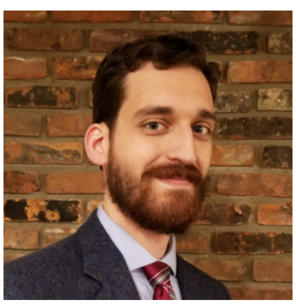
Solid-State Ultraviolet Irradiation for Continuous Disinfection of Occupied Spaces

365nm UV-A irradiation has been proven to provide significant reduction of bacterial and fungal pathogens on surfaces by radiating directly into occupied spaces at irradiances and durations that are below the Threshold Limit Values (TLVs) set by the IEC and ACGIH for human exposure. Lighting devices incorporating this germicidal emission alongside white light for general illumination were found to significantly reduce bioburden on in-use surfaces in hospital rooms and on medical equipment. Inactivation of pathogens by UV-A is achieved by the excitation of endogenous chromophores and the subsequent creation of superoxide radicals which results in cellular oxidative damage. This indirect mechanism of inactivation is however not practical for most viral pathogens, with higher-energy UV-C being required to induce direct DNA or RNA damage. The present availability of low-power UV-C LEDs as an alternative to high-power discharge UV-C sources enables applications with direct radiation into occupied spaces at doses that are below TLVs for actinic irradiation. Recent findings suggest that UV-C irradiation at these conditions is useful for the reduction of aerosolized pathogens, including SARS-CoV-2, the virus that causes the COVID-19 disease.



Kevin Benner

Kevin Benner (BSME, The Ohio State University) is a graduate of GE's Edison Engineering Development Program and has worked for over 10 years in the development of new lighting technologies. He is the Lead Research Engineer for GE Current, a Daintree Company's 365DisInFx™ ultraviolet disinfection technologies and has co-authored multiple peer-reviewed articles concerning the germicidal efficacy and application of UV light for occupied space disinfection. He also holds several US patents concerning disinfection, spectral tuning, and lighting design.

Solid-State Ultraviolet Irradiation for Continuous Disinfection of Occupied Spaces

Kevin Benner

GE Current, a Daintree company

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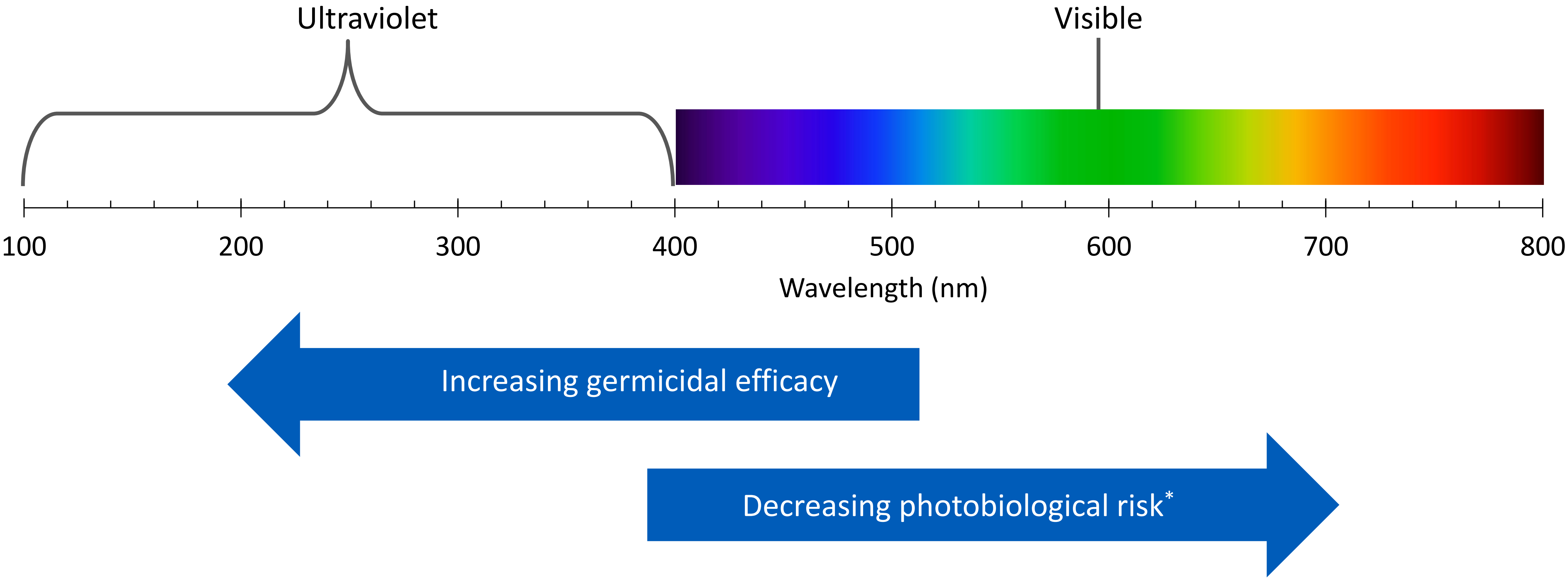
Germicidal irradiation for occupied spaces: wavelength selection



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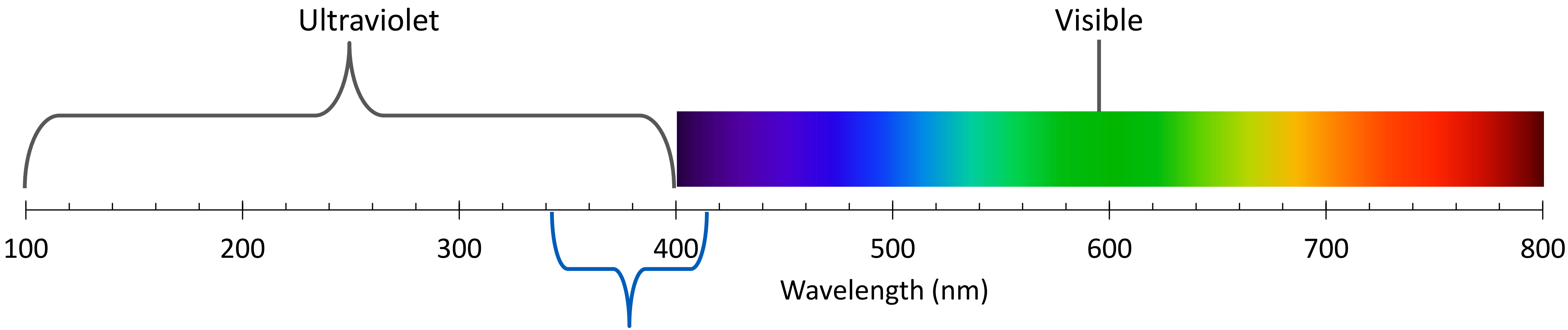
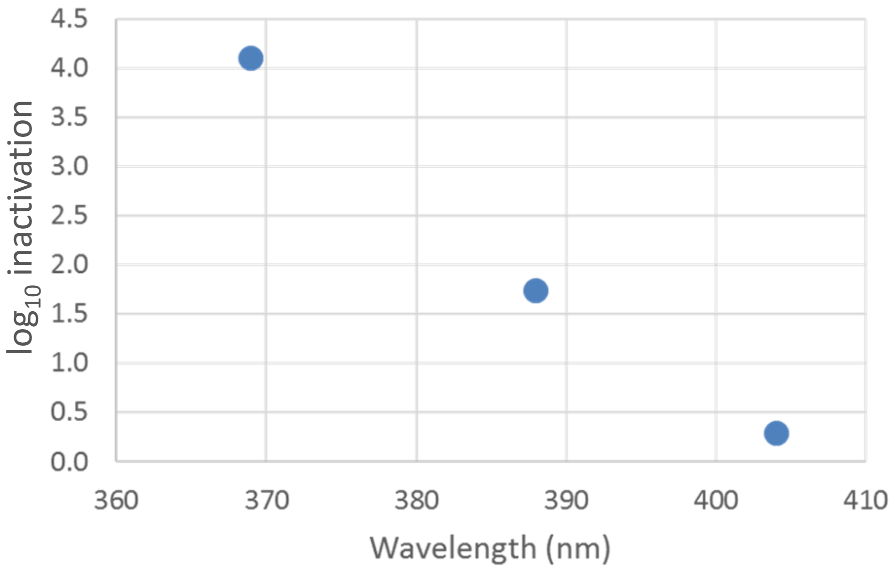
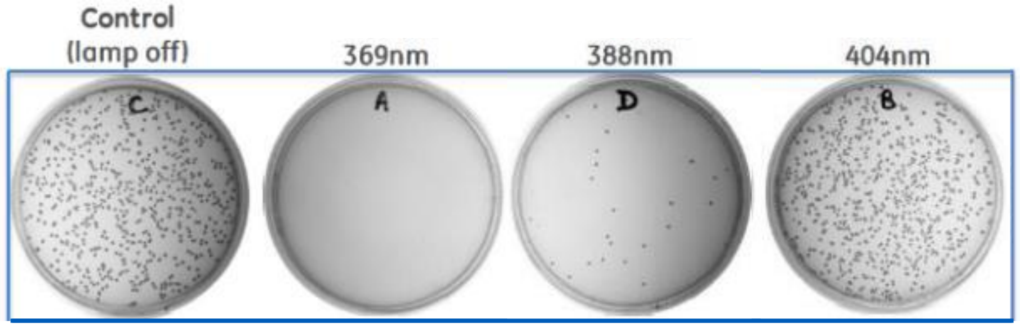
*Based on spectral weighting function for assessing ultraviolet hazards for skin and eye as defined in IEC 62471.
CEI/IEC. 62471:2006 Photobiological safety of lamps and lamp systems. 2006:1-90

Germicidal irradiation for occupied spaces: UVA/Violet



Practical LED wavelengths in UVA/Violet range →





S. aureus inactivation in clean suspension
32 W/m² irradiance, 4-hour exposure
GE Global Research, 2015

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365nm UVA germicidal irradiation for occupied spaces

365nm UVA:

- ✓ Practical LED packages available
- ✓ Lower photobiological risk weighting than lower wavelengths*
- ✓ Higher germicidal efficacy weighting than higher wavelengths†

*Based on spectral weighting function for assessing ultraviolet hazards for skin and eye as defined in IEC 62471.
CEI/IEC. 62471:2006 Photobiological safety of lamps and lamp systems. 2006:1-90
†Based on test data shown previously

UVA vs UVC for inactivation of bacteria on surfaces (using *S. aureus* as example)

D90: dose needed for 1-$\log_{10}$ (90%) reduction

	UVA	UVC	
Wavelength (nm)	365	254	
S. aureus D90 on surface (J/m²)	34,400*	38†	900X
ACGIH TLVs®‡ or IEC 62471 EL§ (J/m²)	270,000	60	4,500X
EL/D90	7.8	1.6	

$\log_{10}$-reduction of pathogen at IEC 62471 exposure limit

UVA is ~5X advantaged vs UVC for surface inactivation of *S. aureus* at exposures below ACGIH TLVs® and IEC 62471 exposure limit

*Kvam E, Benner K. Mechanistic insights into UV-A mediated bacterial disinfection via endogenous photosensitizers. *Journal of Photochemistry and Photobiology B: Biology*. 2020;209:111899. doi:10.1016/j.jphotobiol.2020.111899.
†Kowalski W. Ultraviolet Germicidal Irradiation Handbook. 2009:474.
‡ACGIH. 2020 TLVs and BEIs. 2020:155-160
§CEI/IEC. 62471:2006 Photobiological safety of lamps and lamp systems. 2006:1-90

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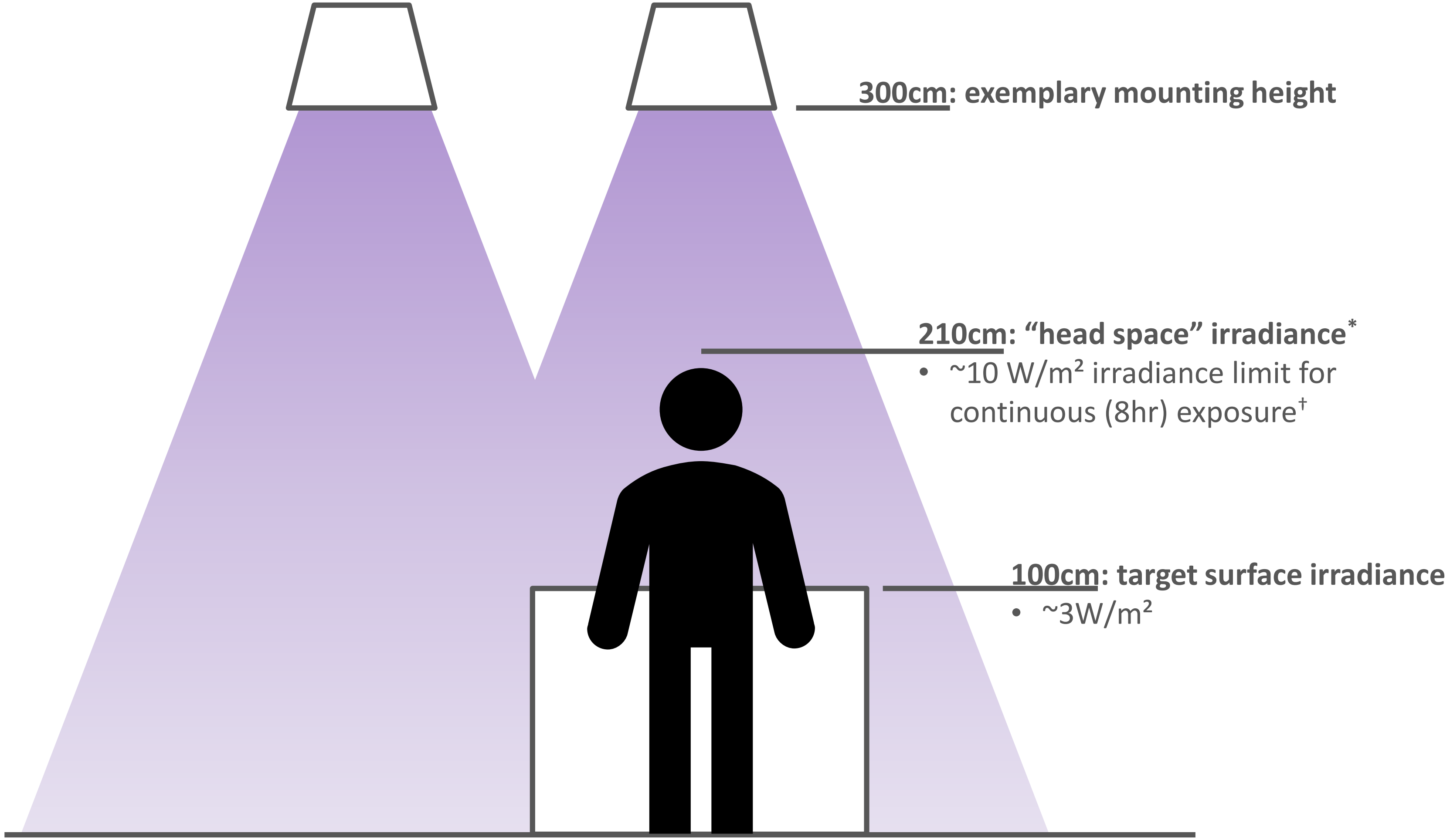
Geometry and application considerations for UVA whole room irradiation below IEC 62471 exposure limit



Exemplary real-world application: 3 W/m² UVA irradiance, 8-hours per day

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*Standard for Luminaires, UL1598

†CEI/IEC. 62471:2006 Photobiological safety of lamps and lamp systems. 2006:1-90

In-situ studies

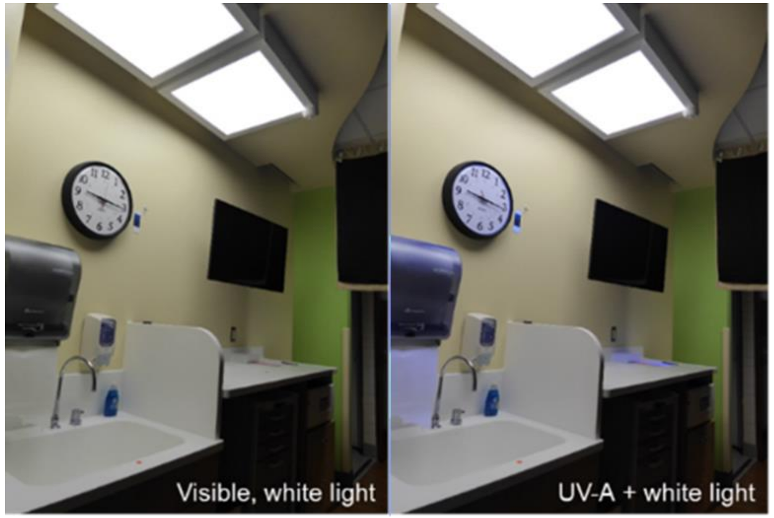
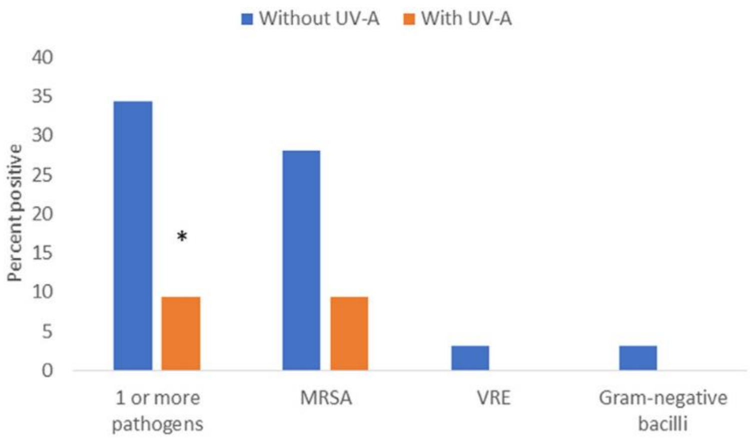
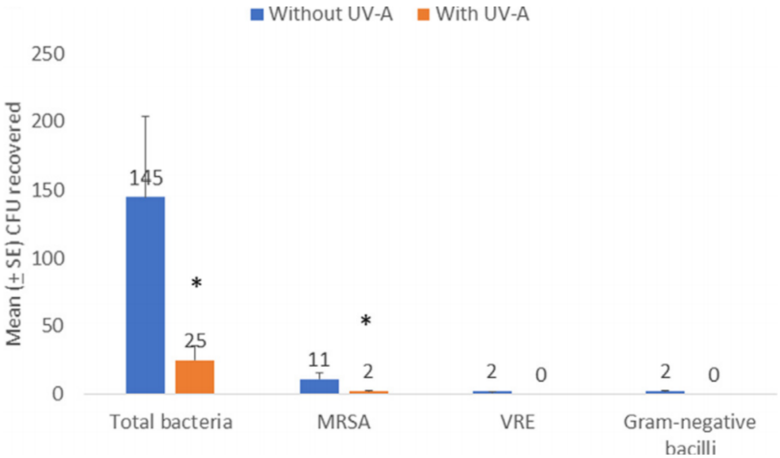


Photo credit: Lighting Research Center at Rensselaer Polytechnic Institute, Troy, NY





Daily 8-hour UVA exposure of countertops in NICU unit†

- statistically significant reductions in bioburden (measured by ATP counts) following the UV-A exposures
- stopping the UV-A treatment led to a significant increase in ATP counts

4-hour exposure of in-use portable medical equipment from medical wards ‡

- significant reduction in the frequency of recovery of 1 or more pathogens from the equipment
- total aerobic bacteria recovered from the equipment on nonselective plates and of MRSA were significantly reduced after UV-A exposure

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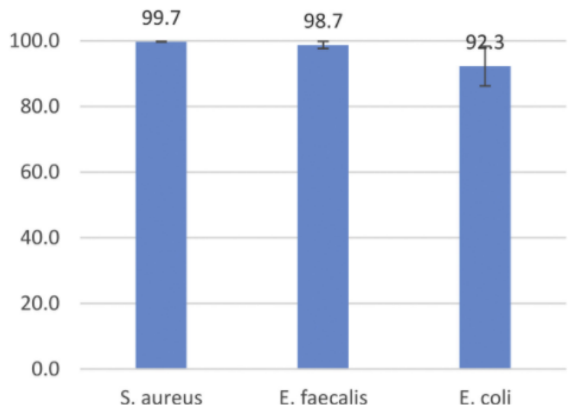
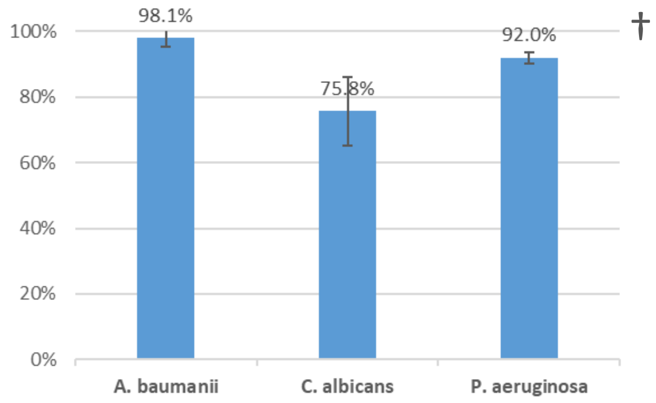
†Brons J, Bierman A, White R, Benner K, Deng L, Rea M. An assessment of a hybrid lighting system that employs ultraviolet-A for mitigating healthcare-associated infections in a newborn intensive care unit. Light. Res. Technol 2020;52:704–721 https://doi.org/10.1177%2F1477153520904107
‡ Livingston SH, Cadnum JL, Benner KJ, Donskey CJ. Efficacy of an ultraviolet-A lighting system for continuous decontamination of health care-associated pathogens on surfaces. Am. J. Infect. Control 2020;48: 337-339. https://doi.org/10.1016/j.ajic.2019.08.003

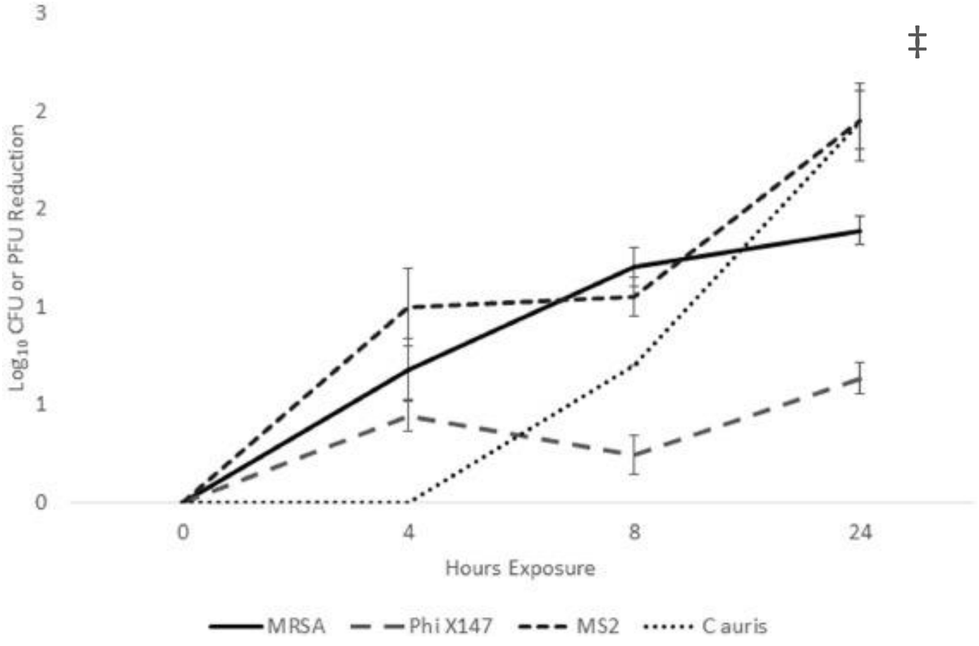
In-vitro studies

% inactivation of dried specimens by 86,000 J/m² UVA





Efficacy of ultraviolet-A light at 3 W/m² in reducing pathogens inoculated on steel disk carriers



*Kvam E, Benner K. Mechanistic insights into UV-A mediated bacterial disinfection via endogenous photosensitizers. *Journal of Photochemistry and Photobiology B: Biology*. 2020;209:111899. doi:10.1016/j.jphotobiol.2020.111899.
†Kvam E, Benner K. 2017GRC0545 Disinfection via LED Lighting: summary of mechanism and results for 365nm-mediated inactivation of microbes. GE Global Research Technical Information Series 2017
‡ Livingston SH, Cadnum JL, Benner KJ, Donskey CJ. Efficacy of an ultraviolet-A lighting system for continuous decontamination of health care-associated pathogens on surfaces. Am. J. Infect. Control 2020;48: 337-339. https://doi.org/10.1016/j.ajic.2019.08.003

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UVA in-vitro studies at doses below IEC 62471 exposure limit, summary by taxonomy

Target organism taxonomy	Qualitative effectiveness	Quantitative effectiveness (log_{10} reduction by 86,000 J/m² UVA on surfaces)
Gram-negative bacteria	✓	1.1-1.7[*,†]
Gram-positive bacteria	✓	1.7-2.6[*]
Fungi	✓	0.6-0.7[†,‡]
Non-enveloped viruses	✓	1.0[‡]
Enveloped viruses	✗	0.3[‡]

*Kvam E, Benner K. Mechanistic insights into UV-A mediated bacterial disinfection via endogenous photosensitizers. *Journal of Photochemistry and Photobiology B: Biology*. 2020;209:111899. doi:10.1016/j.jphotobiol.2020.111899.

†Kvam E, Benner K. 2017GRC0545 Disinfection via LED Lighting: summary of mechanism and results for 365nm-mediated inactivation of microbes. GE Global Research Technical Information Series 2017

‡ Livingston SH, Cadnum JL, Benner KJ, Donskey CJ. Efficacy of an ultraviolet-A lighting system for continuous decontamination of health care-associated pathogens on surfaces. Am. J. Infect. Control 2020;48: 337-339. https://doi.org/10.1016/j.ajic.2019.08.003

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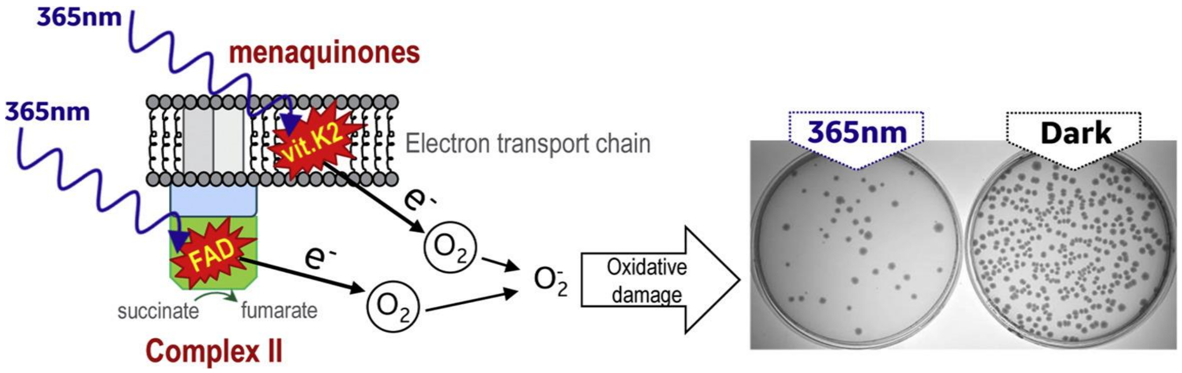
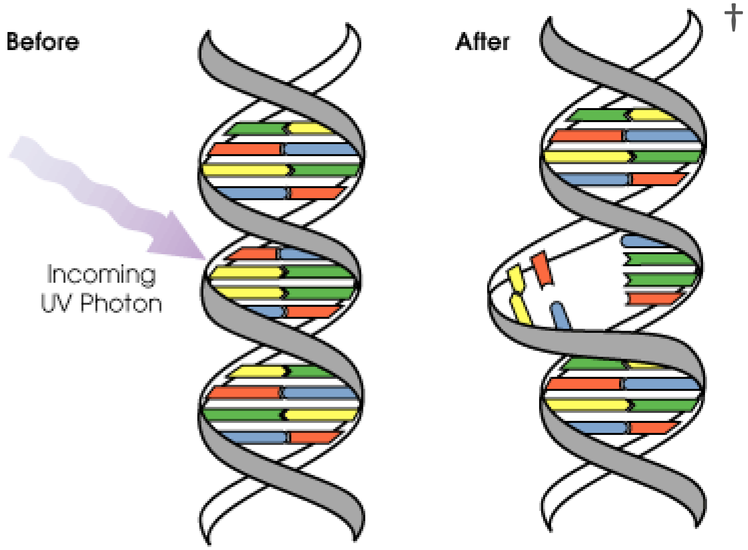
Mechanism of inactivation (365nm)



Excitation of endogenous chromophores in the electron transport chain leads to the formation of superoxide radicals causing loss of respiration and oxidative damage leading to cell death (study in *E. coli*).*

Mechanism of inactivation (254nm)



UVC can inactivate microorganisms by causing the formation of molecular lesions such as pyrimidine dimers when the UVC photons are absorbed by nucleic acids (RNA or DNA) in a microorganism.‡

*Kvam E, Benner K. Mechanistic insights into UV-A mediated bacterial disinfection via endogenous photosensitizers. *Journal of Photochemistry and Photobiology B: Biology*. 2020;209:111899. doi:10.1016/j.jphotobiol.2020.111899.
†Image credit: NASA/David Herring
‡ Chun-Chieh T, Chih-Shan L. Inactivation of Viruses on Surfaces by Ultraviolet Germicidal Irradiation, *Journal of Occupational and Environmental Hygiene*. 2007; 4:6, 400-405, doi:10.1080/15459620701329012

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UVC germicidal irradiation for occupied spaces

- Direct inactivation mechanism of UVC is needed to inactivate most viruses, compared to indirect mechanism of UVA for bacteria and fungi
- Can UVC be useful for reduction of pathogens, particularly viruses, at doses below the IEC 62471 exposure limit?

UVC germicidal irradiation for occupied spaces

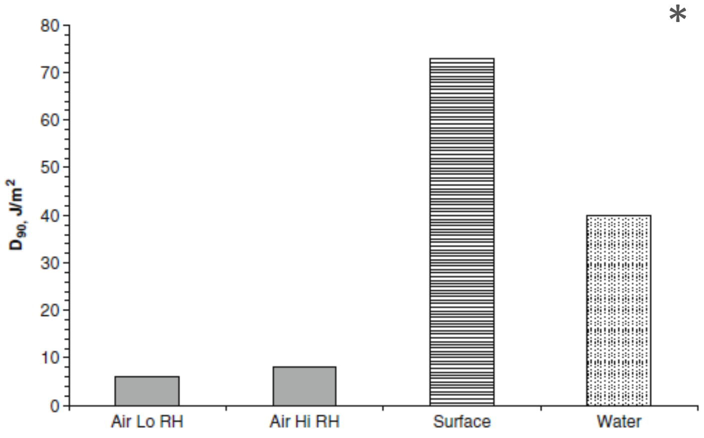

Fig. 4.3 Comparison of overall averages for virus D_{90} values in various media

	Air	Surface	Water
Wavelength (nm)	254	254	254
Approximate average virus D90 (J/m²)*	7	70	40
ACGIH TLVs®† or IEC 62471 EL‡ (J/m²)	60	60	60
EL/D90	8.6	0.9	1.5

log_{10}-reduction of pathogen at IEC 62471 exposure limit

- At 254nm, several-log_{10} inactivation is possible for viruses in air at exposures below ACGIH TLVs® and IEC 62471 exposure limit
- Virus inactivation on surfaces is much less than in air at the same doses

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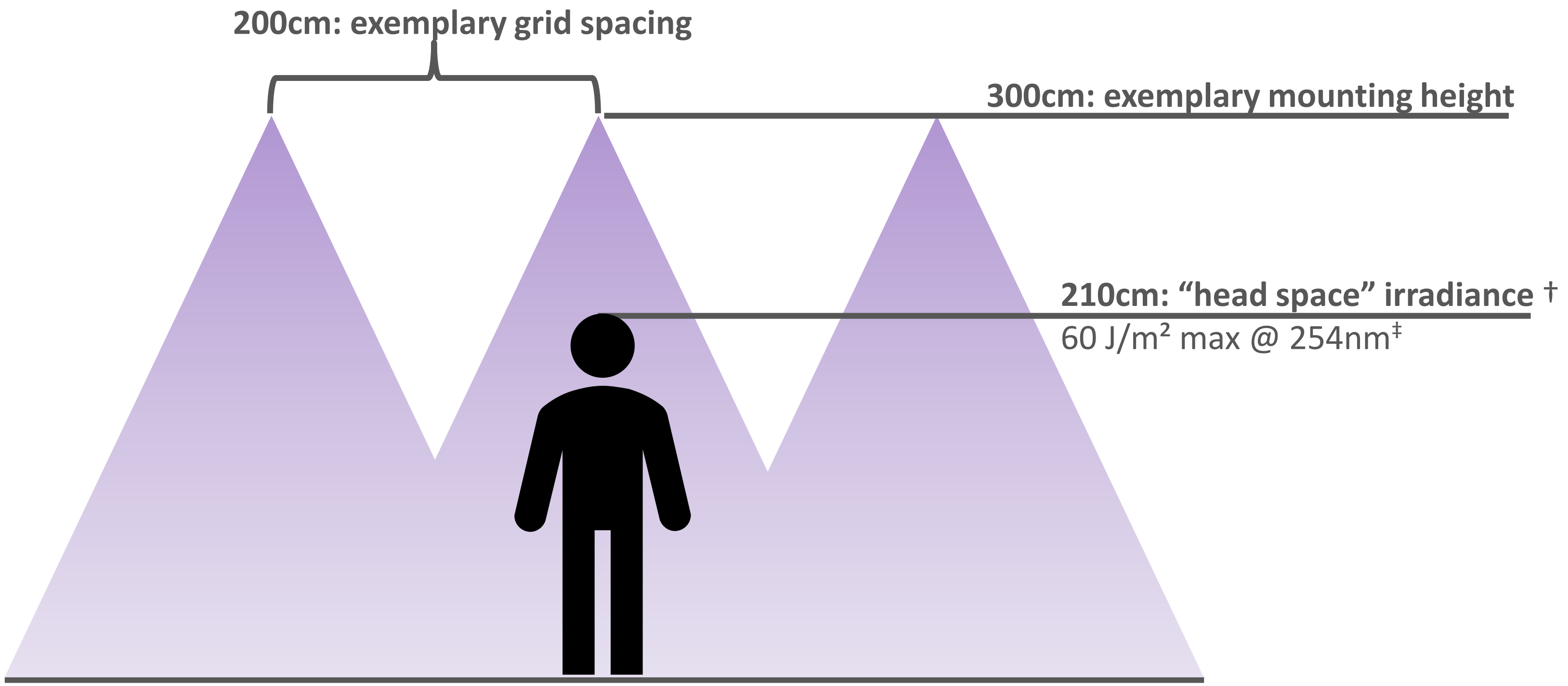
*Kowalski W. Ultraviolet Germicidal Irradiation Handbook. 2009:82.
†ACGIH. 2020 TLVs and BEIs. 2020:155-160
‡CEI/IEC. 62471:2006 Photobiological safety of lamps and lamp systems. 2006:1-90

Application and geometry for UVC whole room irradiation below IEC 62471 exposure limit

- Max dose at 2.1m (80° cone) determines exposure limit compliance
- Average dose (average for whole room) determines effectiveness



- 0.9 AVG:MAX ratio is achievable
- ~54 J/m^2 = ~8-log_{10} inactivation of aerosolized viruses without exceeding EL in occupied space
- ~1-log_{10} inactivation of "average virus*" in 1 hour if dose is applied over 8 hours

*Virus with D90 of 7 J/m^2 in air, per Figure 4.3 of Kowalksi 2009
Kowalski W. Ultraviolet Germicidal Irradiation Handbook. 2009:82.
†Standard for Luminaires, UL1598
‡ CEI/IEC. 62471:2006 Photobiological safety of lamps and lamp systems. 2006:1-90

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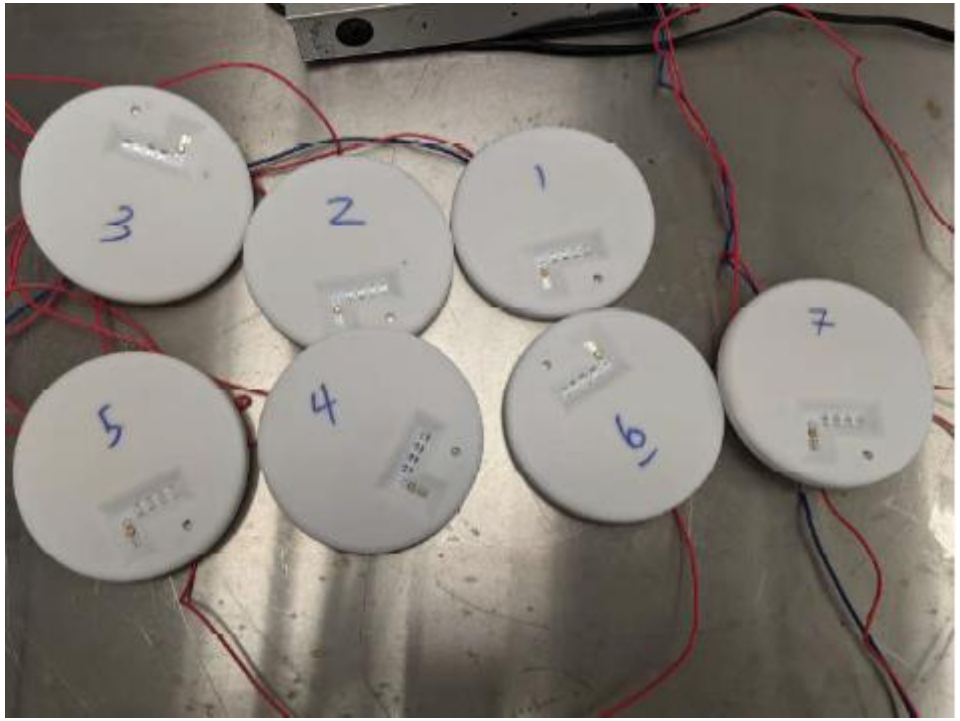
Prototype device and surrogate test

- UVC LED whole-room irradiation devices with peak wavelength 258nm
- Room-scale BSL1 test chamber
  (10ft W x 10ft D X 8ft H)
- Aerosolized surrogate virus (bacteriophage MS2*)



Prototype devices
(Single UVC LED with Wp ~258nm)
~1.7mW radiated per device (enabled by LED)

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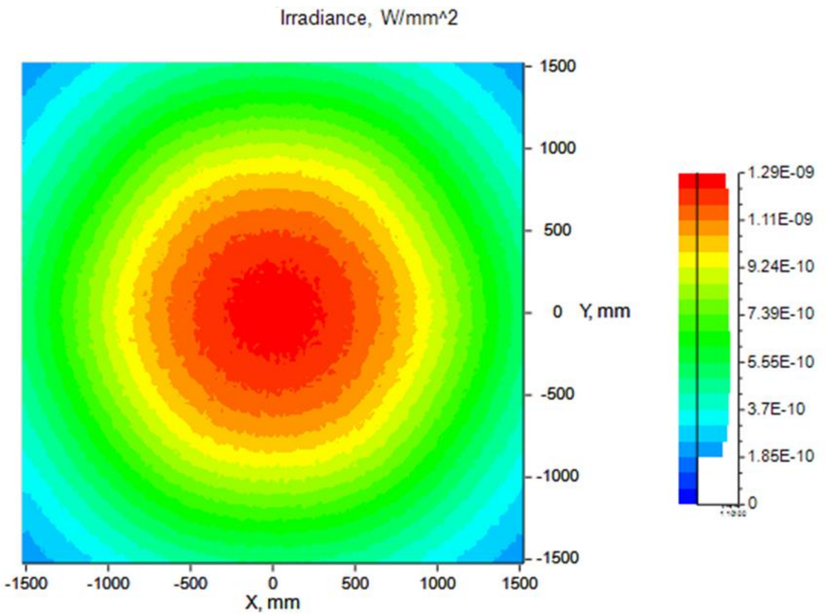
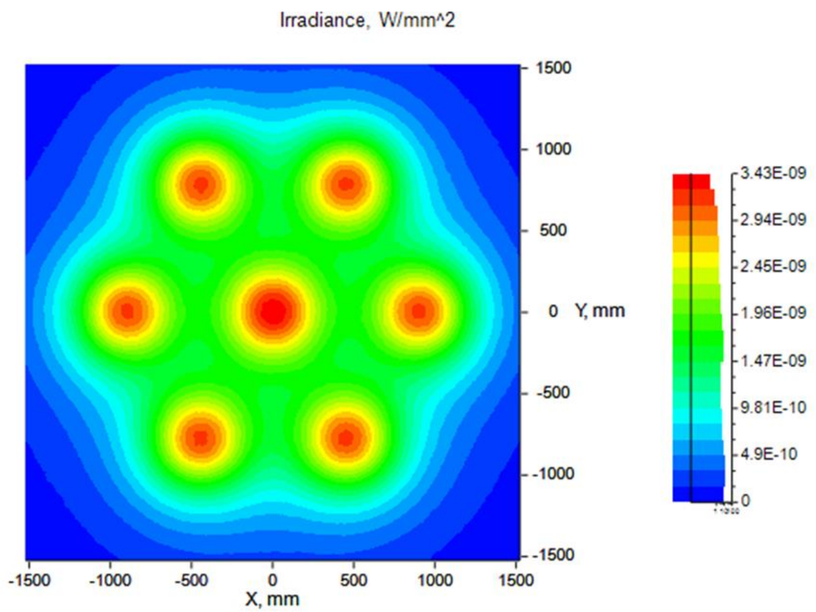
**Escherichia coli bacteriophage MS2* (ATCC® 15597-B1™)

Room-scale chamber and test*



Average room dose: ~10J/m²



Max headspace dose: ~46J/m²

Prototype devices mounted in test chamber

- Low ceiling and small room = low AVG:MAX ratio (0.2 vs up to 0.9 in large room)
- 4-hour exposure

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*Custom aerosol study by Microchem Laboratory, Round Rock TX

Test results

- 9.9 J/m^2 at Wp=258nm, delivered over 4 hours
- 0.93-$\log_{10}$ (88%) reduction of aerosolized bacteriophage MS2 vs control tests without UVC (triplicate measurements)*

Bacteriophage MS2 as a surrogate pathogen

- Use of a BSL1 organism allows testing of devices in full- or close to full-scale conditions, unlike BSL2 (or BSL3) organisms which would need to be used in a biosafety cabinet, requiring small-scale test setups.
- Bacteriophage MS2 is generally more resistant to inactivation than enveloped viruses.†

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* Microchem Laboratory. Study Report: Evaluation of Bioaerosols and Antimicrobial Efficacy of GE Current's Test Device. 2020
† Microchem Laboratory. MS2 Bacteriophage - A Viral Screening Tool. https://microchemlab.com/information/ms2-bacteriophage-viral-screening-tool

Application of findings to an exemplary room, with special consideration to coronaviruses

	Test results	Exemplary room (modeled)
Room size	10ft W x 10ft D x 8ft H	Arbitrary size x 10ft H
Max headspace dose (J/m^2)	46	40
AVG:MAX ratio	0.2	0.8
Average room dose (J/m^2)	9.9	32
$\log_{10}$ reduction of MS2	0.93	3.0
$\log_{10}$ reduction of coronavirus (estimated)		29.8

Coronaviruses are ~10X easier to inactivate with UVC than MS2*
Application to seasonal coronaviruses and SARS-CoV-2 is reasonable

~30-$\log_{10}$ reduction of aerosolized coronaviruses by whole room irradiation may be possible without exposing occupants to doses exceeding the IEC 62471 exposure limit

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*Walker C, Ko G. Effect of Ultraviolet Germicidal Irradiation on Viral Aerosols. *Environ. Sci. Technol*. 2007;41,5460-5465

Exposure duration for whole room irradiation below IEC 62471 exposure limit

Time to 1-$\log_{10}$ (90%) reduction

Equivalent air changes per hour

Exposure Duration (hours)	t_{90} (minutes)*	ACH_{eq}
24	48-135	1-3
12	24-68	2-6
8	16-45	3-9
4	8-23	6-17

$$ACH_{eq} = \frac{-\ln(0.1) \times 60}{t_{90}}$$

(equation adapted from CDC Guidelines for Environmental Infection Control in Health-Care Facilities, Appendix B)†

Whole room irradiation below exposure limits would be expected to provide virus inactivation comparable to mechanical air changes ranging from 1-17 ACH, depending on UVC exposure duration

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*Minimum t_{90} based on coronavirus D90 inferred from previously shown MS2 test, maximum t_{90} based on assumption of D90 of 3.0 J/m^2
†Centers for Disease Control and Prevention. Guidelines for Environmental Infection Control in Health-Care Facilities (2003). https://www.cdc.gov/infectioncontrol/guidelines/environmental/index.html

Technology summary—whole room irradiation below IEC 62471 exposure limit

- UVA irradiation below the IEC 62471 exposure limit has been proven to provide reduction of certain common bacteria and fungi on surfaces.
- UVC irradiation below the IEC 62471 exposure limit has been shown to provide reduction of viruses* in air.
- UV LEDs enable the emission of UVC and UVA into practical embodiments.

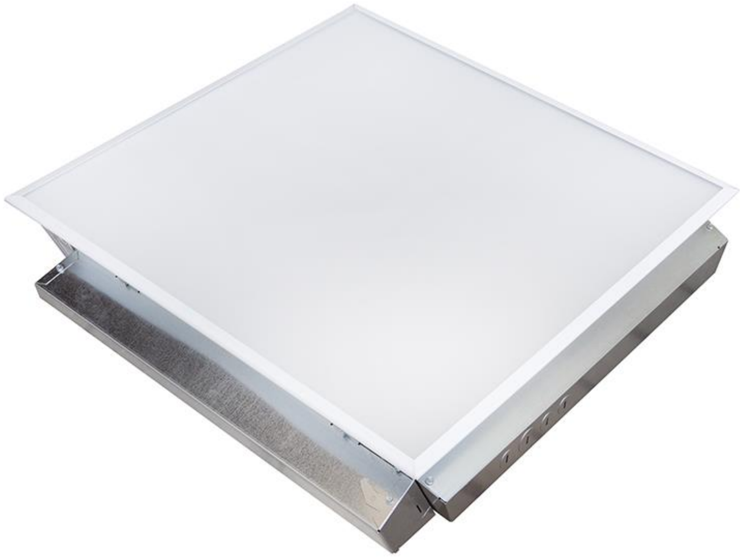
*Tested on bacteriophage MS2, with calculated extensions of findings to other organisms

Commercialization

- Solid-state lighting products incorporating these UVA and UVC approaches are being commercialized by GE Current, a Daintree company

365DisInFx™
UVC technology

365DisInFx™
UVA technology



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