Laboratory of Intelligent Manufacturing, Design and Automation

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Mechanical Engineering

Surface Disinfection Using UV Light – Emerging Technologies and Applications

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Introduction

The use of ultraviolet (UV) light for sterilization and disinfection is a technology that has been around for over a hundred years. UV light has a shorter wavelength than visible light, and has the ability to kill or inactivate pathogens such as viruses. Multiple studies have been conducted on the nature of UV light for disinfection purposes.

With the current COVID-19 pandemic affecting people all over the world, the scientific community has taken a renewed interest in UV light and its disinfectant properties. This is especially so because conventional cleaning methods rely heavily on human workers and are often ineffective in eliminating pathogens. There is also a high risk of infection for the human workers. The use of UV light for disinfection is an additional preventative measure against the spread of disease as it can be used to effectively limit the transmission of viruses and other pathogens.

The motivation behind this research was to help find a way for society to combat the global COVID-19 pandemic. This research was conducted in the hopes that it would provide potential solutions to minimize the spread of the virus and keep more people safe.

This presentation reviews and documents the current state of research regarding:

- Types of UV light used for disinfection
- Sources of UV light
- Application specific UV lights
- Emerging technologies such as autonomous robots that may be incorporated into UV light disinfection

The focus is primarily on surface and air disinfection, as well as 222 nm length UVC light.

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Research Methodology

This research was conducted as a literature review, involving the summary and analysis of multiple scholarly articles and pieces of literature. Videos and websites of commercially available technologies regarding UV disinfection were also looked into.

Part 1: UVGI and Types of UVC

- Topics of research included 207 nm, 222 nm, and 254 nm UVC light
- Researched their efficacy and their effects on the human body

→

Part 2: Sources of UV Light

- Looked at literature on mercury-based UV lamps, excimer lamps, pulsed xenon lamps, and UV LEDs
- Researched how they function, as well as their advantages and disadvantages

→

Part 3: Applications

- Researched a variety of UV light applications, including automated room disinfection systems, reuse of N95 masks, reducing surgical-site infections, disinfection in ambulances, and more

→

Part 4: Emerging Technologies

- Compiled information on UV robots for disinfection, as well as sensors for pathogen detection

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1.0 UVGI and Types of UVC

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1.1 Ultraviolet Germicidal Irradiation (UVGI)

- There are three primary classifications of the UV light spectrum: UVA (320-400 nm), UVB (280-320 nm), UVC (200-280 nm)[9]
- The light with the most powerful germicidal properties is UVC light, which RNA/DNA bases and protein heavily absorb (UVA and UVB lights are not as heavily absorbed as UVC and are generally not powerful enough to inactivate/kill pathogens)[9]

How does UVGI work?[9]

- After absorption of UVC light in the RNA/DNA bases and proteins of pathogens, photodimerization leads to damage in the pathogen's molecular structure
- When the molecular structure is changed, the pathogen no longer has the ability to replicate and it is inactivated

Factors Affecting the Efficacy of UVGI[9]

- Protein and aqueous media surrounding the pathogens will competitively absorb UV photons
- Culture size, culture medium, and shape/size of the material that the pathogen is situated on also greatly impacts the efficacy of UVC doses
- Pathogens also may not receive the full applied dose as well
  - Absorption or shadowing effects in the material surrounding the pathogen result in a lower received dose

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1.2 Conventional Germicidal UVC and Far-UVC

Conventional Germicidal 254 nm UVC

- 254 nm UVC light is a wavelength that is very strongly absorbed by RNA, DNA and other proteins, and has traditionally been the most commonly used wavelength[9]
- It is able to reach cell nuclei with minimal attenuation[18]
- Note: Although 254 nm UV light is effective in inactivating viruses, it can leave harmful effects on human skin and eyes when used directly or in occupied spaces[9]
  - Unprotected use of 254 nm can lead to skin cancer and formation of cataracts[4]

207-222 nm Far-UVC Light

- Far-UVC light is a small light range (207 nm to 222 nm) within the UV spectrum that is able to inactivate pathogens without harming human tissues[6]
- Researchers have shown that 222 nm UVC radiation does not lead to skin cancer through multiple experiments
  - One such experiment exposed 222 nm germicidal lamps to mice with increased susceptibility to UV light, and the mice did not develop any sign of cancer or cataracts[18]

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1.3 Why Isn't Far-UVC Harmful to Humans?

- Although far-UVC light rays are shorter, with greater frequency and energy, their penetration distance in biological samples is limited
  - In biological materials, far-UVC light only has a range of a few micrometers at maximum and cannot even penetrate the cytoplasm of individual cells[6]
  - It is heavily absorbed by the peptide bonds in proteins as well as other biomolecules in human cells' cytoplasms[6]
- Due to this range, it is unable to contact the living cells in our skin and eyes, and is instead absorbed into the stratum corneum (the outer layer of skin composed of dead cells) or the ocular tear layer (outer tear layer which lubricates and protects the eyes, which also does not contain any living cells)[6]
  - Studies conducted on exposed human cells both *in vitro* and *in vivo* show that they do not appear to experience cytotoxic effects from far-UVC light[24]
- Due to the tiny sizes of pathogens however, far-UVC light is still able to penetrate and inactivate them[18]
  - For example, bacterial cells generally only have a maximum diameter of 1 μm, while human cells generally possess a diameter of around 10 to 25 μm[18]

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1.4 Comparing 207 nm, 222 nm, and 254 nm UVC

- A study by Buonanno et al. compared the efficacy of 207 nm, 222 nm, and 254 nm UVC, and demonstrated that they all had the same capability for killing viruses and bacteria[8]
- Studies have also been conducted on the health effects of 207 nm, 222 nm, and 254 nm UVC both *in vitro* and *in vivo*
  – Hairless mice were used for the *in vivo* study, and sections from their dorsal skin were analyzed after exposure to 207 nm, 222 nm, and 254 nm UVC light[8]
  – A minimal erythema (MED) dose test was also conducted[8] (erythema is redness of the skin, and MED is the lowest UV light dose that results in reddening of healthy skin)

Figure 1. Test results of hairless mice exposed to 207 nm, 222 nm, and 254 nm UVC light.[8]

Type of UVC Light	Increase in epidermal layer thickness (hyperkeratosis)	Increase in Premutagenic Skin Lesions	Minimal Erythema dose (MED) value
207 nm	No increase	No significant increase	50 mJ/cm²
222 nm	No increase	No significant increase	300 mJ/cm²
254 nm	2.7 fold increase in thickness	Significant increase	10 mJ/cm²

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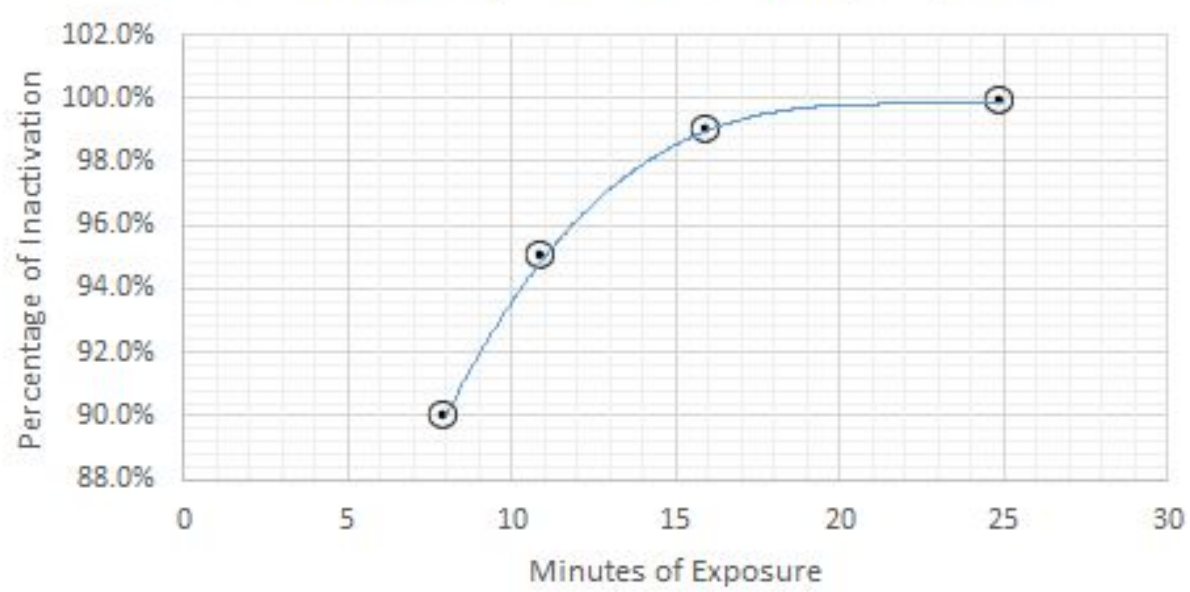
1.5 Far-UVC in Relation to SARS-CoV-2

- Studies have shown that small doses of 222 nm UVC light (1.7 mJ/cm² and 1.2 mJ/cm² respectively) were able to inactivate 99.9% of airborne coronavirus 229E (alpha HCoV-229E) and coronavirus OC43 (beta HCoV-OC43)[6]
- Far-UVC light is predicted to have similar effects on other human coronaviruses such as SARS-CoV-2 due to genomic size similarities (genomic size is an important factor in determining sensitivity to radiation)[6]
- Note: The regulatory exposure limit at the moment in occupied public spaces is around 3 mJ/cm²/hour or 23 mJ/cm² per every 8 hours[6]

Figure 2. Percentage of beta-HCoV-OC43 inactivation after minutes of continuous far-UVC exposure at a limit of 23 mJ/cm² per 8 h.



- From this graph we can see that far-UVC has the potential to reduce the level of airborne coronaviruses in public locations while remaining within the dose limits
- However, hundreds of studies summarized by W.J. Kowalski show that SARS-CoV-1 has a UV D90 value of 360 mJ/cm², the largest UV D90 value compared to around 130 other viruses[9]
- Taking into consideration the similarities between SARS-CoV-1 and SARS-CoV-2, a larger dose is likely also required to inactivate the SARS-CoV-2 virus

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1.6 Summary and Analysis of Part 1

Summary and Analysis of Part 1: UVGI and Types of UVC

- The type of UV light that has the ability to kill and inactivate pathogens is UVC
  - Within the UVC spectrum, the most effective wavelength is 265 nm, however 254 nm light is the most commonly used wavelength and is almost just as effective
  - Both of these wavelengths are harmful to humans, and may lead to cancer and cataracts. They should not be used in the presence of people.

- There is another section within the UVC spectrum in the 207-222 nm wavelength range called far-UVC
  - Both 207 nm and 222 nm UVC light have been shown to be just as effective in killing pathogens as conventional 254 nm UVC light, however they do not cause the same harmful effects on humans as 254 nm UVC does
  - When comparing 207 nm light to 222 nm light, 222 nm UVC light did not cause erythema as quickly as 207 nm UVC light did

- From this research, it appears that 222 nm UVC light is the safest UVC light option to use for disinfection, while still being effective in inactivating pathogens
  - Nonetheless, use of 222 nm UVC light should be kept under the regulatory exposure limit in places where people are present

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2.0 Sources of UV Light

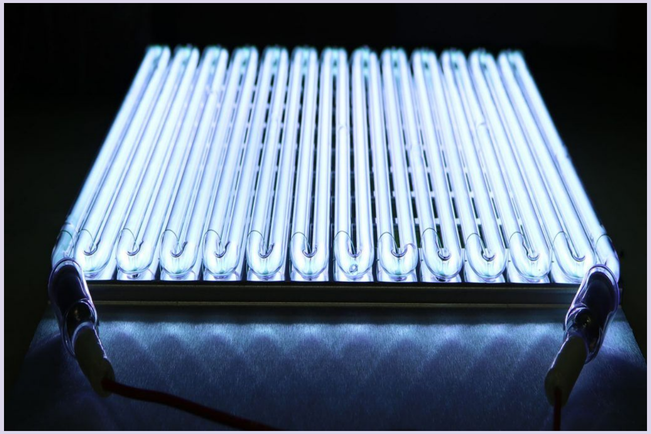
2.1 Mercury-Based UV Lamps

- The most conventional type of UV source, used often for production of 254 nm UVC light
- Filled with mercury and a starting gas (usually Argon)[19]
- Two main types: Low Pressure Lamps, which operate using around 1 Pa, and Medium Pressure Lamps, which operate with greater than 100 kPa[19]
- Note: Mercury is a both a health and environmental hazard; it has harmful health effects on people and animals and can contaminate the environment as well

Low Pressure Lamps (LPs)[19]

- Types include soft glass (25-35% efficiency), standard low pressure (fused quartz, 30-40% efficiency), low pressure high output (fused quartz, 25-35% efficiency), amalgam (fused quartz, 35% efficiency)
- Emits UV light with wavelengths of 253.7 nm and 185.0 nm
- Note: 185 nm radiation combined with oxygen produces ozone, so most lamps are made using a doped/fused quartz envelope material that prevents the transmission of the 185 nm radiation
  - Soft glass (sodium-barium glass) may also be used in LPs, it also does not transmit 185 nm radiation
- LPs operate at wall temperatures of 30°C to greater than 50°C
  - However, If ambient temperature changes by 25°C, then UV output drops by around 10%
- LPs are used more frequently than MPs (medium pressure lamps) in light fixtures to disinfect ambient air and surfaces

Figure 3. A low pressure mercury vapor grid lamp by Jelight Company Inc.[30]



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2.1 Mercury-Based UV Lamps

LP Amalgam Lamps[19]

- A type of low pressure UV lamp, but are not pure mercury lamps
  - Use a mercury amalgam (an alloy of mercury and another metal) instead, usually of mercury and indium
- Among LP lamps, they have the highest specific UVC-Flux per unit arc length (can reach up to 1000 mW/cm)
- Operate at a higher temperature (around 90°C to 120°C), and the UV output is less dependent on ambient temperature than standard LP lamps
  - Less than 10% drop in UV output even if the ambient temperature changes by around 60°C

Figure 4. A LP amalgam lamp by Heraeus Group.[28]

Medium Pressure Lamps (MPs)[19]

- Operate at greater mercury vapor pressure than LPs due to a much greater electrical power input
- Produce a number of wavelengths within the UV spectrum
- Operate at wall temperatures of 500°C to 950°C → can lead to issues with materials that are heat sensitive
- Have an extremely high specific UV flux per unit arc length compared to LP lamps, at up to 25 W/cm
- However, the UVC efficiency of MPs, as well as their lifetime, are much lower (5-15% efficiency)

Figure 5. A medium pressure lamp by Ushio America, Inc.[33]

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2.2 Excimer Lamps

- Used for production of far-UVC light
- Free of mercury
- Involve excited xenon gas molecules that generate UV radiation, and use a quartz glass body[19]
  - Typically have a double cylindrical quartz body
- Excimer lamps have a composition of a halogen and a noble gas[19]
  - Produce different types of radiations depending on the combination[19]
  - For example, krypton and bromine produces 207 nm UVC light, while krypton and chlorine produces 222 nm UVC light[19]
- Comparison to LP Amalgam Lamps:
  - Do not require a warm up time, but have a lower efficiency than amalgam lamps (~8% vs. 35%)[19]
  - However, excimer lamps have a higher specific UV flux per unit arc length than amalgam lamps (up to 3 W/cm vs. up to 1 W/cm)[19]

Figure 6. An excimer lamp by Ushio America, Inc.[32]

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2.3 Pulsed Xenon Lamps (PX-UV)

- Emit high intensity broad spectrum UV light in short pulses through a xenon flash lamp[20]
- Requires less time to attain lethal doses towards pathogens than low-pressure mercury bulbs[20]
- Comparison with UVC:
  - One study comparing the efficacy of PX-UV and UVC produced through mercury bulbs showed that UVC tended to be more effective than PX-UV when tested on pathogens[16]
  - The study conducted a test using slides contaminated with pathogens placed in hospital rooms with similar dimensions, and ran each device for 10 minutes[16]
  - Note however, that efficacy also depends on the UV lamp model used
- Efficacy of PX-UV light is also drastically reduced with increased distance from the light source[16]
- PX-UV does not seem to be as affected by organic material, can penetrate them easier[16]
- Have a lamp wattage range of 300 to 8000 W[14]
- A current application is the sterilization of medical devices[14]

Figure 7. A PX-UV lamp by Warsash Scientific.[34]

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2.4 UV Light-Emitting Diodes (UV-LEDs)

- UV-LEDs emit UV light with wavelengths of 400 nm and shorter[15]
  - Near-ultraviolet light-emitting diodes (NUV-LEDs) emit wavelengths of around 300-400 nm[15]
  - Deep-ultraviolet LEDs (DUV-LEDs) emit wavelengths of around 200-300 nm[15]
- UV-LEDs generate less heat, have a longer lifespan, and are more compact than mercury based UV lamps[15]
- Deep-UV LEDs (or UVC LEDs) utilize AlGaN (aluminium gallium nitride) alloys[25]
- LEDs only produce about 100 mW in power, however they can be utilized in large arrays to increase the total power level for disinfection[25]
- **Wavelengths Produced:**
  - UV-LEDs are able to produce 265 nm UV light, which is the most effective wavelength for disinfection[25]
  - 270 nm UV LED arrays were also shown to be able to kill bacteria using less power than mercury based lamps[25]
  - UV LEDs can also produce 255 nm light, as well as other wavelengths[25]
  - 222 nm UV light has also been produced, using AlGaN-MQW LEDs (aluminium gallium nitride multi-quantum well) → 222 nm is the shortest recorded wavelength ever achieved using a QW LED[11]
- Note: Limited research has been done on 222 nm UV-LEDs

Figure 8. A UV-LED by International Light Technologies.[29]

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2.5 Comparison of UV Light Sources

Figure 9. Comparison of UV Light Sources.[7, 11,14, 15, 16, 19, 20, 25]

Light Source		Type of Light Produced	Advantages	Disadvantages
Mercury-Based UV Lamps	**Low Pressure Lamps (LPs)**	185, 254 nm UVC light	Relatively high efficiency (25-40%)	If ambient temperature changes by 25°C, then UV output drops by around 10%. Requires mercury. Specific UVC-Flux per unit arc length is only up to 350 mW/cm.
	LP Amalgam Lamps	185, 254 nm UVC light	Have the highest specific UVC-Flux per unit arc length among LP lamps (up to 1 W/cm). UV output is less dependent on ambient temperature than standard LP lamps.	Requires mercury.
	Medium Pressure Lamps (MPs)	Polychromatic	Extremely high specific UV flux per unit arc length compared to LP lamps (up to 25 W/cm).	Requires mercury. Low efficiency (5-15%). Shorter lifetime than LP lamps. High operating temperature can lead to issues with heat sensitive materials.
Excimer Lamps		Far-UVC light (207 nm and 222 nm)	Mercury-free. Do not require a warm-up time. Have a higher specific UV flux per unit arc length than amalgam lamps (up to 3 W/cm)	Have a lower efficiency than amalgam lamps (~8%).
Pulsed-Xenon Lamps (PX-UV)		Broad spectrum UV light	Many models are mercury-free. Requires little time to attain lethal doses towards pathogens and can penetrate organic material more easily than mercury-based UV lamps. 300 to 8000 wattage range.	Efficacy drastically reduces with distance from light source.
UV Light-Emitting Diodes (UV-LEDs)		Can be designed to produce multiple wavelengths (eg. 265 nm, 270 nm, 255 nm, 222 nm)	Mercury-free. Generate less heat, have a longer lifespan, and are more compact than mercury-based UV lamps.	Individual LEDs only produce about 100 mW in power.

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3.0 Applications

3.1 Automated Room Disinfection (ARD) Systems

- Studies have been conducted where patients admitted to rooms in which a previous patient was infected with particular pathogens were more likely to acquire those pathogens as well[17]
- Traditional disinfection procedures are limited:
  - Rely on human operators to apply a suitable agent to surfaces for the needed contact time[17]
  - Increase the chances of infection for the human operators as well[17]
- Automated systems reduce the chances of human error and decrease the dependency on operators[17]
  - UVC systems and pulsed-xenon-UV (PX-UV) systems are among the most frequently used ARD systems
- Note: Organic material decreases the effectiveness of ARD systems, so cleaning should be still done before ARD cycles for maximum disinfection[17]

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3.1 Automated Room Disinfection (ARD) Systems

UVC Radiation Systems[17]

- UVC radiation systems generally attain a 2 to 4-log reduction of pathogens on surfaces
- **Case Study:** A recent trial study that utilized UVC in addition to previous room disinfection practices showed that the use of UVC was able to reduce MDRO (multidrug resistant organism) acquisition
  - Involved 31,226 patients and 9 hospitals over 2 years
  - There were significant reductions in MRSA, VRE, and C. difficile bacteria infections
- **Practicality Considerations:**
  - Problem with surfaces out of the line of sight, so multiple cycles from different points in the area may be required
  - The cycles of some UVC systems are determined by the reflected dose light, this means that the cycle length will vary depending on surface materials and how well they reflect light
  - Other factors that affect cycle length include temperature, humidity, and bulb age
  - UV light intensity fades with distance away from the source, so this limits its effective reach
  - Microbes that have received less than lethal doses may mutate

Figure 10. A Lumalier Tru-D UV system[17]

3.1 Automated Room Disinfection (ARD) Systems

Pulsed-Xenon UV (PX-UV) Systems[17]

- PX-UV systems pulse out high-intensity broad spectrum UV in short bursts from a xenon flash lamp
- Studies have shown PX-UV systems to be 95-99% effective against hospital pathogens
  - However, note that many of these studies contain significant or various confounders (such as a committed new hygiene staff, a quality improvement program with multiple components, etc.) so the impact of using PX-UV on its own is unclear
  - In general, PX-UV systems attain around a 1-3 log reduction of pathogens on surfaces
- In one study, which compared UVC system *in vitro* to a PX-UV system *in vitro*, showed that PX-UV systems tended to have a lower level of efficacy during the same operation time, when placed at the same spot in the enclosure
  - On VRE, PX-UV system only attained a <1-log reduction, while UVC system attained a >3-log reduction
- Ultimately, the efficacy of a PX-UV system will depend on the model
- **Practicality Considerations:**
  - Very similar to UVC systems
  - Another factor is that PX-UV systems may be more disruptive, as they employ a series of bright camera flashes

Figure 11. A Xenex PX-UV system[17]

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3.2 Reuse of N95 FFRs

- Depending on the manufacturer and model, the level of UV penetration across the layers of an N95 FFR (Filtering Facepiece Respirator) varies[9]
- Results of studies regarding the impact of disinfection on N95 FFRs:
  - Total applied doses of up to 20 000 mJ/cm² had no significant effect on fit, airflow resistance, or particle penetration for 15 different selected models[9]
  - However, it did have some effects on the strap strength of some models[9]
- **Regarding SARS-CoV-2:**[9]
  - Studies using UVC against SARS-CoV-1 have applied various doses of 254 nm UVC, ranging from 300 to 14 500 mJ/cm², and have had varied outcomes as well
  - Hundreds of studies summarized by W.J. Kowalski show that SARS-CoV-1 had the largest UV D90 value compared to around 130 other viruses, at 360 mJ/cm²
  - For effective deactivation of SARS-CoV-2 on N95 FFRs, Otter et al. estimated that the minimum dose of UVC required is around 1000 mJ/cm² (took into consideration the porous surface of the mask)
  - Otter et al. recommended a 2000 mJ/cm² dose applied to both sides of the mask due to uncertainties about SARS-CoV-2 susceptibility, and other factors such as varying materials and estimation errors regarding the applied dose
  - Also advised against attempting to reuse and disinfect PPE that has already been soiled (due to the properties of protein and aqueous media)
  - Otter et al. also recommended a two-step disinfection process that would theoretically attain a 6-log reduction (first storing intact and unsoiled masks for a minimum of 4 days, then putting the masks through UVGI treatment)

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3.3 Other Applications

- Reducing surgical-site infections (using far-UVC)
  - Based on data from the USA alone, surgical-site infections result from 0.5% to 10% of clean surgeries (amounts to around 275 000 patients a year)[4]
  - Patients with surgical site infections have a death rate that is twice as large as patients who are not infected, stay in the hospital for an average of 7 additional days, have a readmission rate that is 5 times as large[4]
  - Far-UVC light is useful in this case as it is cytotoxic towards bacteria, but has minimal cytotoxic effects on human cells
- Disinfection in ambulances[20]
  - Ambulances are a frequently used and important type of emergency medical transportation, however they are easily contaminated with pathogens brought in by patients during transport
  - These pathogens could be transmitted to the medical workers, as well as the next patients
- Inactivation of airborne viruses in public spaces (using far-UVC)
  - Public spaces include airports, schools, libraries, hotels, public transport
  - Low-level far-UVC light overheads in public spaces may prove to be an efficient and safe way to decrease the spread of airborne microbial diseases, it would not require people to evacuate either[24]
- Sterilization of medical devices
  - Eg. disinfection of stethoscope membranes

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3.4 Summary and Analysis of Part 3

Summary and Analysis of Part 3: Applications

- UV light can be applied to a manifold of situations to effectively limit the transmission of pathogens
- However, safety precautions must be taken with all usage of UV disinfectant technology
- With the exception of far-UVC, UV light should never be used in the presence of people as it can lead to detrimental health effects
- For this reason, far-UVC is the only type of UV light that may be used in any of the listed applications, including to disinfect public spaces where there are often many people

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4.0 Emerging Technologies

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4.1 UV Robots

- Noncontact automated/remote-controlled robots could be utilized for faster, safer, and more effective disinfection methods[27]
- Aspects of potential development of these robots include smart navigation and recognition/detection of high-touch areas[27]
- For UV wavelengths that are not in the far-UVC spectrum, the room must be emptied of people before the robot begins to operate
  - A motion detector may be placed near the inside entrance of the room, which will shut off the robot if a human comes near[2]
  - It can also be installed in the robot to detect movement within the room
- Dosage of UVC depends on the pathogen[2]
  - A shorter operation time length requires a higher light intensity, whereas a lower light intensity requires a longer operation time
  - If a UV robot is operated for less than the necessary time, pathogens will survive and potentially lead to people becoming sick
  - In this situation, a robot that can measure room conditions and calculate the necessary length of time and power is beneficial

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4.2 Examples of UV Robots

IRiS™ 3200m

- A powerful continuous UVC robot that is also able to kill pathogens in shadows[2]
- Measures room conditions (including size, humidity, and temperature) to determine power, time, and dose necessary for full disinfection[2]
- Also has real-time UV dose sensors installed which ensure that the entire room, including both direct and indirect surfaces, is treated[26]
- Takes 8-18 min to achieve a 6-log reduction in a 200 square foot room[26]
- Controlled with a wireless handheld device[2]

Figure 12. UVC dosage that reaches surfaces in 10 minutes using the IRiS™ 3200m.[26]

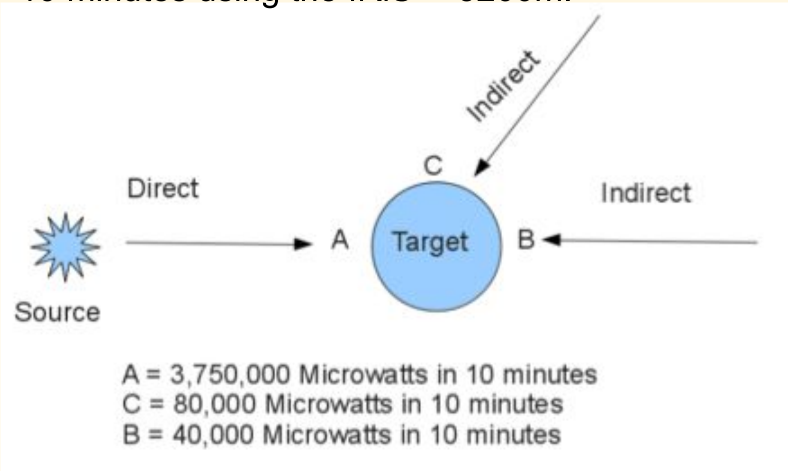

Figure 13. IRiS™ 3200m model.[14]

- The robot's UV power output is maximized where necessary due to a patented Field Balancing™ technology[14]
- Does not require multiple repositionings within a room[14]

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4.2 Examples of UV Robots

Sterilray Autonomous Disinfection Vehicle (ADV)[21]

- A programmable robot that utilizes patented Excimer Wave Sterilray™ technology (ie. uses far-UVC)
- Able to monitor, adjust speed, pause in important areas, and keep archives of trips that have been completed
- While operating, the robot navigates through the entire room, moving within 18” of all surfaces (it has multiple sensors installed to avoid objects)
- On a single charge, it disinfects up to 6 operating rooms, however it take 2-3 hours to recharge
- Shuts off lamps if it senses other movement
- iPad controller app

Figure 14. Movement of a Sterilray ADV within a room.[21]

Figure 15. Sterilray Autonomous Disinfection Vehicle.[21]

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4.3 Biosensor-Based Pathogen Detection Methods

- Conventional methods for pathogen detection involve using agar plates to culture microorganisms, which is inconvenient and takes up to 3 days to receive initial results, then determining the specific type of microorganism takes up to a week as well[1]
- Newer sensor-based methods are being developed for real-time pathogen detection[1]
  - These sensors can be installed onto robots to ensure that all areas with pathogens receive enough UV light treatment
- Biosensors involve measuring chemical and physical quantities followed by a conversion into electrical signals[1]
  - Biosensors detect chemicals in living organisms by utilizing a molecular species (bioreceptor) that will bind with the target pathogen for measurements[1]
  - There are a variety of bioreceptor types, efficiency of measurement depends on the bioreceptor
    - Types include: antigen/antibody, enzymes, DNA/RNA, cells/cellular structures, biomimetic, bacteriophage[1]

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4.3 Biosensor-Based Pathogen Detection Methods

Optical-Based Biosensors[1]

- Successful method, but expensive
- Dispersion, absorption, refraction, and reflection are all techniques used in optical biosensors
- Tapered optical fibre is installed on the detection surface, laser light then passes through this fibre and the resulting light, which indicates the presence of pathogens, is detected

Electrochemical-Based Biosensors[1]

- A change in potential and current occurs when the target pathogen interacts with a sensing electrode
- Different types include: amperometric, potentiometric, conductometric, impedimetric
- Advantages of electrochemical-based biosensors: small, relatively low cost
- Disadvantages: less selective and sensitive than optical biosensors, requires many washing steps, however their performance can be improved when combined with other bio-sensing methods

Mass-Sensitivity Biosensors[1]

- Include quartz crystal microbalance (QCM) biosensors and surface acoustic wave (SAW) biosensors
- Cost is relatively low, but so are specificity and sensitivity

Nanomaterial-Based Sensors[1]

- Nanomaterial is used to modify the sensing electrode in a biosensor, this allows the electrons to transfer at a greater speed
- Sensors that are nanowire-based are more sensitive and selective

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4.4 Example of a System Involving Biosensors

MIT Lincoln Laboratory's PANTHER and CANARY[13]

- PANTHER stands for Pathogen Analyzer for Threatening Environmental Releases, while CANARY stands for Cellular Analysis and Notification of Antigen Risks and Yields
- PANTHER uses CANARY technology
- CANARY utilizes genetically engineered B cells, which are white blood cells that are able to bind to and subsequently recognize pathogens in just seconds
  - Genetic engineering enables the B cells to focus on target pathogens
  - These B cells then indicate the binding and identification information by emitting photons
  - In less than 2 minutes, CANARY is able to detect up to 200 pathogen particles
- PANTHER utilizes a specialized collection technology to speed up the process even further
  - Involves a nozzle that sends aerosol particles onto 1 of 16 collection sites on a disk
  - B cells are then released when the disks are spun at high speeds, and proceed to emit light after seconds of contact
  - The rotating disk passes a photomultiplier, which is a light detector that converts photons into electrons

Figure 16. PANTHER Biosensor Prototype.[31]

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Overall Analysis and Discussion

After investigating the various types of UV lights, UV light applications, and emerging technologies that may be incorporated into UV light disinfection, the use of UV light for disinfection of surfaces and air appears to be a very feasible and effective method for limiting the transmission of pathogens. Multiple studies have shown that using UV light disinfection in addition to traditional cleaning methods decreases the spread of disease and pathogens. 222 nm UVC light in particular is a strong option to utilize for this purpose, as it does not create the same health hazards as 254 nm UVC light, and is also slightly safer than 207 nm UVC light.

222 nm UVC light may be used in any space that is in need of disinfection, regardless of the presence of human beings. However, in public spaces, the use of 222 nm UVC light should still be kept under regulatory exposure limits. 222 nm UVC light can be incorporated into a variety of different technologies to achieve disinfection. These technologies include simple overhead lights, as well as robots and other more complex smart technologies.

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Potential Impact and Future Prospects

Community

- The incorporation of UV disinfectant technologies into our daily lives could provide a safer environment for people to live in, with less chances of catching disease
- In addition, it would decrease the chances of another global pandemic occurring again on a scale such as the COVID-19 pandemic
- At the current moment, incorporating more UV disinfectant technologies into places such as hospitals, schools, and other public spaces would likely also be effective in controlling the number of new COVID-19 cases and preventing more waves of illness

Science and Technology

- There are still many possibilities in regards to the development of UV disinfection methods, especially concerning the incorporation of smart technologies
- Autonomous robots provide an advantage because they decrease the reliance on human workers to perform disinfection manually, and also reduce the chances of infection for the workers
- With UV robots, there is a great potential for development in smart navigation and recognition/detection of high-touch areas to ensure even higher levels of disinfection

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