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Methods of Aircraft Disinfection to Reduce Airborne Infectious Disease Transmission

Charles DeJohn; Kris Belland; Diego Garcia

INTRODUCTION: This review aims to assess the safety and efficacy of the use of ultraviolet-C technology for disinfecting aircraft and compare it with other methods currently used in the aviation industry.

METHODS: The authors conducted a comprehensive, systematic review of the literature on disinfection of aircraft. Independent double reviews were conducted and consultations with a third reviewer were performed in the event of disagreements.

DISCUSSION: Although infectious disease transmission in aircraft cabins has been shown to be low, a recent study has described reports of passengers on commercial aircraft infecting other passengers. Incorporating ultraviolet-C technology into aircraft disinfection protocols holds the potential to add a significant level of risk mitigation to effectively reduce disease transmission and enhance safety.

KEYWORDS: pathogen, transmission, disinfection, risk mitigation, ultraviolet-C, UV-C.

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Previous studies have documented the occurrence of various respiratory illnesses, including influenza and severe acute respiratory syndrome (SARS) on aircraft.[1,2] While the transmission of infectious diseases within aircraft cabins is generally low, instances of passengers infecting fellow travelers on commercial flights have been documented, and a 2023 study found strong evidence of in-flight transmission.[3]

One promising approach is the incorporation of ultraviolet-C (UV-C) technology into aircraft disinfection protocols. UV-C is ultraviolet (UV) radiation with wavelengths between 100–280 nm. This technology has the potential to significantly mitigate the risk of disease transmission when proper optical engineering controls are in place. The optical engineering system should be designed with multiple redundancies to provide reliable emitter processing integrity, employing the use of multiple redundant sensor-types, such as ultrasound and infrared ranging. The application of UV-C light can potentially deactivate pathogens that might be introduced if an infected passenger boards the aircraft following episodic disinfection between flights. While further research is needed to fully endorse continuous UV-C utilization on aircraft, this review suggests that combining UV-C disinfection with proper optical engineering controls, together with other methods, could contribute to maintaining a safer aircraft cabin environment.

The objective of this study is to conduct a comprehensive literature review to compare the safety and effectiveness of different methods currently used for disinfecting aircraft and explore the potential benefits and limitations of using UV-C technology as an adjunct to current methods of aircraft disinfection.

METHODS

A systematic search was conducted to identify relevant studies on the efficacy and safety of different methods of aircraft disinfection, with an emphasis on UV disinfection. Multiple electronic databases, including Google Scholar, PubMed, Medline,

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EMBASE, Scopus, and Web of Science, were searched using keywords related to aircraft disinfection, air travel, manual disinfection, UV robotic disinfection, high efficiency particulate air (HEPA) filtration, UV disinfection, UV-C, and infectious diseases. Time of publication was restricted to 1985–2023. The search was limited to articles published in English.

The initial search yielded 1056 articles, which were screened based on their titles and abstracts by three different reviewers. Duplicated papers and studies that did not directly address methods of aircraft disinfection or were not focused on airborne transmission of diseases were excluded. Articles of potentially relevant studies were retained for further evaluation. In addition to the initial literature search, manuals and policy documents were also used to obtain further references.

The inclusion criteria for the review were as follows: 1) studies that evaluated the efficacy or safety of aircraft disinfection, 2) studies that provided quantitative or qualitative data on the effectiveness of disinfection methods, and 3) studies conducted in both laboratory and real-world settings. Exclusion criteria included studies that focused solely on surface disinfection, as well as studies that did not provide sufficient information on the disinfection methods employed.

After inclusion and exclusion criteria were applied, 38 studies were included. The quality of the included studies was assessed employing an independent double review process using a modified Sanra-JBI scale (Appendix, found online at https://doi.org/10.3357/AMHP.6348sd.2024). Any discordance between reviewers was resolved through a third reviewer. The articles used in this study are publicly available, and the authors did not have access to subject privacy information; therefore, the study was not considered human subject research and was Institutional Review Board exempt.

DISCUSSION

Pathogen transmission can potentially occur aboard an aircraft when individuals who are infected with the virus travel while exhibiting symptoms or during infectious presymptomatic periods of the illness.[2] The virus is typically released when an individual talks, coughs, sneezes, or sings, primarily in the form of droplets that have the potential to travel short distances. In some cases, it can also disperse as smaller aerosol particles, which can remain suspended in the air and travel greater distances.[4] Transmission takes place when these particles make contact with another person's mouth or nose, either through direct exposure or by touching contaminated surfaces.[5]

Although some studies have shown that infectious disease transmission in aircraft cabins has been relatively low,[6–8] international air traffic has been shown to influence the global transmission of SARS-CoV-2,[9] and studies have described reports of passengers infecting other passengers.[3,10,11] A 2023 study by Rafferty et al. showed strong evidence for in-flight transmission of a range of respiratory pathogens on airline flights worldwide, particularly for SARS-CoV-2. Overall, 43.6% (72/165) of investigations studied provided evidence for in-flight transmission,[3] implying it is a serious health concern. In light of these findings, it is essential to explore ways to reduce the risk of disease transmission.

A recent risk analysis by Allen and Mills concluded that in-flight transmission of seasonal influenza on U.S. air carriers ultimately resulted in an average of 950,000 infections and over 600 deaths per year at a cost of $1.6 billion (Allen G, Mills W. Personal communication; 2023). The COVID-19 pandemic has further highlighted the potential risk of in-flight transmission of infectious diseases. During the Delta wave of the COVID-19 pandemic from February 2020 through September 2021, in-flight transmission was responsible for a total of over 2 million infections, approximately 8000 deaths, and over $200 billion in additional economic costs (Allen G, Mills W. Personal communication; 2023). It should be noted, however, that these estimates encompassed both the initial transmission of the disease to passengers during flight and subsequent infections among individuals who were later exposed.

The COVID-19 pandemic has prompted the aviation industry to implement a range of measures aimed at minimizing the risk of in-flight transmission of infectious diseases. These measures encompass several key strategies, including mandatory mask-wearing, adherence to social distancing guidelines, manual cleaning of aircraft interiors between flights, and the utilization of robotic UV light within the cabin during the turnaround process. While these measures have undeniably contributed to mitigating the risk of in-flight transmission of COVID-19 and other diseases, it is evident that the challenge of preventing in-flight transmission of infectious diseases persists within the aviation sector. In this review, our primary focus will revolve around the comparison of the use of UV light as an additional disinfection method in aircraft cabins and how it may integrate with other methods of aircraft disinfection.

Manual cleaning has been widely recognized as an effective method for the disinfection of aircraft cabin interior surfaces.[12,13] However, manual disinfection presents notable limitations. One major concern is the possibility of recontamination of the cabin interior if an infectious passenger boards the aircraft following the completion of the cleaning process. Furthermore, human error is a potential drawback of manual disinfection. The reliance on human diligence introduces the potential for inconsistencies in the quality of cleaning. Cleaning personnel may inadvertently fail to apply disinfectants correctly or overlook certain areas, compromising the effectiveness of the cleaning process and increasing the risk of disease transmission. Another challenge associated with manual disinfection is the time-consuming, labor-intensive nature of the process. Because manual cleaning is normally conducted between flights, this can lead to longer turnaround times, which can impact operational efficiency and potentially result in delays and scheduling challenges. Moreover, manual disinfection alone may not be sufficient to effectively control the spread of highly infectious diseases, even when strong cleaning agents are employed. However, the use of aggressive cleaning agents raises concerns regarding potential harm to aircraft cleaners, passengers, and crew, emphasizing the need for alternative or

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supplementary measures to ensure comprehensive protection. The risk of recontamination, potential for human error, time and labor requirements, and the potential need for additional measures to control the spread of infectious diseases are factors that should be carefully considered if manual cleaning is used for aircraft cabin disinfection. Exploring a combination of manual cleaning, enhanced aircraft ventilation, and automated systems could potentially address these challenges, providing a more comprehensive approach to disinfection and ensuring the safety of passengers and crew members.

Episodic robotic disinfection between flights has proven effective in temporarily decontaminating aircraft cabin surfaces and is recognized as an effective approach for reducing the risk of transmission of COVID-19 and other infectious diseases.[14] Equipped with UV lamps, these robots navigate the aircraft cabin, emitting UV light to primarily disinfect surfaces. During the COVID-19 pandemic, airlines started implementing robotic technology to disinfect aircraft between flights.[15,16] However, the effective performance of robotic cleaning systems depends on the quality of their hardware, software, sensors, algorithms, and sophisticated programming.[14] Robust and reliable technologies are crucial for ensuring accurate navigation of the cabin interior and proper coverage, and the required level of robotic technology may not yet be universally available. Another major concern of robotic cleaning systems is that once the disinfection process is complete, if an infected passenger boards the aircraft, the cabin is no longer disinfected. Although significant progress has been made in the adoption of robotic technologies for disinfection, the level of UV radiation they currently employ could pose a hazard to human skin and eyes.[17] Therefore, the most effective approach would be to combine robotic disinfection with other methods of aircraft disinfection.

HEPA filters, as part of the aircraft environmental control systems, play a crucial role in purifying cabin air and reducing the risk of infectious disease transmission during flights. In multilayered decontamination systems, the various mitigation measures act as layers. Risk can be reduced through the combined application of these mitigation measures, such as HEPA filters and a high cabin air-flow rate, although the extremely high air-flow rate is primarily responsible for the disinfection of cabin air.

Most airliners maintain cabin air quality and cabin pressure by using a blend of approximately 50% fresh outdoor air and 50% air that has been recirculated and filtered through a HEPA filter.[18] HEPA filters are at least 99.97% efficient at filtering 0.3-μm particles. The most penetrating particle size is 0.2 μm (99.94% efficient), with penetration greater for both smaller and larger particles.[19] HEPA filters are highly efficient at removing most viruses from the air; however, for HEPA filters to work effectively, airborne pathogens must first pass through them. The effectiveness of HEPA filters relies on proper maintenance. A dirty or damaged filter can compromise its performance, emphasizing the necessity of regular replacement and maintenance to ensure optimal filtration efficiency. It is recommended that HEPA filters be replaced at least once a year or more frequently if they become clogged or damaged.[18] In addition, the air circulation systems in cabins could potentially facilitate the movement of droplets generated by an infected passenger throughout the cabin cross-section. This poses a risk as these droplets can potentially infect passengers several rows before and after the index patient. Despite significant advancements, Wang concluded that current airliner cabin environmental control systems have made limited progress in mitigating the risk of disease transmission.[20] Consequently, without a supplemental method of continuous in-flight decontamination, the potential for disease transmission between occupants in flight, relying on HEPA filtration alone, might not be sufficient for continuous in-flight disinfection. A comprehensive approach, combining multiple preventive measures, may be necessary to further minimize the risk of aerosol pathogen transmission during air travel. These measures may include a combination of enhanced ventilation systems, the use of UV-light disinfection, improved episodic methods, and strict adherence to other preventive measures such as mask-wearing and social distancing.

The integration of continuous UV-C light for disinfecting cabin air in flight has recently been investigated as an adjunct to other modes of aircraft disinfection. UV-C light emitting diodes (LEDs) have emerged as effective tools for inactivating microorganisms and hold potential for disinfecting aircraft cabin air.[21] UV-C light has a broad-spectrum disinfection capability, enabling it to target a wide range of microorganisms, including bacteria and viruses.[22–24] It effectively inactivates pathogens by damaging their deoxyribonucleic acid (DNA). The primary mechanism of inactivation is in the formation of pyrimidine dimers between neighboring thymine bases, rendering the microbe unable to replicate.[25,26]

Because UV-C light could potentially be used continuously in flight, it may be effective at decontaminating the cabin if a contaminated passenger were to board the aircraft following episodic disinfection. Unlike chemical-based disinfection methods, UV-C disinfection does not rely on the use of strong cleaning agents that can leave behind residues posing potential health risks to passengers and crew members.

UV radiation could pose a hazard to human skin and eyes, particularly if the recommended exposure limit (EL) is exceeded and proper engineering safeguards are not employed. However, Far UV-C radiation distinguishes itself from UV-A and UV-B by its limited ability to penetrate the stratum corneum of the skin, or the corneal epithelium of the eye.[27,28] In addition, when proper optical engineering controls are employed and the dose (irradiance × exposure time) received by individuals is held below the EL,[29] its use is considered by some researchers to be safe for short-term human exposure.[22,28,30]

While UV-C LEDs offer an additional risk-mitigation layer in aircraft cabin air disinfection, careful consideration should be given to include additional cleaning methods. The different disinfection methods are summarized in **Table I**.

As early as 1845, researchers recognized the impact of light on microorganisms. A significant breakthrough occurred in 1877 when it was observed that exposing test tubes containing Pasteur's solution to sunlight effectively inhibited the growth of microorganisms within the tubes. Subsequent studies revealed

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Table I. Comparison of Disinfection Methods.

METHOD	RECONTAMINATION PROTECTION	INCREASED GROUND TIME	HARSH CHEMICALS	POTENTIAL HEALTH RISKS	REQUIRES MODIFICATION
Manual Cleaning		X	X	X	
Robotic UV Cleaning		X			X
HEPA Filters	X				
Continuous UV-C	X			X	X

that sunlight's bacteria-neutralizing ability depended on intensity, duration, and wavelength, with shorter wavelengths proving to be the most effective.[26]

In 1933, the concept of airborne infection through droplet nuclei was introduced. By 1935, experiments demonstrated that ultraviolet germicidal irradiation (UVGI) efficiently deactivated airborne microorganisms, confirming the concept of airborne infection transmission. In the 1960s and 1970s, the use of upper-room UVGI was introduced, and by the 1990s, extensive efforts were underway to quantitatively assess the efficacy and safety of UVGI methods.[26]

Over the years, UV-C light has found use in various fields, such as water treatment and air purification. During World War II, UV-C light was employed to disinfect air in hospitals and military facilities, further establishing its effectiveness. The 1950s saw significant technological advancements that made UV-C light for disinfection more accessible, and thus, led to its increased adoption. Today, UV-C decontamination is extensively utilized in diverse settings.[22,31,32] It serves as a valuable supplement to other cleaning and disinfection methods, effectively inactivating bacteria, viruses, and other pathogens.[21,24]

UV technologies are now being reexamined as a viable disinfection method to combat the SARS-CoV-2 virus. UV-C light has played a crucial role in the decontamination of personal protective equipment during the COVID-19 pandemic, offering a reliable method to ensure safety and mitigate the risk of transmission, and studies have evaluated its effectiveness in reducing pathogen contamination on aircraft cabin surfaces.[14,21]

Recently, there has been a growing focus on the use of continuous UV light during flights, shifting away from relying solely on episodic robotic UV disinfection between flights. The use of UV-C light could result in the reduction of the risk of infection in occupied spaces by up to 90%.[33] By targeting pathogens suspended in the air, the use of UV-C light can potentially help to reduce the risk of airborne transmission within the aircraft cabin during flight. By employing direct irradiation below the EL (DIBEL) technology, inactivation of pathogens can safely be achieved in occupied aircraft cabins during flight.[34]

Far UV-C light, due to its limited ability to penetrate the outer, nonliving layers of human skin, as well as the corneal epithelium of the eye and other organs, is considered by some researchers to be safe for short-term human exposure.[23,28,34] However, bacteria and viruses, being substantially smaller in size than the depth of human skin layers, can still be effectively neutralized by far UV-C radiation.[21]

One key advantage of UV-C disinfection is its relatively rapid disinfection process compared to traditional methods, resulting in high disinfection rates of aircraft cabins within minutes.[34,35] **Fig. 1** indicates the time in minutes required for 90% inactivation of representative pathogens at three different UV-C irradiance levels: the EL, the irradiance which could be safely used in the occupied aircraft cabin with optical engineering controls, and in an unoccupied aircraft lavatory.

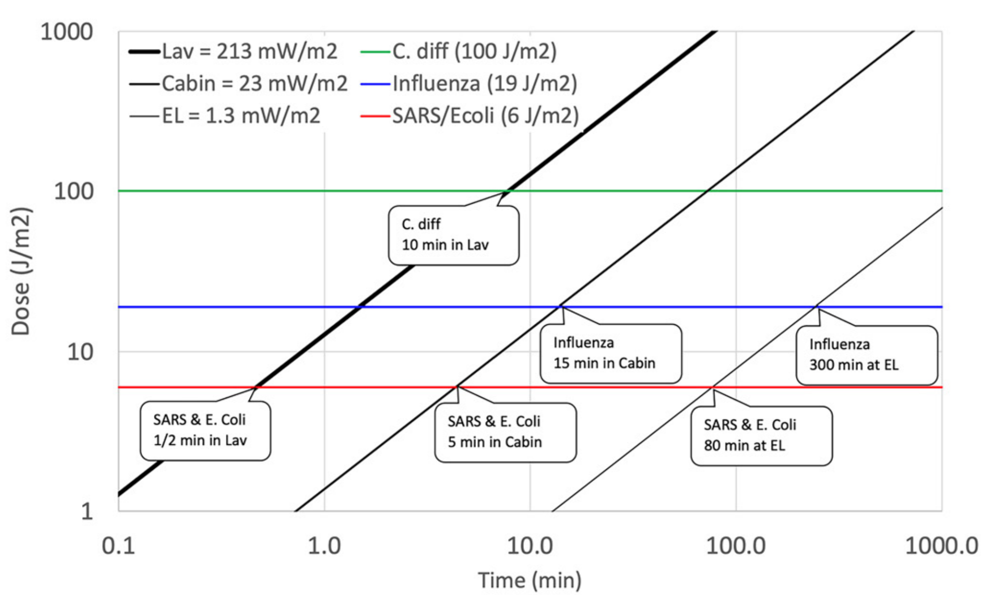

Fig. 1. Ninety-percent inactivation times for representative viruses. Graph provided by and used with permission of Gary Allen, Ph.D.

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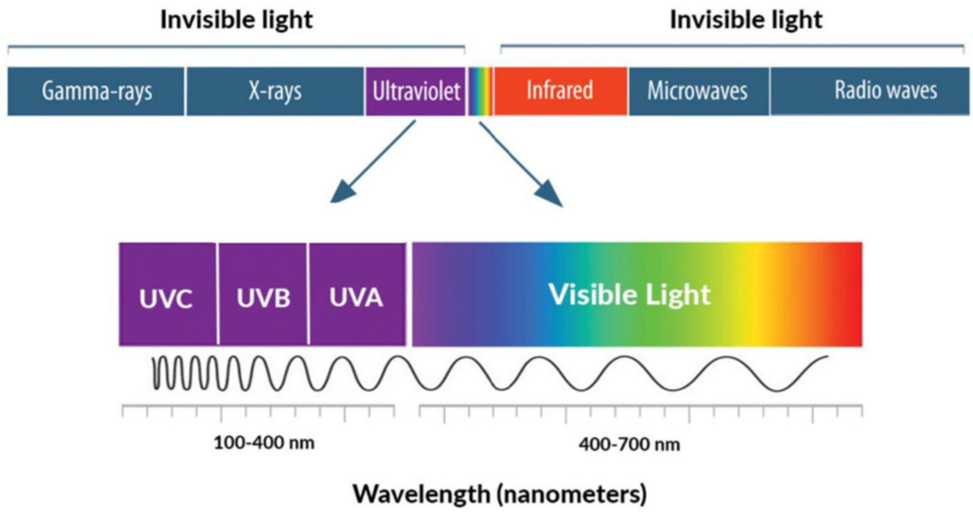

Fig. 2. Ultraviolet spectrum. (National Eye Institute. Protecting your eyes from the sun's UV light; 2022. [Accessed October 9, 2024.] Available from https://www.nei.nih.gov/about/news-and-events/news/protecting-your-eyes-suns-uv-light#:~:text=Wearing%20sunglasses%20and%20a%20hat,high%20even%20on%20cloudy%20days.)

Fig. 1 indicates that none of the pathogens are inactivated rapidly enough when limited by the EL in 5 min; however, SARS is 90% inactivated and influenza is 90% inactivated in 15 min in an occupied cabin, and *C. difficile* is 90% inactivated in 10 min in an unoccupied lavatory.

The benefits of continuous UV-C disinfection are that it does not involve the use of strong cleaning agents, it is not limited to episodic disinfection, and when used continuously with appropriate engineering controls, it could effectively decontaminate cabin air in the event of an infected passenger boarding the aircraft following episodic disinfection.

UV light can be categorized into three bands dependent upon wavelength: UV-A, UV-B, and UV-C as depicted in **Fig. 2** below. Among these bands, UV-C has a shorter wavelength, higher energy, and greater reactivity compared to UV-A or UV-B. UV-A light, due to its lower reactivity, can penetrate deeply into the epidermis without reacting with the cells of the stratum corneum or basal layer, while UV-B is mostly absorbed by the epidermis with limited penetration into the dermis. Due to its higher energy, UV-C light reacts with the outer dermal layer and does not penetrate beyond it, making it a suitable option for disinfection in occupied aircraft cabins,[28] as shown in **Fig. 3**. Similarly, UV-A light, due to its lower reactivity, can penetrate deeply into the vitreous of the eye without reacting with the cells of the cornea or lens, while UV-B is mostly absorbed by the cornea with limited penetration into the lens and vitreous. Again, due to its higher energy, UV-C light reacts with the outer cornea and does not penetrate beyond it, as shown in Fig. 3.

The limited depth to which UV-C light can penetrate human tissue can result in superficial injuries.[21,28] Acute damage can occur with a one-time overexposure that significantly surpasses the allowable EL within an 8-h period, which can result in erythema and edema of the skin and photokeratitis of the eyes, typically resolving within 1–2 d as the affected tissues repair themselves. Chronic exposure to UV-C radiation above allowable ELs can lead to more severe consequences, including an increased risk of nonmelanoma skin cancer, which can develop over time due to cumulative DNA damage.[36] Importantly, the body's natural cell turnover process may play a crucial role in resolving these injuries.[30]

Despite the potential benefits of UV-C light in these applications, it is crucial to take proper safety precautions to prevent

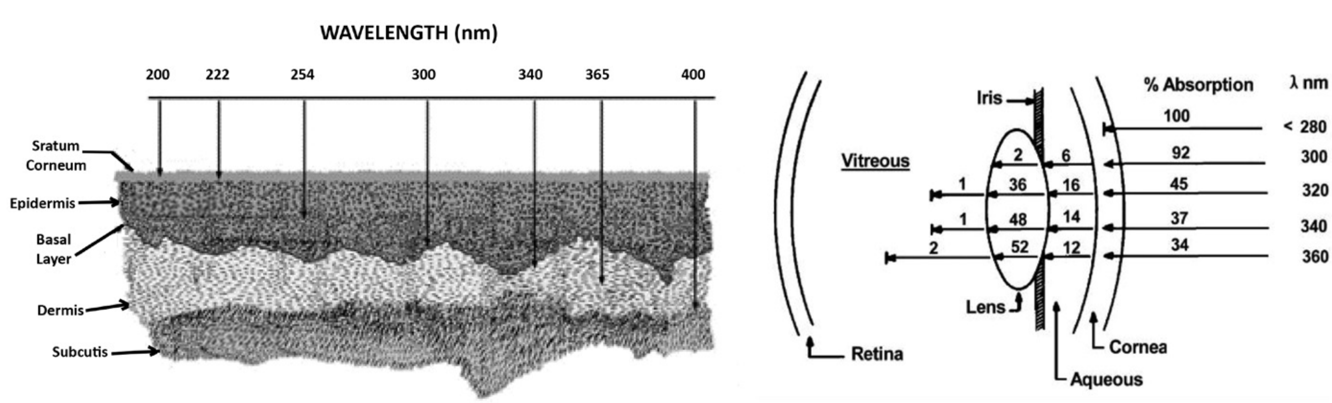

Fig. 3. Ultraviolet penetration of skin and eye. Drawings provided by and used with permission of David H. Sliney, Ph.D.

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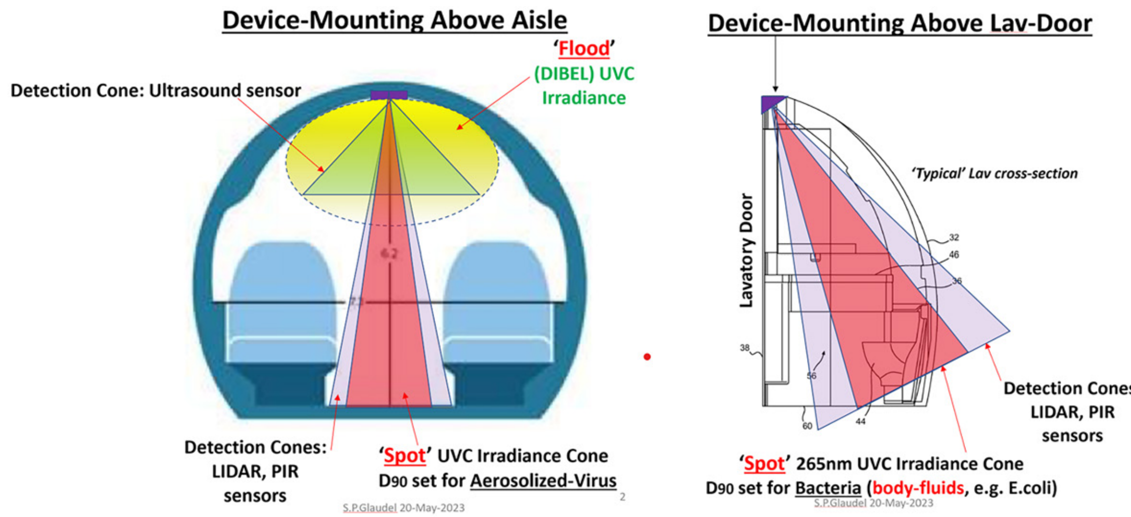

Fig. 4. Examples of engineering control systems. Drawings provided by and used with permission of Stephen Glaudel, M.B.A.

overexposure. A comprehensive source for technical information regarding UVGI and its application to air and surface disinfection has been provided by Kowalski.[37] The International Electrotechnical Commission defines an acceptable EL of $30\,J \cdot m^{-2}$ in any 8-h period.[38] The ELs were developed by considering lightly pigmented populations with the greatest sensitivity and predisposition to adverse health effects from exposure to UV light; however, ELs are not intended to apply to photosensitive individuals or to neonates.

To safeguard individuals from these consequences, it is vital to ensure UV-C exposure remains within safe limits as defined by industry-standard ELs. The development of DIBEL protocols, coupled with optical engineering controls made feasible through advancements in UV-C LED technology, are essential to maintaining UV light levels well below the recommended ELs in occupied spaces. By adhering to these ELs and implementing appropriate engineering measures, such as reliable monitoring systems as shown in **Fig. 4**, the risk of harm to the skin and eyes of aircraft occupants can be effectively minimized.

Devices installed in the cabin, such as the example shown on the left in Fig. 4, are designed to protect occupants when continuous UV-C light is employed during flight, while devices installed in the lavatory, such as the example shown on the right, are designed to provide higher levels of UV-C light only when the space is unoccupied.

While none of the international regulations and guidelines explicitly address EL interpretation beyond 8-h, additional safety margins are incorporated into ELs when applied in real-world scenarios, suggesting that irradiance may be safely applied beyond an 8-h duration. Cellular repair mechanisms allow cells to endure irradiation without cumulative damage beyond 8 h, and Sliney has suggested applying ELs for up to 24 h,[30] which could have implications for extended flight durations.

While further research is needed to firmly establish the efficacy of continuous usage of UV-C in occupied cabins, this review has found that UV-C disinfection, when implemented with the appropriate optical engineering safeguards,[30,34] holds promise in complementing other disinfection methods, thereby improving the safety of the aircraft environment. Utilizing UV-C light for disinfection in aircraft cabins appears to offer a relatively low-risk approach, free from reliance on potentially toxic chemicals and not restricted to episodic disinfection between flights. Because it could be applied continuously during flights, it could potentially neutralize pathogens that may be introduced in the event of an infected passenger boarding the aircraft following episodic disinfection between flights.[21,27,34]

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