{-3} = 127.2 mW = **2 lamps (30 W)**	189 mW = **2 lamps (30 W)** 211 mW = **3 lamps (45 W)**	908 mW = **10 lamps (150W)** 1011 mW = **11 lamps (165W)**
(simulation) # of lamps (Power consumption) Area based calculation Volume based calculation	9.6 m2 x 10.4 mWm-2 = 99.8 mW = **1 lamp (15 W)** 24 m^3 x 4.6 mWm^{-3} = 110.4 mW = 2 **lamps (30 W)**	165 mW = **2 lamps (30 W)** 183 mW = **2 lamps (30 W)**	794 mW = 8 **lamps (120 W)** 877 mW = 9 **lamps (135 W)**

8 Conclusions

Overall, our study concludes that Far-UVC has substantial potential to reduce the concentration of microorganisms in the air and that it is also likely to bring benefits in reducing contamination of surfaces. It is likely to be an energy efficient and safe way of enhancing airborne infection control which can provide higher equivalent ventilation rates than alternative approaches. Our findings are based primarily on experiments and models from controlled settings which do not fully consider all of the factors present in a real-world setting. However we suggest that Far-UVC is a promising technology which merits further exploration. We have detailed specific conclusions, implications and recommendations for further research below.

8.1 Experimental study

The experimental study shows that Far-UVC effectively reduces the airborne pathogen load in a room under controlled conditions. We have tested devices against two microorganisms, *Staphylococcus aureus*, and *Pseudomonas aeruginosa*, and the results demonstrate both are inactivated suggesting that Far-UVC is very likely to inactivate pathogens that are relevant to healthcare settings. Lab scale studies carried out by other groups internationally suggest that Far-UVC is also effective against a range of viruses.

The results from our preliminary work that demonstrated inactivation at one ventilation rate (Eadie et al. 2022) have been shown in this study to be robust to changes in ventilation regime, ventilation rate and sample location. As expected Far-UVC is more effective when more lamps are used and hence there is a higher quantity of UV in the room. We also see in both experiments and computational modelling that having lamps distributed across the room leads to results that have less variability than having a single UVC lamp in the room. Experimental results show that the difference with ventilation regime and sample location are small, and it is likely that the differences we see are driven by variations in experiments more than the influence of the set-up. As expected the relative performance of the Far-UVC is better at a lower ventilation rate, and we also see less variation in the results.

Initial experiments to explore the ability of a Far-UV device to inactive microorganisms at closer proximity to a source show promise, with a reduced but still substantial reduction in concentration seen at the closer source-sampling distance

set up. However, experiments to measure the influence of distance are challenging to set-up and we were only able to conduct a small number of tests during the timescale for this study.

8.2 Computational modelling and analysis.

Computational models results show excellent agreement with the experimental results suggesting that the model is able to effectively capture the UVC field distribution, airflow paths and inactivation of pathogens. Results suggest that the optimum number of lamps per unit volume could be lower than used in experiments, with modelling suggesting that 4 lamps may have produced results very similar to the 5 lamps used within the chamber study. This would need to be explored with further experiments.

A simple theoretical analysis of inactivation performance at different ventilation rates concurs with both experiments and computational model findings and illustrates the relative benefit of the Far-UVC devices is greatest in poorly ventilated rooms; this is the case for all additional air cleaning technologies.

The overall aim of adding Far-UVC to a room would be to optimise inactivation of pathogen for the lowest possible electrical power input. Our results provide guidance with current lamp wall plug efficiency, which is only about 1%, i.e. a 15 W lamp produces about 0.1 W of Far-UVC. In the chamber scenario used in our study, we calculate that a 90% reduction in microbial concentration could be achieved with around 1.9 W/m^3 of electrical power. To achieve the equivalent benefits with HEPA filter based devices would require a similar power input (around 1.5 W/m^3) but would be challenging due to space and noise constraints.

8.3 Implications and Future Research

8.3.1 Health Effects

We have not measured health effects in this study, however our other ongoing work and international evidence has not identified any acute effects, such as erythema (redness), on human skin with filtered KrCl lamps - even at very large exposures above guideline limits. Typical deployment of the technology in an office environment has also demonstrated no eye discomfort in humans [Kousha et al. In preparation], although (anecdotally) deliberate close proximity direct viewing of these

sources does cause immediate irritation (personal communication). Data on animal eyes has shown limited penetration without permanent damage at exposures within guideline exposure limits. Evidence from cell and animal studies suggests that long term Far-UVC exposure is unlikely to cause non-melanoma skin cancer. Whilst the physics of limited penetration depth from Far-UVC indicates other long-term risks are low, research is needed to rule out the induction of melanoma skin cancer or long-term immune-mediated adverse effects.

8.3.2 Potential Application in Healthcare Settings

We have not directly considered usability and acceptability in this study, but both are important factors for a real-world deployment. Our experience across ongoing studies and through interaction with others in the UK and internationally working on Far-UVC and other air cleaning technologies suggests that the following are important to consider in the next stage of an evaluation:

- Communication/consultation with staff and patients. Far-UVC (as with other open-field UV technologies) when used in occupied rooms results in some exposure to the UV light for people. While any application would have to comply with exposure limits, it is also important that work is carried out to gauge understanding of Far-UVC for those exposure and to evaluate any concerns or views around the potential benefits. Some people may be concerned about “radiation” while others could see the technology as providing a “safe” environment and hence other protocols do not need to be followed. Evidence for both of these aspects is currently very limited.
- Evaluation of product design and robustness. Lamps used in our studies were modified for the experimental scenarios including adding in diffusers to reduce the UVC output and to change the operational setting from an on/off cycle to a constant output; this was essential to be able to measure reliably in an experimental set up. We have not carried out any formal assessment of product quality, but have already seen a small number of lamp failures – it would be important to understand the reliability of these devices from manufacturers. As a relatively new technology it is expected that product quality and reliability will improve as lamp technology develops further. There

are a wide range of different lamps on the market and we have not carried out any assessment of which are most suitable for healthcare application.

- Consideration of which spaces would be most suitable for installation. Although Far-UVC is considerably safer than other wavelengths of UV light, the technology does result in exposure for people. It would therefore be important to consider who would be exposed for how long, and whether there are any groups who could be more vulnerable/concerned by the use of Far-UVC. Exposure limits are based on occupational settings and assume an 8 hour exposure over a 24 hour period. In settings where people could be exposed for longer periods of time, it may be necessary to reduce the Far-UVC irradiance, which may result in a system that is less effective. As there is very limited data on application we would suggest that in the first instance it may not be appropriate to implement Far-UVC in settings where the same person is exposed continuously for 24 hours or more. It is likely that spaces such as toilets, bathrooms, waiting rooms and some treatment rooms may be the most appropriate places to set up trial deployments of Far-UVC. These spaces tend to have intermittent occupancy and may be more appropriate for studies to understand real-world application and acceptability.

8.3.3 Future Research

Our study has shown that Far-UVC has a great deal of potential, however our experiments and computational models are of well-defined and very controlled scenarios without the complexity of fixtures, furnishings or people. Alongside trial deployments highlighted above, there remain a number of research questions which would further inform efficacy and application:

- We have considered three microorganisms in the timescale of this study, two bacteria and a bacteriophage. In a previous study we have some very preliminary data from work with influenza, however it is challenging to work with viruses in chamber studies. It would be important to test against a wider range of microorganisms including fungi.
- Our experiments were all carried out at normal-warm room temperatures and normal humidity. Within the timescale of the study were not able to explore the influence of these parameters, but further research is needed, particularly

as evidence from 254nm UVC work suggests that performance may be lower in higher humidity environments.

- We have focused on the impact of Far-UVC on microorganisms in air, and alongside the air samples we have measured the impact on deposition onto surfaces. However we have not looked at the impact of Far-UVC on surface contamination over time and in environments where contamination can happen due to hand contacts as well as deposition. That Far-UVC is a technology which exposes the whole room to UVC light, means that it has the potential to more widely contribute to surface hygiene. It is not considered as a decontamination technology in this study, however it would be beneficial to understand the routine impacts on surface bioburden.
- Our experiments are carried out using aerosolisation of the microorganisms in distilled water using a colison nebuliser. This is a very common approach for aerosol studies as it is a reliable method that generates a consistent aerosol with a narrow size range. However, this does not fully represent the aerosol size range or composition of human respiratory aerosols. Experiments using realistic human aerosol generation are more complex – we hope to explore this, and the effects of distance from the source further in our future work.
- Some air cleaning technologies have been associated with the generation of chemical byproducts including ozone. 222nm and the lamps used in our study are not known to produce ozone or other byproducts, but we have not measured any impacts of the Far-UVC on indoor air chemistry. International evidence suggests that this risk is very low, however it would be advantageous for further research to evaluate this possibility.

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