Safety and Effectiveness Assessment of Ultraviolet-C Disinfection in Aircraft Cabins

Kris Belland; Diego Garcia; Charles DeJohn; Gary R. Allen; William D. Mills; Stephen P. Glaudel

INTRODUCTION: Aircraft cabins, susceptible to disease transmission, require effective strategies to minimize the spread of airborne diseases. This paper reviews the James Reason Swiss Cheese Theory in mitigating these risks, as implemented by the International Civil Aviation Organization during the COVID-19 pandemic. It also evaluates the use of airborne ultraviolet-C (UV-C) light as an additional protective measure.

METHODS: Our approach involved a thorough literature review by experts and a detailed risk-vs.-benefit analysis. The review covered existing research to understand the scientific foundation, while the analysis used established techniques to assess the impact of influenza and COVID-19 in terms of infections, deaths, and economic costs.

RESULTS: Integrating UV-C light in aircraft cabins, when applied with appropriate scientific understanding and engineering safeguards, has the potential to reduce in-flight disease transmission. This additional mitigation strategy can work synergistically with existing measures.

DISCUSSION: The research and risk-vs.-benefit analysis present strong evidence for the safety and effectiveness of continuous UV-C disinfection in aircraft cabins. It suggests that UV-C light, maintained below exposure limits, can be a valuable addition to existing measures against disease transmission during flights.

KEYWORDS: UV-C disinfection, ultraviolet-C, UV-C, aircraft, sanitization, airborne pathogen, disease disinfection, disease transmission, disease translocation, risk mitigation strategy.

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The use of ultraviolet (UV) light to decrease in-flight disease transmission has received attention as a potential measure to reduce the spread of infectious diseases, particularly during the COVID-19 pandemic. This paper is prepared in support of adding UV-C light-emitting diode (LED) lighting aboard aircraft to reduce the transmission and translocation of airborne diseases. Infectious diseases claim millions of lives globally each year.[12,57,58] The World Health Organization (WHO) addresses this situation as a major global health challenge, especially for low- and middle-income countries.[57] Many respiratory pathogens, including severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2), influenza, respiratory syncytial virus, common colds, tuberculosis (TB), etc., are transmitted via three principal mechanisms: 1) inhaling infectious airborne droplets (from unshielded coughs or sneezes) before they fall to the floor (within 1–2 m);[40,42,53] 2) touching contaminated surfaces (fomites) before the pathogen decays; and 3) exposure to infected persons even by simple breathing or talking, which can produce aerosols that linger for minutes to hours and travel much farther than the 1–2 m traveled by droplets.[8,9,53] Early in COVID-19 pandemic, it was recognized that aerosols are a significant route of infection in indoor environments.[31] All pathogens that possess either DNA or RNA—viruses, bacteria, fungi, protozoa—are susceptible to UV disinfection.[1] This by no means suggests that UV-C airborne use is the only risk-mitigation strategy, but that it supplements other multiple layers including high efficiency particulate air (HEPA) filters, air flow, outside air ventilation, masks, vaccines,

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education, training, engineering design, public health measures, and policies, to name a few.[36,44,50] In the extremely dry air of an aircraft in flight, with typically less than 20% relative humidity, all exhaled droplets smaller than 10 μm in diameter will quickly lose their moisture and shrink to a diameter of less than 1 μm in about 1 s or less due to evaporation (becoming almost "weightless") and, thereafter, remain airborne as aerosols indefinitely. The largest exhaled droplets of up to 100 μm, likewise, become aerosolized in less than 10 s.[40,53] Because of this uniquely dry environment in flight, the cabin presents an unusual situation where virtually all exhaled virions (particles containing viable virus) remain aloft as aerosols and do not alight onto surfaces due to gravity. Once aerosolized, the only opportunity for mitigation is to disinfect exhaled viruses and inactivate them while airborne (i.e., between passengers), either by continual ventilation and/or continuous UV disinfection. Surfaces (fomites) are not a primary path for respiratory viral infections such as corona and influenza; therefore, surface disinfection is not as easily employed continuously while in flight, and must be done episodically, prior to the flight.

A significant number of cases of onboard transmission have been reported for a number of respiratory diseases, including TB, influenza, SARS, measles, and meningococcal disease, since the late 1970s.[16,32,38] Following the SARS outbreak of 2003, international air travel stakeholders and other umbrella organizations worked together to develop guidance for cabin crew for the management of a suspected case of communicable disease onboard a commercial aircraft. This guidance is published on the International Air Transport Association website and is used by most international airlines.[18] Recent information published during the COVID-19 crisis from aircraft manufacturers on the dynamics of pathogen distribution onboard airliners offered a new perspective on the matter and called for a review of the guidance.[23,24,60]

Aviation Safety Management System (ASMS) is a systematic approach to managing safety in the aviation industry. It focuses on identifying and managing potential safety risks and continuously improving safety performance. ASMS encompasses a range of processes, including hazard identification, risk assessment, and continuous monitoring and review. One excellent example of an integrated ASMS, which includes a multilayered risk management process, is the International Civil Aviation Organization's (ICAO) and WHO's "Considerations for implementing a risk-based approach to international travel in the context of COVID-19," which is considered essential in the context of a public health risk management framework. The objective of the ICAO/WHO processes is to identify the residual risk of unknowingly transporting an infectious passenger or translocating the SARS-CoV-2 virus, considering various risk mitigation measures in place. This approach is scalable in complexity and considered the baseline for more sophisticated processes (e.g., end-to-end risk assessment models).[19]

Risk mitigation is the most appropriate strategy in the context of pandemic risk management in air transport. In multilayered defense models, the various mitigation measures are depicted as layers (e.g., based on the James Reason Swiss Cheese Model). Risk-free travel is not possible, but the risk can be reduced through the combined application of these mitigation measures. Currently, scientific, peer-reviewed, and evidence-based efficacy measures for these mitigation strategies are limited; therefore, in some cases, the scope of their impact on transforming the inherent risk must be based on expert consensus, modeling, and available evidence. As a result, much of the risk assessment is qualitative and provides the flexibility to be adopted and integrated into national public health and aviation plans. The risk assessment process will consider the chosen mitigation measures and regularly re-evaluate how they affect the likelihood and impact of the inherent risk. A state can then determine if the residual risk is within its public health management capacity.[19] Current evidence suggests that utilization of UV-C light in flight can be an additional effective, synergistic risk-mitigation strategy that will ultimately reduce transmission of infectious diseases, including existing and emerging airborne infections (viral, bacterial, fungal).[10,29,33]

In their recent study, Allen and Mills (Allen GR, Mills WD. Personal communication; 2023; [Detailed analysis is available from the first author of this paper on request]) provide a comprehensive analysis of the impact of in-flight transmission of airborne diseases, including influenza and the Delta variant of COVID-19. Their findings indicate a significant annual burden attributed to in-flight transmission of influenza, estimated at nearly 950,000 cases, over 600 fatalities, and an economic impact of approximately $1.6 billion. The period of the COVID-19 Delta wave (February 2020 to September 2021) saw a substantial increase in these figures, with over 2 million infections, 8000 deaths, and an economic cost exceeding $200 billion.

The study further explores the efficacy of implementing far-UV-C disinfection technology in aircraft cabins. The results suggest that such an intervention could potentially reduce infection and mortality rates associated with in-flight transmission by up to 80%. This reduction is pertinent not only to established airborne diseases, like TB, measles, and meningitis, but also holds significant promise for emerging pathogens including COVID-19, SARS-CoV-2, and future infectious disease outbreaks.

The research also presents a comparative analysis of the impact of far-UV-C implementation against increased air-exchange rates in airliners. It was observed that the addition of far-UV-C equates to enhancing the air-exchange rate by 2–4 times during flight and approximately 12 times when the aircraft is on the ground. Consequently, this could lead to an 80% reduction in residual airborne pathogen concentration during flight (assuming 30 air exchanges per hour) and up to a 96% reduction when the aircraft is grounded (with 5 air exchanges per hour).

Furthermore, the study addresses safety concerns regarding UV-C disinfection. Previous research, spanning several decades, affirms the safety of UV-C application for disinfection purposes. The maximum permissible exposure to UV-C is relatively low, comparable to less than 5 min of exposure to summer sunlight. It is important to note that these findings are particularly significant considering the reduced number of air passengers during the study period and the implementation of mask mandates.

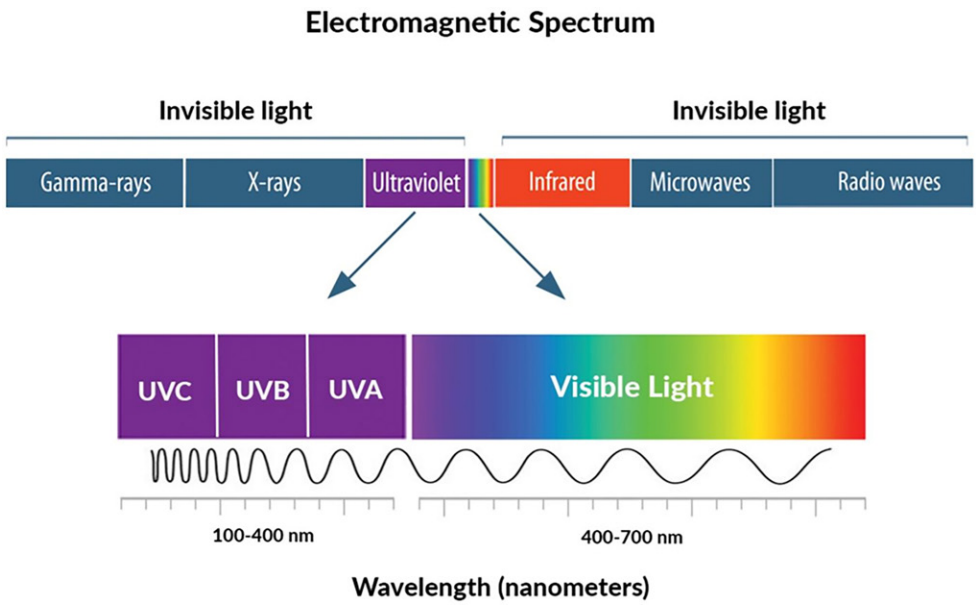

Fig. 1. The radiation spectrum (from the National Institute of Health, National Eye Institute. Protecting your eyes from the sun's UV light. July 5, 2022. Available from https://www.nei.nih.gov/about/news-and-events/news/protecting-your-eyes-suns-uv-light).

Fig. 1 illustrates the electromagnetic radiation spectrum, highlighting the range of UV germicidal irradiation, which, particularly in the UV-C range (200–280 nm), is a well-established method for disinfecting air, water, and surfaces. This is primarily achieved at a wavelength of 254 nm, where UV-C disrupts the base pair bonds in DNA and RNA, rendering them incapable of transcription or translation (as detailed in **Fig. 2**).[13,28,34]

Earlier methods using UV irradiation for decontamination (e.g., potable water) had to rely on high-power (tens of Watts), low-pressure mercury lamps, which, due to their high output, could not be used to directly irradiate the air or surfaces in an occupied space without greatly exceeding the published exposure limits (EL) for UV irradiation. Therefore, mercury lamps could only be used in unoccupied spaces, shielded from humans (e.g., at least 7 ft above the floor or inside the heating ventilation and air-conditioning ducts); however, none of these are ideal methods because they are limited by the airflow in the space.

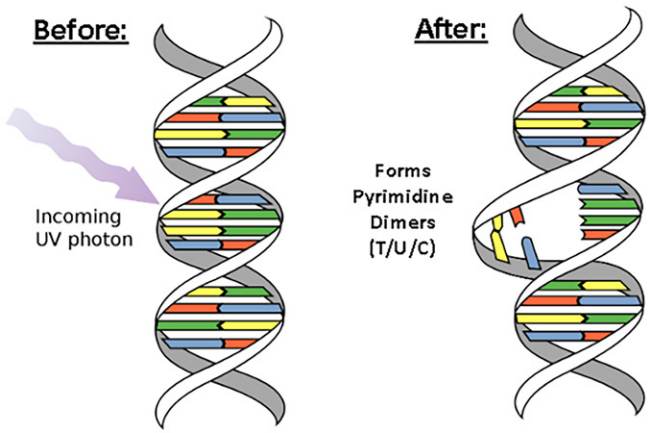

Fig. 2. Inactivation of a virus by UV-C light. Adapted from "Ultraviolet (UV) photons harm the DNA molecules of living organisms in different ways"; illustration by David Herring. In: Allen J. Ultraviolet radiation: how it affects life on earth. NASA Earth Observatory; September 6, 2021. Available from https://earthobservatory.nasa.gov/features/UVB.

In the last decade or so, excimer lamp technology has provided two excimer combinations: krypton with bromine that emits strongly at 207 nm and krypton with chlorine that emits at 222 nm. The latter, krypton with chlorine excimer emission at 222 nm, has proven a promising path toward safe and effective disinfection of pathogens with direct exposure of skin and eyes. The reason this region, called far-UV, is of such interest is that the American Conference of Governmental Industrial Hygienists threshold limit values, or ELs, are much higher than at the 250–280 nm range. The irradiance at 222 nm can be raised at least one, possibly two, orders of magnitude higher than for irradiance between 250–280 nm. This increase in irradiance allows much faster disinfection of pathogens without harming skin or eyes. Much research on the effectiveness of excimer lamps in the disinfection of various pathogens is ongoing, as is research in the short- and long-term safety to skin and eyes from exposure to 222-nm irradiation.

More recently, the use of low-power UV-C LEDs for the inactivation of pathogens, especially airborne pathogens, using UV radiation emitted directly into occupied spaces and exposing occupants to a dose below the accepted actinic ELs, has been successfully developed. This method is referred to as direct irradiation below exposure limits (DIBEL).[1] It has been demonstrated that UV-DIBEL can be an effective component of efforts to combat airborne pathogens such as SARS-CoV-2, influenza A, the common cold, healthcare-acquired bacterial infections, and others.[1] DIBEL technology can achieve significant levels of pathogen inactivation by providing direct, continuous radiation into the occupied breathing zone while adhering to actinic dose EL.[1] Over the last several decades, photobiological studies have evaluated the sensitivities of a wide array of

bacterial, fungal, and viral organisms to UV, particularly UV-C.[25,35,47] The Allen and Mills study (Allen GR, Mills WD. Personal communication; 2023) has shown that inactivation rates of aerosolized SARS-CoV-2 and other pathogens have been experimentally measured using 275-nm LEDs emitting UV light below the EL in a controlled room-sized aerosol chamber, confirming the expected D_{90} dose and the expected inactivation times for aircraft application.

According to the ICAO Aviation Multi-Layered Disease Defense Strategy, multiple independent methods should ideally be used to disinfect both surfaces and air in the aircraft cabin. UV-C DIBEL is primarily an air disinfection technology with a lesser impact on surface pathogens. Regarding surface disinfection, the primary methods are manual wiping with chemical disinfectants and a one-time sweep of the cabin, while unoccupied, using an intense UV-C source such as a "robot." Both techniques are effective only on surfaces where the manual wiping is done, or where the line-of-sight path from the UV source of the robot can "see" the surface. Both techniques are done when the cabin is unoccupied and not repeated after the passengers board the cabin. Both techniques likely leave a significant fraction of surfaces that could be touched by passengers uncleaned (e.g., under armrests or seats, crevices around buttons or controls), and the application of UV-C LED DIBEL using current UV-C LED technology will likely not remedy those missed sections. If there is no line of sight from the missed sections to the UV source of the robot, then there may also not be a line of sight to the UV-C LED in the DIBEL system, either.

However, as soon as the cabin is occupied, any surfaces that had been cleaned manually or by the robot while unoccupied can immediately be recontaminated by a contaminated passenger or article introduced into the cabin. Fortunately, transmission of most airborne pathogens (and especially SARS-CoV-2) via contaminated surfaces (called fomites) is not the primary path of transmission between people. Instead, the dominant transmission paths are via (large) airborne droplets and, more typically, by (small) aerosolized pathogens. This transmission would not be due to aerosols left behind by the robot, but rather by aerosols exhaled by infected passengers, starting as soon as boarding commences.

Even after boarding, when the option for broad cabin disinfection with intense "above-EL" UVC doses using robots becomes unavailable, it is possible for "above-EL" sources to be safely employed as long as they can automatically and redundantly sense the absence of personnel in generally unoccupied areas of the aircraft (such as in the lavatories), thus safely disinfecting those areas in-between passenger visits. This important, most likely path of infection transmission for many respiratory pathogens, which is currently missing in the ICAO Aviation Multi-Layered Disease Defense Strategy, is addressed by the extra layer of UV-C DIBEL protection.

Pathogens may be physically removed from the air in an occupied environment by ventilation or filtration of the air. The air is first moved to an unoccupied space, where the pathogens are inactivated and/or mixed with outside air, and then the decontaminated air is returned to the occupied zone.[1] Since most airborne infectious diseases are either bacteria (or bacterial spores), viruses, or fungi, these pathogens may be inactivated and rendered unable to infect a host by UV radiation in the unoccupied space.[25,33,55]

HEPA filters are capable of filtering viruses of submicron sizes, including SARS-CoV-2[49]; however, there are shortcomings of this technology. First, it should be noted that some aircraft, including most smaller private aircraft and most business jets, are not equipped with HEPA filtration. For instance, certain private jets and regional airliners, such as the Embraer 145 fleet operated by United and American Airlines, lack HEPA filters, as do all CRJ200 aircraft flown on behalf of United and Delta. Additionally, most regional turboprop aircraft, such as the Dash 8-1/2/3 Series, Embraer 120, and Fokker 50, provide minimal to no filtration of cabin air, as well as the ATR-42/72. Even Gulfstream private jets (all models) do not contain HEPA filters. Second, in order for HEPA filters to function properly, cabin air must flow through the filters, potentially moving air past infectious passengers toward susceptible passengers. Unfortunately, airflow patterns created by aircraft ventilation systems can result in uncirculated pockets of air, creating dead zones within the cabin, reducing the effectiveness of the HEPA system, and potentially allowing airborne transmission of disease. Most importantly, the most aggressive use of ventilation in aircraft, providing up to 30–35 air changes per hour (ACH, described below), is overwhelmed by the extreme crowding of passengers in the aircraft cabin. Additionally, ACH rates are markedly reduced during ground passenger-loading or during times when environmental controls are reduced or turned off (engine start or external ground support). It has been shown that the ACH should be increased by 5–10× to reduce the risk of airborne infection to levels comparable to crowded terrestrial settings (Allen GR, Mills WD. Personal communication; 2023). Only the addition of UV-C disinfection can provide the required supplemental ACH inside an aircraft cabin, whereas UV radiation applied in DIBEL mode, while occupied, provides direct inactivation of pathogens in the air between the passengers.[25,44,60] Most airborne infectious diseases are easily inactivated by UV radiation rendering them unable to infect a host.[1,47]

The UV-C subset of UV radiation between 200–280 nm has been employed extensively in germicidal applications.[11,33,34] Extensive scientific literature exists confirming the applicability, efficacy, and safety of UV-C environmental irradiation.[26,27,37] Over the UV-C range, the detrimental effect on pathogens occurs because their intracellular components (RNA, DNA, and proteins) can absorb UV-C photons.[7,25,35] Absorbed UV-C photons cause critical damage to the genomic system of microorganisms, preventing them from replicating.[33] UV light in the traditional UV-C range has photon energies that are nearly resonant with the absorption bands of DNA and RNA, enabling very effective inactivation of many types of viruses, bacteria, and bacterial spores, as well as fungi and protists.[28,30,41]

Although viruses have no active metabolic processes that can be interrupted, UV-C primarily inactivates pathogens through the creation of dimers in adjacent pyrimidine bases of their nucleic acids, interrupting transcription or translation,

thus rendering the pathogens inactivated.[1,25,34] Therefore, the effect of UV irradiation on such pathogens is called "inactivation" and not "killing."[34] This process is depicted in Fig. 2.

UV-C light is significantly attenuated by the human stratum corneum (the outer dead-cell skin layer), the ocular tear layer, and the cytoplasm of individual human cells (**Fig. 3**). Thus, very little UV-C light reaches the living cells in the human skin or the human eye, causing negligible damage compared with the longer wavelengths of UV-A and especially UV-B, which do effectively penetrate these sensitive cells.[11]

Far-UV light (207–222 nm), produced by excimers, has been shown to be as efficacious as conventional germicidal UV light (low-pressure mercury emission is primarily at 254 nm) in inactivating microorganisms,[10,11,33] with the advantage that shorter wavelengths have shallower penetration into the skin and ocular tear layer compared to the conventional, longer-wavelength germicidal UV light.[37,39,45]

Some research groups (e.g., Columbia University), manufacturers (e.g., Ushio, Far UV, and Eden Park), and lighting system providers (e.g., Acuity) have endorsed the use of far-UV-C light (222 nm) in occupied public locations, using excimer lamps, as a safe and efficient antimicrobial technology.[11] The approach is based on the biophysical principle that far-UV-C light has a limited ability to penetrate biological materials and can effectively inactivate viruses. It cannot penetrate the outer dead-cell layers of human skin or the outer tear layer on the surface of the human eye.[11,45,46] However, if shorter wavelengths like 222 nm are used, the potential dangers of emitted ozone should be considered. Other limitations of far-UV excimer sources for aircraft applications include the possibility that the system could be too large (the "bulb" plus its electronic "ballast", and/or to accommodate optics that may be needed to control the direction of the UV light), the greater expense than UV-C LEDs (ref: Haitz's Law), and the shorter operating lifetime,[1] pointing to the parity of 222-nm excimer sources relative to 265-nm LED sources at the present time for aircraft cabin applications.

Because of the shallower penetration depth of shorter wavelengths of UV-C, the actinic hazard function allows for a higher EL at the shorter wavelengths; for example, 229 J · m^{-2} at 222 nm vs. 60 J · m^{-2} at 254 nm, and 37 J · m^{-2} at 265 nm (a 6.2-fold advantage for 222 nm vs. 265 nm). It is often misstated that this means that far-UV (shorter wavelength) is "safer" than conventional UV-C; however, this is not the case.

Far-UV (shorter wavelength, e.g., 222 nm) is allowed a higher EL (again, dose = irradiance × time) than conventional (longer wavelength, e.g., 254 nm) UV-C, but it is not "safer." If the dose onto a person's skin or eyes is below the EL of 37 J · m^{-2} at 265 nm, that is comparably safe as a dose below the EL of 229 J · m^{-2} at 222 nm. A 222-nm system will typically be designed to operate with a safe margin below the EL of 229 J · m^{-2}, and a 265-nm system will typically be designed to operate with a safe margin below the EL of 37 J · m^{-2}, so that they are comparably safe.[4] However, as wavelengths become even longer (into the UV-B range, above 280 nm), skin-depth penetration rises dramatically. This validates that the absorption of UV-C by the skin increases rapidly below 240 nm. Thus, the penetration of the UV irradiance into the basal layer is significantly decreased at 222 nm compared to 265 nm.

The question then is how efficacious the 222-nm system is when operating somewhat below 229 J · m^{-2} vs. the 265-nm system when operating somewhat below 37 J · m^{-2}. At first blush, the answer is that the 222-nm system can be 6.2× more efficacious, but that is not true. The excimer light source operating at 222 nm is too large (about 30 mm) to accommodate optics to spatially confine the irradiation, while a UV-C LED (about 1 mm) can provide a narrow beam using a lens having only about a 10-mm diameter. By contrast, LEDs are small solid-state compound-semiconductor devices, which can be fitted with lenses to direct light as needed, such as in unoccupied spaces. The optical advantage of a small LED (1 × 1 mm) vs. a much larger excimer lamp (45 × 60 mm) is readily apparent.

A typical application of DIBEL technology in an occupied aircraft cabin is depicted in **Fig. 4**, showing the UV-C intensity

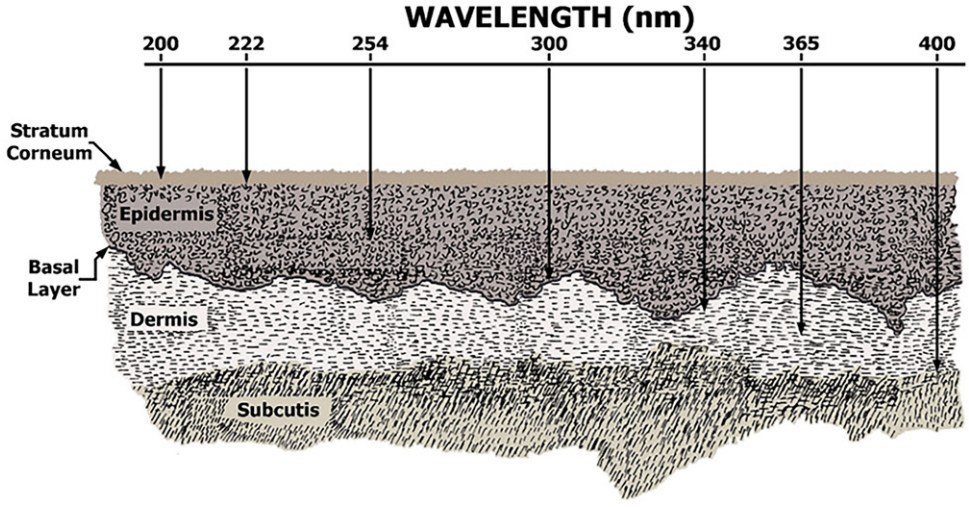

Fig. 3. Penetration of human skin by ultraviolet energy (with Permission, David Sliney, Ph.D., 2023).

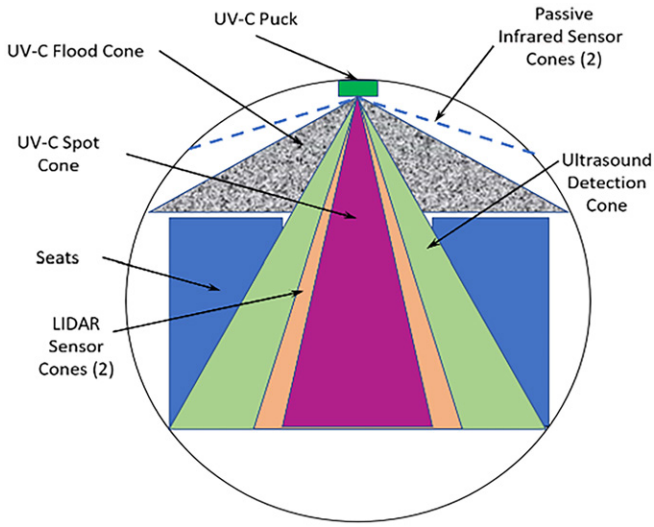

Fig. 4. Typical application of DIBEL technology (used in an array fashion) in an occupied space. The array in this application could be a linear array along the center of the aisle ceiling, with UV-C Pucks spaced a few feet apart, for example.

distribution emitted from a single UV-C Puck mounted in the ceiling above the aisle, midway between opposing rows of seats. Fig. 4 indicates both a narrow "UV-C spot cone" and a broad "UV-C flood cone." Typically, in this application, a linear array of UV-C Pucks is mounted along the center of the ceiling of the aisle, with UV-C Pucks spaced a few feet apart, sufficiently close together that the overlap of the UV-C flood cones provides nearly uniform irradiance throughout the occupied space, not to exceed the maximum allowed EL.[1]

Even though the UV-C flood cones provide a dose well below the EL to a seated passenger, if a passenger stands up or raises a hand in close proximity to the LED source, the EL may be exceeded. In fact, the UV-C irradiance (dose) increases with the inverse square of the distance between the UV source and the subject (i.e., "Inverse Square Law), such that a dose that is safe at a distance of 2 ft from the LED will be 4× higher at a distance of only 1 ft from the LED. A pair of redundant passive infrared (IR) detectors determine if a passenger's head or hand enters the zone where the irradiance exceeds the EL, and then turns off the LEDs in that UV-C Puck until the passive IR sensors detect the absence of personnel within the EL range.

In contrast, the UV-C spot cones have a beam width narrow enough to be limited to the aisle, with negligible (≪ EL) UV-C shining on a passenger seated in a seat adjacent to the aisle. The UV-C dose within the spot cone exceeds the EL so that the contaminated air within the aisle may be disinfected at a much higher rate than that provided by the lower irradiance flood cones. To ensure safety, the spot cone is monitored by both a pair of redundant ultrasound sensors and a pair of redundant LIDAR sensors for each UV-C Puck. The sensing range of the sensors is such that if any passenger is standing, kneeling, or even lying down in the aisle, the LEDs of that UV-C will be turned off until the zone is again unoccupied. Further, if a passenger's arm is extended more than a few inches beyond the armrest, the sensors are likewise activated to turn off that UV-C Puck. The installation is configured such that within the occupied zone (the top of which is depicted by the dashed line in Fig. 4), the irradiation is within the allowable EL.[1]

METHODS

This study employed a rigorous methodology consisting of a comprehensive literature review by subject-matter experts, as well as a risk-vs.-benefit analysis. The literature review encompassed existing research, ensuring that both a thorough understanding of the current scientific landscape and a baseline understanding of the current foundational scientific underpinnings are provided (Allen GR, Mills WD. Personal communication; 2023). In addition, a meticulous risk-vs.-benefit analysis was performed using established analytical techniques that showed the combined negative impact of influenza and COVID-19, including millions of infections, thousands of deaths, and substantial negative economic costs, on an annual basis (DeJohn CA, Garcia DM, Belland KM. Personal communication; 2023).

The efficacy of UV irradiation for air disinfection may be quantitatively compared with traditional air disinfection technologies by a method related to ACH. A straightforward example of a traditional air-cleaning technology used in aircraft is the introduction of outside air and the filtering of recirculated air by the cabin ventilation system. A common metric used to compare air-disinfection technologies is the air-exchange rate (AER) measured in ACH, defined as:

$$\mathrm{ACH} = \mathrm{Q} / \mathrm{V}$$

where Q is the airflow rate ($m^3 \cdot h^{-1}$) and V is the volume (m^3).[1] The American Society of Heating, Refrigerating and Air Conditioning Engineers recommends AERs between approximately 6–8 ACH for residences, 10–12 ACH for offices, and 14–18 ACH for restaurants and public buildings.[22] A typical AER in wide-body aircraft is variously quoted between about 5 ACH on the ground and up to 35 ACH when cruising.[52] When ventilation is used to replace existing, potentially contaminated air with fresh air, the air is not flushed through like a piston, but rather flows and diffuses from the air inlet to the air outlet through the volume of the cabin. When a volume of air equal to the volume of the cabin is introduced, only 63% of the original air exits the cabin, along with 37% of the newly introduced fresh air. With 63% of the existing air replaced by fresh air during each air change, it takes 2.3 air changes to replace 90% of the original air with fresh air. For example, if the AER in the cabin is 15 ACH, then 90% of the cabin air is replaced by fresh air in about 9 min. If a susceptible person inhales enough airborne pathogens to become infected in less than about 9 min, typical for infection by SARS-CoV-2, then an ACH of 15 is only marginally good enough to mitigate the risk of infection.[15,21,60]

Air disinfection by UV irradiance can be quantitatively compared to air disinfection by ventilation by introducing an

Table I. D_{90} Values for UV-C Disinfection in Air at 254 nm for Various Microbes.

PATHOGEN	TYPE	D_{90} IN AIR (J/m^2)	D_{90} CATEGORY
SARS-CoV-2	Virus	5	Low
Mycobacterium tuberculosis	Bacteria	5	Low
Staphylococcus aureus (e.g., MRSA)	Bacteria	5	Low
Coronavirus (some common colds)	Virus	6	Low
Pathogens responsible for pneumonia: *S. aureus* (5), *Klebsiella pneumoniae* (7), *Pseudomonas aeruginosa* (4), *Streptococcus pneumoniae* (~5)	Bacteria	6	Low
Escherichia coli	Bacteria	8	Low
Influenza A	Virus	19	Medium
Adenovirus	Virus	44	High
Candida auris	Fungus	~50	High
Clostridioides difficile	Bacterial Spore	~50	High

MRSA = methicillin-resistant *Staphylococcus aureus*.

equivalent ACH (ACH_{eq}) for UV disinfection that is derived quantitatively.[1]

$$ACH_{eq} = 2.30 \; x \; E \; / \; D_{90}$$

where E is the UV irradiance ($J \cdot m^{-2}$) averaged throughout the volume of the cabin, and D_{90} ($J \cdot m^{-2}$) is the UV dose required to achieve 90% inactivation of a pathogen in or on a solid, liquid, or gas medium. For example, D_{90} for SARS-CoV-2 in air in the UV-C is about 6 $J \cdot m^{-2}$, and[23] the irradiance, E, when operated at the allowable EL for 265 nm, is 36 $J \cdot m^{-2}$, so that the theoretical ACH_{eq} is about 14 per hour if the dose is limited by the EL. In practice, an engineering margin of at least 20% below the EL should be used and the irradiance cannot be perfectly uniform throughout the irradiated volume (assume the average is 50% of the maximum), so that ACH_{eq} is reduced by a factor of about $0.5 \times 0.8 = 0.4$, so that the theoretical $ACH_{eq} = 14$ may be about 5 per hour in practice. Using sensors, controls, and optics, ACH_{eq} may be enhanced by a factor of about 10–50. A practical system using 275-nm LEDs has been demonstrated with an estimated ACH_{eq} of ~40 per hour.

D_{90} values for UV disinfection in air at 254 nm for various viruses, bacteria, and spores are shown in **Table I**.[1,28] D_{90} for influenza A, common colds, pneumonia, TB, measles, etc., are typically about 2–5× higher than for SARS-CoV-2 in the air (i.e., about 10–25 $J \cdot m^{-2}$), so these other airborne pathogens will be inactivated at lower ACH_{eq} rates up to about 50 per hour, following the above examples.

Another commonly used designation for dose is D_{99}, which is simply twice the D_{90} dose. That is because the first D_{90} dose inactivates 90% of the pathogens and then another D_{90} dose inactivates 90% of the remaining 10% of pathogens, leaving only 1% of the original pathogens.[21] Similarly a $D_{99.9}$ dose will be three times that of the D_{90} dose. The linearity of this relationship typically holds through 99–99.9% inactivation, then begins to saturate at higher doses.[21] This is an enabling feature of providing continuous disinfection, whereby the contamination level continuously declines unless additional contamination is added after some initial contamination.

ACH_{eq} is proportional to the UV irradiance (flux density) and inversely proportional to D_{90}, as shown in the equation above.[1] Therefore, to provide the highest possible ACH_{eq}, a UV disinfection system (e.g., DIBEL and/or spot) should maximize the UV flux throughout the occupied space without exceeding the EL. For a UV disinfection system that is limited to DIBEL only (without spot beams that locally exceed the EL), **Table II** shows ACH_{eq} values for D_{90} for 8 h of continuous DIBEL for low, medium, and high categories of pathogens in the air at 254 nm.[1] The ACH_{eq} values for 275-nm irradiation would be lower by twofold, and for 222 nm, it would be higher by a factor of 3.8.

The DIBEL efficacy estimates in Table II apply only to the flood beam in a flood-plus-spot system. The present-day values of ACH_{eq} are not hypothetical. They have been confirmed by actual measurements of ACH_{eq}, using a flood beam only, in a room-sized aerosol chamber provided with aerosolized SARS-COV-2 virus using the UV-C LED DIBEL technology as presented in this paper. The addition of a spot beam leverages the ability to exceed the EL at locations in the cabin that are not occupied for long periods of time, such as the aisles, galley, or lavatory, by sensing occupancy in the region of the spot beam and turning off the spot beam while that zone is occupied. The ACH_{eq} in an aircraft cabin is typically enhanced by up to 10× by the addition of occupancy-controlled spot beams, such that a typical combined efficacy is 30–60 ACH_{eq}, or higher, depending on the spatial control of the spot beam and the amount of UV-C emission available from today's LEDs, which are rapidly improving year by year.

Table II. ACH_{eq} Values for $D_{90\,for}$ 8 h of Continuous DIBEL.

D_{90} CATEGORY IN AIR (J/m^2)	EXAMPLE PATHOGENS	ACH_{eq} (h^{-1}) 2020 (275 nm)	2021 (275 nm + OPTICS)	2025 (255 nm + OPTICS)	POTENTIAL (225 nm + OPTICS)
Low ~5	SARS-CoV-2, tuberculosis, pneumonia-causing bacteria, MRSA	1.1	4	8	150
Medium ~20	influenza A	0.3	1.2	2.2	40
High ~50	adenovirus, *C. auris*, *C. difficile*	0.1	0.4	0.8	15

It is anticipated (although not yet verified) that a flood-only (DIBEL) system will provide ACH_{eq} in aircraft applications exceeding 100 ACH_{eq} within a few years (see "Potential" column in Table II), which may be further enhanced by adding spot disinfection. This is to be compared with the current typical range of ACH in aircraft of about 5–30 per hour.

Because of the method used to mathematically derive ACH_{eq} for UV disinfection, the ACH values for ventilation and the ACH_{eq} values for UV disinfection are additive. For example, if the aircraft provides 30 ACH of ventilation and the UV disinfection provides 120 ACH_{eq}, then the total ACH in the cabin is 150 per hour. So, while the ventilation alone would disinfect 90% of the cabin air in about 9 min, the combination of ventilation and UV disinfection would disinfect 90% of the cabin air in about 2 min, or five times faster.[12,48]

Although the dose is not exactly linearly proportional to the risk of infection, the risk of infection will also be significantly reduced, comparable to the fivefold factor. This scale of ACH_{eq} has been demonstrated in prototypes with today's LEDs and optics. With the rapid advent of improved UV-C LEDs and UV-C optics at shorter wavelengths, this 5-fold factor is expected to become approximately 30-fold or more within a few years. The 30-fold improvement will reduce the time to 90% inactivation from 2 min down to about 20 s. Notably, from Table II, this 20-s disinfection time applies to SARS-CoV-2, TB, pneumonia, and methicillin-resistant *Staphylococcus aureus* (MRSA), while the 90% disinfection time for influenza A would be about 1 min. The eventual capability of UV-C disinfection inside the cabin (90% disinfection of many airborne viruses in 20 s) will be comparable to the transit time for aerosols from an infected person's mouth to a susceptible person's mouth a few meters away.

RESULTS

Integrating UV-C light in aircraft cabins, when applied with appropriate scientific understanding and engineering safeguards, has the potential to reduce in-flight disease transmission. This additional mitigation strategy can work synergistically with existing measures.

DISCUSSION

Every wavelength of light, from UV through IR, can potentially pose a health risk to humans if the dose exceeds the allowed EL. The EL for actinic hazard (as provided in International Electrotechnical Commission Standard 62,471:2006) is $30\ J \cdot m^{-2}$ in any 8-h period.[1,20] This regulation is based on the maximum sensitivity of the human eye, which was found to be at approximately 270 nm, and pertains to the fairest skin and eye phenotypes, but does not apply to individuals with rare drug-induced or genetic hypersensitivity to UV.[17,20,39]

The known side-effects of overexposure to UV-C radiation include transient corneal and conjunctival photokeratoconjunctivitis and erythema of the skin.[1] The National Toxicology Program has stated that UV-C radiation is reasonably anticipated to be a human carcinogen, and the International Agency for Research on Cancer has reported that UV radiation (including UV-A, UV-B, and UV-C) is carcinogenic to humans.[2]

> *Most skin cancers are a result of exposure to the UV rays in sunlight. Both basal cell and squamous cell cancers (the most common types of skin cancer) tend to be found on sun-exposed parts of the body, and their occurrence is typically related to lifetime sun exposure. The risk of melanoma, a more serious but less common type of skin cancer, is also related to sun exposure, although perhaps not as strongly.*[2]

Fortunately, radiant energy in the UV-C band has very shallow penetration depths, which accounts for the superficial nature of any injury from excessive exposure. These effects are transient, lasting 24–48 h, because only the corneal epithelium and the superficial epidermis are significantly affected, and normal cell turnover soon causes the signs and symptoms to resolve.[45,46,56]

Recent studies show no evidence of induced skin cancer or other skin abnormalities after long-term (66 wk) chronic exposure to 222-nm far-UV-C radiation, which underscores that there is little to no anticipated risk associated with in-flight germicidal use of far-UV-C. In short, the use of UV-C as a disinfecting tool outweighs safety issues with the standardization of dose.[37,41,54]

UV is no more hazardous than visible or IR light when the dose is maintained below the appropriate EL. Conversely, when received at a dose exceeding the EL for visible light, visible light is more hazardous than UV light when the UV light is maintained below its respective EL.[1,16] DIBEL protocols can ensure that the dose (irradiance × exposure time) received by individuals in the irradiated space remains below the EL. The limits defined by these protocols represent the conditions to which individuals can be repeatedly exposed for $8\ h \cdot d^{-1}$ over a working lifetime without the risk of photobiological effects such as skin or eye damage. For perspective, a DIBEL system operating for 8 h below the allowed EL for UV-C poses less risk than 5 min of sunshine per day.[1] In addition to the superficial short-term risks, the long-term risk from an accumulated daily exposure to 254-nm radiation at the EL received over 8 h, $5\ d \cdot wk^{-1}$ for 20 yr, would increase the risk of nonmelanoma skin cancer by a factor of about 0.37%.[1]

Furthermore, per the well-established photobiological effect of time-weighted averaging (TWA), receiving an irradiance exceeding the EL for a brief, or even extended, time does not create a hazard to the skin or eyes, unless the dose (irradiance × time) exceeds the 8-h allowed dose per the EL. In other words, a person may receive 10× the allowed irradiance for 30 min and accrue only five-eighths of the TWA dose that is allowed for 8 h. In addition, the TWA is a time-moving 8-h average, such that the allowed dose is effectively renewed every 8 h due to the relatively short recovery time of the human skin and eyes to the UV-C dose.[3,48]

With the increasing application of UV-C lamps for disinfection, questions regarding the generation of ozone in the air have been raised, making ozone concentration an important

design consideration when using UV-C emitting lamps.[13] The Occupational Safety and Health Administration limit for 8-h exposure to ozone is 0.1 ppm, and the Food and Drug Administration limit for long-term exposure is 0.05 ppm. The minimum detectable (smell) level for a typical person is 0.01–0.04 ppm. Fortunately, current DIBEL protocols result in ozone production which is $10^{-3}\times$ lower than the Food and Drug Administration long-term limit with a 1-MW UV LED at 254 nm.[51]

UV devices for disinfection of frequently touched surfaces and circulating air streams are in use in public, high-traffic spaces worldwide, including vehicles, hospitals, airports, and shopping malls.[30–32] Although UV irradiation has been used for disinfection for many years, in the past it has mostly been limited to applications where humans are absent or shielded from the UV source. DIBEL is a method of applying germicidal UV radiation in a way that occupied spaces may be directly disinfected by limiting UV to doses that are below industry-accepted ELs for repeated exposure of humans, while simultaneously maintaining doses above those required for acceptable reductions of pathogenic organisms in the space.[1]

The benefits of a DIBEL technology that differentiate it from conventional disinfection technologies include:

- continuous, direct disinfection while occupied; and
- no required air movement, so that disinfection occurs in the space between an infected person and susceptible people, providing an effective shield between infectious and susceptible individuals that is proportional to the ACH_{eq} provided by the DIBEL system.[1]

In the event of accidental overexposure, the risks are also well-established and demonstrated to be minor relative to the benefits of disease prevention.[45,54,56] High-traffic areas with increased risks of aerosolization and dissemination due to aircraft airflow dynamics (such as lavatories) should, at a minimum, be equipped with UV-C disinfection.[14,24,59]

In summary, far-UV-C light is anticipated to have about the same antimicrobial properties as conventional germicidal UV light, but with higher allowed exposure limits than for longer UV wavelengths.[11,37,39] The findings in this document are supported by peer-reviewed datasets and accepted analytical techniques. Current evidence suggests that utilization of UV-C light in flight can be an additional effective, synergistic risk-mitigation strategy that will ultimately reduce transmission of infectious diseases, including existing and emerging airborne infections (viral, bacterial, and fungal).[5,6,43] The risk-vs.-benefit analysis favors the continuous use of airborne UV-C below exposure limits.

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REFERENCES

1. Allen GR, Benner KJ, Bahnfleth WP. Inactivation of pathogens in air using ultraviolet direct irradiation below exposure limits. J Res Natl Inst Stand Technol. 2021; 126:126052.
2. American Cancer Society. Does UV radiation cause cancer? July 10, 2019. [Accessed May 1, 2023]. Available from https://www.cancer.org/healthy/cancer-causes/radiation-exposure/uv-radiation.html.
3. American Conference of Governmental Industrial Hygienists. TLV/BEI Guidelines. [Accessed May 1, 2023]. Available from https://www.acgih.org/science/tlv-bei-guidelines/.
4. Barnard IRM, Eadie E, Wood K. Further evidence that far-UVC for disinfection is unlikely to cause erythema or pre-mutagenic DNA lesions in skin. Photodermatol Photoimmunol Photomed. 2020; 36(6): 476–477.
5. Bhardwaj SK, Singh H, Deep A, Khatri M, Bhaumik J, et al. UVC-based photoinactivation as an efficient tool to control the transmission of coronaviruses. Sci Total Environ. 2021; 792:148548.
6. Blatchley ER, Brenner DJ, Claus H, Cowan TE, Linden KG, et al. Far UV-C radiation: an emerging tool for pandemic control. Crit Rev Environ Sci Technol. 2023; 53(6):733–753.
7. Bolton JR, Cotton CA. The ultraviolet disinfection handbook. 2nd ed. Denver (CO): American Water Works Association; 2011.
8. Bourouiba L. Turbulent gas clouds and respiratory pathogen emissions: potential implications for reducing transmission of COVID-19. JAMA. 2020; 323(18):1837–1838.
9. Bourouiba L, Dehandschoewercker E, Bush JWM. Violent expiratory events: on coughing and sneezing. J Fluid Mech. 2014; 745:537–563.
10. Buonanno M, Randers-Pehrson G, Bigelow AW, Trivedi S, Lowy FD, et al. 207-nm UV Light - a promising tool for safe low-cost reduction of surgical site infections. i: *in vitro* studies. PLoS One. 2013; 8(10): e76968.
11. Buonanno M, Welch D, Shuryak I, Brenner DJ. Far-UVC light (222 nm) efficiently and safely inactivates airborne human coronaviruses. Sci Rep. 2020; 10:10285. Erratum in: Sci Rep. 2021; 11:19569.
12. Centers for Disease Control and Prevention. Estimated COVID-19 Burden. 2022. [Accessed April 17, 2023]. Available from https://www.cdc.gov/coronavirus/2019-ncov/cases-updates/burden.html.
13. Claus H. Ozone generation by ultraviolet lamps. Photochem Photobiol. 2021; 97(3):471–476.
14. Crimaldi JP, True AC, Linden KG, Hernandez MT, Larson LT, Pauls AK. Commercial toilets emit energetic and rapidly spreading aerosol plumes. Sci Rep. 2022; 12(1):20493.
15. Heilingloh CS, Aufderhorst UW, Schipper L, Dittmer U, Witzke O, et al. Susceptibility of SARS-CoV-2 to UV irradiation. Am J Infect Control. 2020; 48(10):1273–1275.

16. Hoehl S, Karaca O, Kohmer N, Westhaus S, Graf J, et al. Assessment of SARS-CoV-2 transmission on an international flight and among a tourist group. JAMA Netw Open. 2020; 3(8):e2018044.
17. International Agency for Research on Cancer. IARC working group on the evaluation of carcinogenic risks to humans. Lyon (France): Solar and Ultraviolet Radiation; 1992. [Accessed on January 19, 2024]. Available from https://www.ncbi.nlm.nih.gov/books/NBK401588/.
18. International Air Transport Association. Cabin air & low risk of on board transmission. [Accessed May 1, 2023]. Available from https://www.iata.org/en/youandiata/travelers/health/low-risk-transmission/.
19. International Civil Aviation Organization. Manual on COVID-19 cross-border risk management. Montreal (Canada): International Civil Aviation Organization. 2021. Report No.: Doc. 10152.
20. International Electrotechnical Commission. Photobiological safety of lamps and lamp systems. 2006. Report No.: IEC 62471:2006.
21. Jones RM, Brosseau LM. Aerosol transmission of infectious disease. J Occup Environ Med. 2015; 57(5):501–508.
22. Kennedy HE. Ultraviolet air and surface treatment. In: 2019 ASHRAE Handbook—HVAC Applications. Atlanta (GA): American Society of Heating, Refrigerating and Air-conditioning Engineers; 2019:62.1–62.17. Available from https://www.ashrae.org/file%20library/technical%20resources/covid-19/i-p_a19_ch62_uvairandsurfacetreatment.pdf.
23. Khanh NC, Thai PQ, Quach H-L, Thi N-AH, Dinh PC, et al. Transmission of SARS-CoV 2 during long-haul flight. Emerg Infect Dis. 2020; 26(11):2617–2624.
24. Kinahan SM, Silcott DB, Silcott BE, Silcott RM, Silcott PJ, et al. Aerosol tracer testing in Boeing 767 and 777 aircraft to simulate exposure potential of infectious aerosol such as SARS-CoV-2. PLoS One. 2021; 16(12): e0246916.
25. Kowalski W. Ultraviolet germicidal irradiation handbook: UVGI for air and surface disinfection. Berlin, Heidelberg (Germany): Springer; 2009.
26. Ma B, Burke-Bevis S, Tiefel L, Rosen J, Feeney B, Linden KG. Reflection of UVC wavelengths from common materials during surface UV disinfection: assessment of human UV exposure and ozone generation. Sci Total Environ. 2023; 869:161848.
27. Ma B, Linden YS, Gundy PM, Gerba CP, Sobsey MD, Linden KG. Inactivation of coronaviruses and Phage Phi6 from irradiation across UVC wavelengths. Environ Sci Technol Lett. 2021; 8(5):425–430.
28. Masjoudi M, Mohseni M, Bolton JR. Sensitivity of bacteria, protozoa, viruses, and other microorganisms to ultraviolet radiation. J Res Natl Inst Stand Technol. 2021; 126:126021.
29. Memarzadeh F. A review of recent evidence for utilizing ultraviolet irradiation technology to disinfect both indoor air and surfaces. Appl Biosaf. 2021; 26(1):52–56.
30. Michelini Z, Mazzei C, Magurano F, Baggieri M, Marchi A, et al. Ultraviolet SANitizing system for sterilization of ambulances fleets and for real-time monitoring of their sterilization level. Int J Environ Res Public Health. 2022; 19(1):331.
31. Morawska L, Tang JW, Bahnfleth W, Bluyssen PM, Boerstra A, et al. How can airborne transmission of COVID-19 indoors be minimised? Environ Int. 2020; 142:105832.
32. Moser MR, Bender TR, Margolis HS, Noble GR, Kendal AP, Ritter DG. An outbreak of influenza aboard a commercial airliner. Am J Epidemiol. 1979; 110(1):1–6.
33. Narita K, Asano K, Naito K, Ohashi H, Sasaki M, et al. Ultraviolet C light with wavelength of 222 nm inactivates a wide spectrum of microbial pathogens. J Hosp Infect. 2020; 105(3):459–467.
34. Naunovic Z, Lim S, Blatchley ER. Investigation of microbial inactivation efficiency of a UV disinfection system employing an excimer lamp. Water Res. 2008; 42(19):4838–4846.
35. Oh C, Sun PP, Araud E, Nguyen TH. Mechanism and efficacy of virus inactivation by a microplasma UV lamp generating monochromatic UV irradiation at 222 nm. Water Res. 2020; 186:116386.
36. Olsen SJ, Chang H-L, Cheung TY-Y, Tang AF-Y, Fisk TL, et al. Transmission of the severe acute respiratory syndrome on aircraft. N Engl J Med. 2003; 349(25):2416–2422.
37. Raeiszadeh M, Adeli B. A critical review on ultraviolet disinfection systems against COVID-19 outbreak: applicability, validation, and safety considerations. ACS Photonics. 2020; 7(11):2941–2951.
38. Rafferty AC, Bofkin K, Hughes W, Souter S, Hosegood I, et al. Does 2x2 airplane passenger contact tracing for infectious respiratory pathogens work? A systematic review of the evidence. PLoS One. 2023; 18(2):e0264294.
39. Ramos CCR, Roque JLA, Sarmiento DB, Suarez LEG, Sunio JTP, et al. Use of ultraviolet-C in environmental sterilization in hospitals: a systematic review on efficacy and safety. Int J Health Sci (Qassim). 2020; 14(6):52–65.
40. Redrow J, Mao S, Celik I, Posada JA, Feng Z. Modeling the evaporation and dispersion of airborne sputum droplets expelled from a human cough. Build Environ. 2011; 46(10):2042–2051.
41. Reed NG. The history of ultraviolet germicidal irradiation for air disinfection. Public Health Rep. 2010; 125(1):15–27.
42. Riley RL, Nardell EA. Clearing the air: the theory and application of ultraviolet air disinfection. Am Rev Respir Dis. 1989; 139(5):1286–1294.
43. Sellera FP, Sabino CP, Cabral FV, Ribeiro MS. A systematic scoping review of ultraviolet C (UVC) light systems for SARS-CoV-2 inactivation. J Photochem Photobiol. 2021; 8:100068.
44. Silcott D, Kinahan SM, Santarpia JL, Silcott B, Silcott R, et al. TRANSCOM/AMC Commercial Aircraft Cabin Aerosol Dispersion Tests. Omaha (NE): National Strategic Research Institute; 2020. Available from https://apps.dtic.mil/sti/pdfs/AD1118088.pdf.
45. Sliney D. Balancing the risk of eye irritation from UV-C with infection from bioaerosols. Photochem Photobiol. 2013; 89(4):770–776.
46. Sliney DH, Stuck BE. A need to revise human exposure limits for ultraviolet UV-C radiation. Photochem Photobiol. 2021; 97(3):485–492.
47. Spicer DB. Methods and mechanisms of photonic disinfection. J Res Natl Inst Stand Technol. 2021; 126:126016.
48. Stamatas GN, Nikolovski J, Mack MC, Kollias N. Infant skin physiology and development during the first years of life: a review of recent findings based on *in vivo* studies. Int J Cosmet Sci. 2011; 33(1):17–24.
49. Sze To GN, Wan MP, Chao CYH, Fang L, Melikov A. Experimental study of dispersion and deposition of expiratory aerosols in aircraft cabins and impact on infectious disease transmission. Aerosol Sci Technol. 2009; 43(5):466–485.
50. Tang JW, Bahnfleth WP, Bluyssen PM, Buonanno G, Jimenez JL, et al. Dismantling myths on the airborne transmission of severe acute respiratory syndrome coronavirus-2 (SARS-CoV-2). J Hosp Infect. 2021; 110: 89–96.
51. U.S. Food and Drug Administration. Ultraviolet (UV) Radiation. 2020. [Accessed November 18, 2023]. Available from https://www.fda.gov/radiation-emitting-products/tanning/ultraviolet-uv-radiation.
52. Walkinshaw DS. A brief introduction to passenger aircraft cabin air quality. ASHRAE J. 2020; 62(10):12–18. [Accessed January 19, 2024]. Available from https://www.ashrae.org/file%20library/technical%20resources/covid-19/12-19_walkinshaw.pdf.
53. Wang CC, Prather KA, Sznitman J, Jimenez JL, Lakdawala SS, et al. Airborne transmission of respiratory viruses. Science. 2021; 373(6558): eabd9149.
54. Welch D, Kleiman NJ, Arden PC, Kuryla CL, Buonanno M, et al. No evidence of induced skin cancer or other skin abnormalities after long-term (66 week) chronic exposure to 222-nm far-UVC radiation. Photochem Photobiol. 2023; 99(1):168–175.
55. Whalen JJ. Environmental control for tuberculosis: basic upper-room ultraviolet germicidal irradiation guidelines for healthcare settings guide. Washington (DC): National Institute for Occupational Safety and Health; 2009. Report No.: (NIOSH) 2009-105. [Accessed January 19, 2024]. Available from https://stacks.cdc.gov/view/cdc/5306.
56. Woods JA, Evans A, Forbes PD, Coates PJ, Gardner J, et al. The effect of 222-nm UVC phototesting on healthy volunteer skin: a pilot study. Photodermatol Photoimmunol Photomed. 2015; 31(3):159–166.
57. World Health Organization. WHO reveals leading causes of death and disability worldwide: 2000-2019. 2020. [Accessed January 31, 2023].

Available from https://www.who.int/news/item/09-12-2020-who-reveals-leading-causes-of-death-and-disability-worldwide-2000-2019.
58. World Health Organization. World health statistics 2022: monitoring health for the SDGs, sustainable development goals. 2022. [Accessed January 31, 2023]. Available from https://www.who.int/publications-detail-redirect/9789240051157.
59. Xiao F, Sun J, Xu Y, Li F, Huang X, et al. Infectious SARS-CoV-2 in feces of patient with severe COVID-19. Emerg Infect Dis. 2020; 26(8): 1920–1922.
60. You R, Lin C-H, Wei D, Chen Q. Evaluating the commercial airliner cabin environment with different air distribution systems. Indoor Air. 2019; 29(5):840–853.