Disinfection with Far-UV (222 nm Ultraviolet light)

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Abstract

Ultraviolet light (light at wavelengths between 100nm and 400 nm) has well-known disinfection properties. These properties stem from the ability of UV light to damage the proteins and genomic material of bacteria and viruses through the disruption of chemical bonds. Most UV disinfection systems use germicidal lamps of wavelengths 240nm-280nm, with the most common being 254nm. Unfortunately, exposure to 254nm UVC light also causes damage to skin and eyes in humans.

However, recently published studies have demonstrated that UV light at 222nm has the same germicidal capabilities of 254nm light without damaging skin or eyes. The studies suggest that this may be due to the shorter UV 222nm wavelength (known as Far-UV, 200 to 235 nm) having reduced penetration depths in live tissue when compared with 254 nm light. While the effects on live tissue are diminished, Far-UV (222 nm light being the most prevalent) has increased efficacy for killing bacteria and viruses.

Like standard UVC, Far-UV light breaks pathogen (bacteria and virus) DNA bonds, which is the primary source of microbial deactivation. Combined with the small size of bacteria and viruses, when compared to mammalian cells, the short penetration depth of Far-UV successfully deactivates these pathogens. The current literature also points to more deactivation of bacteria at lower doses of 222nm light than that required for 254nm light.

This paper provides an overview of Far-UV 222 nm technology and its disinfection capability. Far-UV 222 nm is safer and more effective than the existing 250 to 280 nm UVC systems, with advantages that include reduced UV damage to skin and eyes, faster on/off times, more rapid disinfection, and the elimination of mercury from the lamp.

Introduction

An outcome of the COVID-19 pandemic is an increased need for safe, disinfected public spaces. It is imperative to reduce risk in the commercial aviation industry, which moved one billion people across the globe in 2019.[1] Widespread public concerns of the health risks of travel have not subsided, despite data that suggest that engineering controls such as high volume air recirculation substantially reduce the risk of disease transmission in flight.[2,3] Aircraft passengers will also continue to expect reasonable gate turnaround times, and competitive aircraft fares, even as more rigorous disinfection is required between flights. Thorough and efficient disinfection procedures must be implemented to return to pre-pandemic air traffic levels quickly and cost-effectively.

Although 254 nm light is the prevalent UV source in current disinfection devices, the SARS-CoV-2 outbreak has focused interest on the potential to instead use Far-UV light in the 200 to 235 nm range for disinfection. Specifically, disinfection with 222 nm light is an attractive alternative because unlike disinfection with 254 nm light, it has been shown in recent studies that 222 nm light kills pathogens (bacteria and viruses) without causing skin and eye damage.[4–8] According to these studies, the lack of hazard is due to the fact that Far-UV light has a penetration range of only a few micrometers when interacting with cellular system components and thus cannot reach the genetic material of living mammalian cells. Pathogens, being generally less than one micron in diameter, are fully penetrated by 222 nm light, resulting in killing of the pathogen.[7]

1. The Difference Between Far-UV light and UVC light

Ultraviolet (UV) is light at wavelengths shorter than 400 nm and greater than 100 nm as shown in Figure 1. UVA is nearly visible and is the UV waveband commonly called black-light [(Merriam Webster, 2020)]. UVB is a slightly shorter waveband and is a major factor in getting sunburned. Both UVA and UVB easily enter the earth's atmosphere and are present in daylight [(Merriam Webster, 2020)]. On the other hand, the UV wavelengths shorter than UVB are blocked by ozone in the earth's upper atmosphere and are not typically present in sunlight at the surface of the earth. This is important for germicidal effectiveness because it means pathogens have not evolved defenses against shorter UV wavelengths.

Figure 1: UV Spectrum

Depending upon the reference, the entire UV spectrum to the left of UVB might be called UVC. However, this paper uses a more precise definition of the UV spectrum that breaks the 200 to 280 nm Germicidal UV range into two sub-wavebands: UVC and Far-UV. UVC light is in the 240–280 nm region of the spectrum (254 nm sources being most prevalent) and Far-UV is in the 200 to 235 nm region (222nm sources being the most prevalent). Because shorter wavelengths have more energy than longer wavelengths, UVC and Far-UV are both effective at adding energy to molecules they contact, providing an absorbance target is available. It is this ability to add energy to molecules that gives UV light its germicidal properties.

The UVC waveband has been in use for germicidal disinfection for decades. Although UVC systems in the 250 to 280 nm range are now commercially available, most UVC systems currently available use a mercury vapor lamp to generate UVC light at 254 nm. Mercury vapor lamps were first developed for disinfection in the 1930s, and their use has grown over the last 60 years. Thus, the vast majority of public data on UVC disinfection is specifically data from 254 nm mercury vapor lamps.

Only recently have companies begun to develop and market lamps in the Far-UV waveband, with 222 nm being the most prevalent. The 222 nm wavelength is proving to be both safer and more effective than the existing 254 nm UVC systems.[4–8] Far-UV 222 nm system improvements over existing UVC 254 nm systems include: reduced damage to eyes and skin, faster on/off times resulting in more rapid disinfection, and the elimination of mercury (a toxic substance) from the lamp.

Effect of Wavelength on Pathogen Molecular Bonds

Photons from 235–280 nm UVC systems are absorbed by pathogen DNA molecules. The absorbance of UVC by the pathogen DNA causes specific DNA molecular bonds to fail. Because UVC primarily causes pathogen DNA damage, the individual microbe is not generally killed immediately. However, the pathogen DNA damage can prevent the microbe from replicating. For this reason a pathogen sterilized by UVC is refered to as "inactivated." In many cases the microbe can repair the DNA damage and "reactivate" itself using ordinary blue light in a process called photo-reactivation. The photo-reactivation capability has been shown for a wide variety of bacteria and some viruses.[9] For this reason UVC data sometimes shows effectiveness both before and after reactivation.

Far-UV, on the other hand, is absorbed by both pathogen proteins and DNA. Although Far-UV is absorbed by pathogen DNA, its second pathogen kill mechanism is breaking the peptide bonds in the outer protein coating of single cell microbes and viruses. Pathogen protein absorbs 20 times more 222 nm Far-UV energy than 254 nm UVC energy for the same number of photons. Thus, pathogen protein bonds are 20 times more likely to fail due to the energy absorption from 222 nm light than 254 nm. This dual kill mechanism of both pathogen DNA damage and protein shell damage greatly increases the effectiveness of 222 nm Far-UV compared to 254 nm UVC and prevents microbes from photo-reactivation. Figures 2 and 3 show DNA and protein absorption rates for UVC and two commercially available Far-UV wavelengths at both 222 and 230 nm.

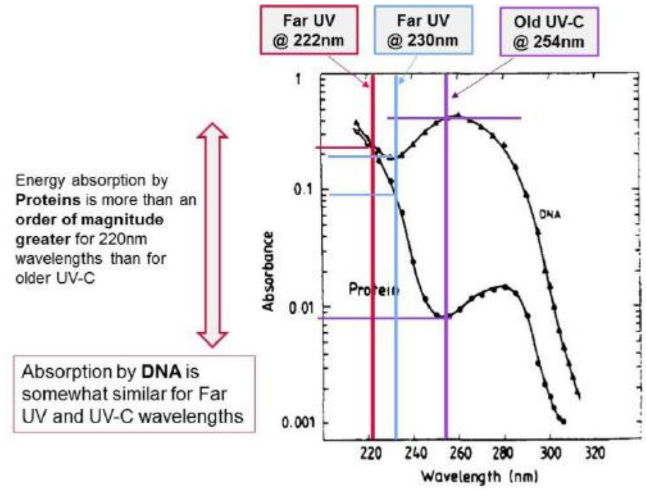

Figure 2: UV Absorption by Proteins & DNA ***(reproduced from Harm 1980)***

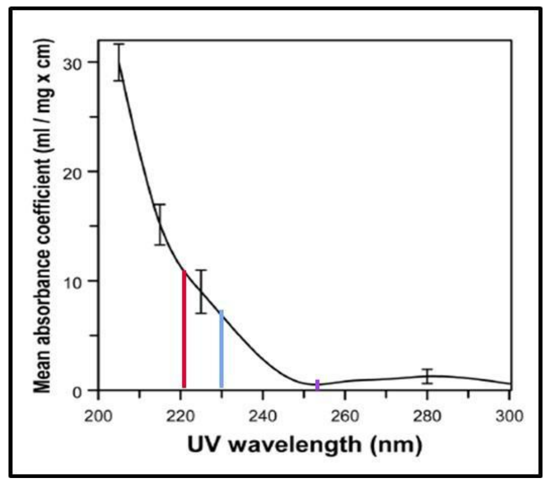

Figure 3: Mean wavelength-dependent UV absorbance coefficients, averaged over published measurements for eight common proteins

2. Far-UV light efficacy

UV dosage (also known as fluence) is measured in units of millijoules per square centimeters (mJ/cm^2). This dosage is the product of the intensity of the light and the exposure time. A millijoule (mJ) is one thousanth of a watt or milliwatt (mW) of power times one second of time. For example, 20 mJ/cm^2 can be achieved by projecting ten milliwatts of light power onto one square centimeter for two seconds.

The exact UV dosage required to kill or inactivate varies for specific pathogens and a specific wavelength of UV light. In general, the Far-UV 222 nm or UVC 254 nm dose is similar for most pathogens. Some pathogens require as little as two millijoules per square centimeter (~2 mJ/cm^2) of Far-UV or UVC to be killed or inactivated. A wide variety of pathogens can be killed or inactivated with less than twenty millijoules per square centimeter (~20 mJ/cm^2) of Far -UV or UVC light.

The reduction of micro-organisms (either killed or inactivated) is classified using a logarithmic scale. A single log reduction is a 90% reduction of organisms. A two log reduction is a 99% reduction of organisms, followed by a three log reduction (99.9%), etc. For most applications, a three log reduction (99.9%) is sufficient to greatly reduce pathogen transmission.

Far-UV 222 nm Effectiveness Against Surface and Airborne Coronavirus

Both UVC and Far-UV wavelengths have been tested against a variety of pathogens. This paper focuses primarily for efficacy against coronaviruses.

Dr. David Brenner and others from Columbia University have been investigating 222 nm Far-UV efficacy against airborne human coronaviruses alpha HCoV-229E and beta HCoV-OC43[7]. According to their research, as shown in Figure 4, low doses of 1.7 and 1.2 mJ/cm^2 inactivated 99.9% (Log 3 reduction) of aerosolized coronavirus 229E and OC43, respectively.

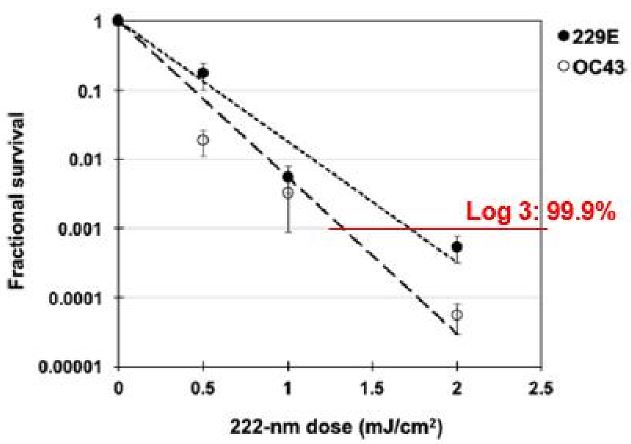

Figure 4: Coronavirus survival as function of the dose of Far-UV light. Fractional survival, PFUUV/PFU controls, is plotted as a function of the 222 nm Far-UV dose.

A related study published in the American Journal of Infection Control examined the effectiveness of Far-UV 222 nm against the SARS-CoV-2 virus on surfaces.[10] In this study, a Far-UV 222 nm dose of 3 mJ/cm^2 results in a 99.7% reduction in viable SARS-CoV-2 virus on a surface.

These two studies combined show that even a two to three mJ/cm^2 dose of 222 nm Far-UV will be effective in combating transmission of the virus responsible for COVID-19. This level of Far-UV is easily achieved using 222 nm lamps.

Additionally, Boeing evaluated the efficacy of a Far-UV 222nm lamp against representative viruses and bacteria in a lab environment to get an indication of performance. A similar test was conducted with a prototype Far-UV 222nm system installed in a Boeing ecoDemonstrator 777 flight test airplane in November 2019 to validate performance.

The efficacy target was a 99.9% pathogen reduction after one 5-second exposure. Boeing was able to achieve 99.9% (log 3) reduction for all tested organisms, which included the following: *Escherichia coli* bacteria, *Pseudomonas aeruginosa* bacteria (planktonic and biofilm), the fungus *Aspergillus niger*, MS2 bacteriophage (surrogate for Norovirus), and the yeast *Rhodotorula mucilaginosa*. A reduction of 99.999% was achieved for *E. coli* and *planktonic P. aeruginosa*.

3. Far-UV 222 nm Technology Overview

All commercially available Far-UV 222 nm lamps have excimer lamps at their core. Excimer lamps are a lighting technology that excite a gas using high voltage electric discharges. Different gas mixtures generate different frequencies of light. Far-UV 222 nm light is produced by excimer lamps filled with a mixture of krypton (Kr) and chloride (Cl) gas (normally less than 3% chloride). These Kr/Cl excimer lamps can be made in many form factors, but are typically cylindrical.

Kr/Cl 222 nm excimer lamps eliminate the use of hazardous materials such as mercury. The 222 nm excimer lamps are reliable and can be expected to last thousands of hours. They are capable of handling high vibrations and high thermal temperatures. They can be turned on and off at full power instantly. The output intensity of the 222 nm light can be varied by changing the input power, allowing the lamp to be instantly brightened or dimmed as required. Excimer lamps can be run at power levels from as low as a few watts to kilowatts.

Boeing Far-UV 222nm Applications

Boeing developed a Far-UV 222 nm mobile wand prototype using a Kr/Cl cylindrical lamp, as shown in Figure 5, to address the near term need for a safe, hand-operated, fully mobile UV disinfection system for complex spaces where sensitive instrumentation may exist.

Figure 5: Kr/Cl 222 nm excimer lamp in Boeing Far-UV 222nm mobile wand prototype.

The Boeing Far-UV 222nm mobile wand prototype, when operated per instruction, will effectively sanitize high touch surfaces by a single operator, and be able to treat an area such as the flight deck in less than 15 minutes. It is capable of producing the 3 mJ/cm^2 needed for SARS-CoV-2 disinfection in a fraction of a second at operational ranges.

This is in contrast to standard UVC 254 nm mercury bulbs, which require a significant warm-up time to reach full illumination power and contain the toxic chemical mercury. Mercury is not allowed on commercial aircraft without a waiver from the FAA, making mercury lamps difficult to qualify for aircraft use.

Boeing verified the system safety, material compatibility, and efficacy of the Far-UV 222 nm excimer bulb system used in the Boeing mobile wand prototype. This included performing a series of exposure tests to individual electronic components from the 737MAX, 787, and 777 flight decks using brand-new units in controlled environments simulating both the power-on and power-off states. Boeing also evaluated material compatibility, electromagnetic interference (EMI) and ozone levels.

Prior to the Far-UV 222 nm mobile UV wand development effort, *The Boeing Clean Cabin Fresh Lavatory* (Figure 6) was a product development study in 2016 that explored the use of a Kr/Cl 222 nm excimer lamps in a lavatory setting to disinfect the lavatory after every use. The learning and the technology developed for that project contributed significantly toward the rapid development of the Boeing Far-UV 222 nm mobile wand prototype.

Figure 6: Boeing product development concept of Far-UV 222 nm implementation in a 787 lavatory

4. Safety of Far-UV 222 nm

All cell walls are made from protein and Far-UV wavelengths between 200 and 230 nm interact strongly with proteins. Multiple university studies have demonstrated that 222 nm light typically will not penetrate deeper than three microns into the surface of a cell wall.[5] In the case of pathogen microbes, their diameter is typically 0.1 to 1 micron. Thus, they are fully penetrated and destroyed. Human cells, in contrast, are generally more than 40 microns in diameter and are not fully penetrated by 222 nm UV light. These studies have shown that the outer layer of the skin and the tear layer of the eyes form a protein shield for the cells beneath.[5]

Additional university studies on the safety of mammalian skin and eye exposure to 200 to 235 nm Far-UV wavelengths have been conducted. The collective body of data indicates Far-UV wavelength does not cause skin or eye damage. A 60 week study of hairless mice exposed eight hours a day to 222 nm light is being conducted by Columbia University. The current data from the study indicates no skin or eye damage over the 60 weeks.[11]

Government Regulatory UV Exposure Limits

There are no US Government regulatory UV radiation exposure limits. However, a non-governmental organization, the American Conference of Governmental Industrial Hygienists (ACGIH), publishes Threshold Limit Values (TLVs), which are recommended exposure limits over an eight-hour day and are widely used as a guideline. The UV exposure limits are wavelength dependent, ranging from 3 mJ/cm^2 to 100,000 mJ/cm^2.

Figure 7 shows the current TLVs for UV wavelengths. Note that although 222 nm light is often more effective against pathogens than light in the 254 to 270 nm range, the TLV is much higher. The TLV for 222 nm, 254 nm, and 270 nm is 23, 6, and 3mJ/cm2 respectively. Since the coronavirus disinfection dose is approximately 3mJ/cm2, at 270 nm the disinfection dose and the threshold limit for human exposure are the same. This implies that even incidental exposure to 270 nm light may exceed the Threshold Limit.

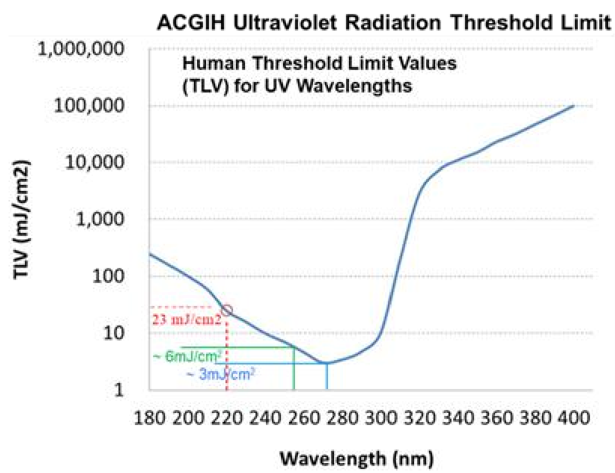

Figure 7: Threshold Limit Values (TLVs) for UV Light

The current TLV for 222 nm light does not reflect the recent data indicating that Far-UV (200 to 235 nm) light does not cause the DNA lesions, erythema, photo-keratitis, and other associated effects of 254 nm light exposure. The American Conference of Governmental Industrial Hygienists (ACGIH) is currently reviewing the 222 nm safety data with the goal of revising the TLV upward for 222 nm light. Progress toward this revision is ongoing. Although studies have shown 222nm light is safer than 254 nm light, use of appropriate personal protective equipment (PPE) remains necessary when using high powered 222 nm systems until the ACGIH revises the TLV.

Ozone Generation

All UV lights generate some level of ozone and so care must be taken accommodate that. Most of the ozone generated by 222 nm excimer lamps is a result of high voltage interaction at the outer electrodes. This can be mitigated by placing the lamp behind a sealed UV transparent glass. In addition, some ozone is generated by 222 nm photon interaction with air. This is generally mitigated by air exchange.

5. Summary

Ultraviolet (UV) light in the 222 nm wavelength has the same germicidal capabilities of 254 nm light to kill or inactivate pathogens (bacteria and viruses) without the same damaging effects of 254 nm exposure on the skin or eyes. This is due to the shorter UV wavelengths (known as Far-UV, wavelength 200 to 235 nm), that have reduced penetration depths in live tissue when compared with standard UVC (240 to 280 nm) light. While the effects on live tissue, such as skin and eyes, are diminished, Far-UV (222 nm light being the most prevalent) has increased efficacy for killing bacteria and viruses.

Like standard UVC, Far-UV light breaks pathogen DNA bonds. In addition, Far-UV is highly effective at breaking protein bonds in the membrane shells of pathogens, including SARS CoV-2. This same protein interaction makes Far-UV 222 nm much safer for human exposure, including: reduced UV damage to skin and eyes, faster on/off times, more rapid disinfection, and the elimination of mercury from the lamp.

Boeing recently entered into patent and technology licenses with Healthe® Inc. and FarUV Technologies. Under these licenses, both companies will produce and distribute a commercial Far-UV 222 nm mobile wand, helping airlines and potentially others reduce the impact of the coronavirus pandemic.

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