Far-UVC Applications in Healthcare

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1. Abstract

Current methods of sterilizing environments are simply insufficient, as has been brought to public attention by the emergence of the coronavirus pandemic that began earlier this year. As of right now, there is not a safe way to consistently and thoroughly eliminate viruses from high traffic areas during the many hours that people (possible carriers) are passing through them. This makes areas, namely hospital rooms, where there is an increased rate of carriers and immunodeficiencies, high risk for transmission and disease development. A far-UVC light disinfection device would address these issues by constantly deactivating viruses while people are present, significantly reducing the opportunity for spread in a simple and time effective manner. Ideal characteristics for this device incorporate a large coverage area (320 square feet or 29.7 square meters), 99.9% sterilization, cost and manufacturing efficiency, and proven safety for non-target organisms, specifically humans.Additionally, this product must not interfere with the operations of hospital rooms.

2. Introduction

2.1 Motivation

With the emergence of the novel coronavirus SARS-CoV-2, increased attention has been drawn to maintaining environments sterile from easily spread pathogens. Chemical disinfectants are commonly used but can cause pathogens to develop resistance, can have negative effects when in contact with humans, and are ineffective against aerosolized pathogens [1]. Germicidal UVC lights have been developed to address the drawbacks of chemical disinfectants, providing a way to deactivate pathogens, rendering them unable to develop resistance and disabling aerosolized pathogens [2]. However, UVC radiation outside of the range of far-UVC is still harmful to humans, causing afflictions like cancer and cataracts [2]. Without being able to expose humans directly, populated areas are still hotbeds for pathogen transmission. Far-UVC light addresses this issue as its short wavelengths should not be able to penetrate the outer cell layer of skin or the outer layers of the eyes [3]. Far-UVC lights will be able to constantly disinfect high traffic and high risk areas to significantly reduce spread and transmission of viruses.

2.2 Competing Designs

A wide range of disinfection devices that incorporate far-UVC light exist, but many are not commercially available as of right now and have price points ranging from $500 to multiple thousands of dollars. Additionally, many of them only disinfect small, targeted areas and have short or unspecified ranges.

2.2.1 222nm Far-UVC Light

Shown below is a 222nm excimer lamp that comes with a 120V power supply that operates at 150W [4]. This device is priced at $1000 dollars and provides a narrow emission line of 222nm light [4]. No quantitative information is given on effectiveness of the light produced against pathogens but the description does state that it “prevents the regrowth of bacteria”.

Figure 1: Sailon UVC - 222nm Far-UV Light - 150W

2.2.2 Standing Far-UVC Lamp

The Sterilray ADV is a vertical standing, autonomous far-UVC disinfection device that senses and navigates through a room within 18” of target objects [5]. The speeds and routes can be manually modified and archived for increased targeting of high contact areas and the device itself is capable of autonomous charging. Sterilray has done some tests on the effectiveness of their far-UVC light against certain bacteria but only at a distance of 2 inches. Pricing is only available given a request for the device.

Figure 2: The Sterilray Autonomous Disinfection Vehicle

2.2.3 Far-UVC Disinfection Light Fixture

This far-UVC light fixture includes 3 far-UVC lamps in parallel contained in metal, overhead housing. This fixture claims a 99% disinfection rate of viruses and other germs but does not provide specifications on coverage and does provide some health warnings about exposure [6]. With dimensions of about 3ft x 7ft, coverage can be assumed to be somewhat large, but this also requires a 120V and 120W power source and costs approximately $7000 [6].

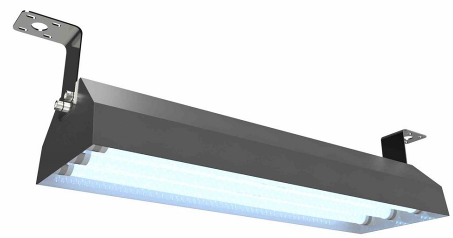


Figure 3: 120W Far-UVC Excimer Disinfection Fixture

2.2.4 Far-UVC Box Sanitizer

This sanitation box provides 360 degree disinfection using 2 separate far-UVC lights [7]. Personal items placed in it and a 99.99% sterilization rate after 1 minute of exposure and requires a 120V, 12.5 amp power source [7]. There is also control of the wavelengths of light produced and Sterilray claims easy operational use with an automatic cutoff system [7]. However, this product also requires a request of the device and delivery is estimated at 8-10 weeks as the company is unable to produce products at the rate that they are being ordered.

Figure 4: Far-UV Sterilray™ Pathogen Reduction Box (PRB) Model S1000

2.2.5 Far-UVC Disinfection Wand

The far-UVC wand design is beneficial for its mobility and quick and easy use. High contact areas can be targeted and disinfected quickly and often with this device. Sterilray claims a “high level of disinfection” when passing the light 1-2” over the target area at about 2 feet per second [8]. As previously stated in section 2.2.2, controlled testing of just the light against a variety of bacteria and viruses has shown significant but variable results, and are dependent on exposure time, distance and intensity. This product also requires a request for pricing.

Figure 5: Excimer Wave Sterilray Disinfection Wand

2.3 Problem Statement

Our group is tasked with performing a meta analysis to determine and then create a far-UVC light disinfection device to be used in hospital rooms. This device will be used to sterilize rooms of commonly spread bacteria and viruses like the fecal patina that can be found on people and on any number of surfaces with high efficiency. This means the far-UVC light must be able to perform this sterilization while people are present without harming them. A mathematical relationship must be derived between intensity of the light, distance from the light and exposure time to determine performance and how the light should be used. Testing also must be done to ensure this as well as to prove efficacy against targeted viruses. Additionally, this design must be cost effective, quickly manufacturable and should not hinder the activities that occur in the hospital room.

3. Background

3.1 Background Research

With the SARS-CoV-2 global pandemic disrupting everyday life around the world, light has been at the forefront of acting as a source of disinfectant. Its history as a preventative of microorganism growth dates back to 1877 when Arthur Downes and Thomas P. Blunt observed that light could prevent pathogen growth. After studies and understanding grew about light and its effects, William F. Wells pioneered the first use of ultraviolet germicidal light as a disinfectant against microorganisms in 1935 [9]. Between 1950-1990, there was a lull in utilizing light against organisms, but a reemergence of UVC light as a disinfectant began in 1992 after a rise in tuberculosis in the United States [9]. It has been on an upward trend since and has now been put on center-stage due to the current situation. However, the current light disinfectant, germicidal UV (GUV) light, poses health risks to humans in direct exposure to this light, preventing this light from being able to disinfect populated areas. Therefore, Far-UVC light has become a focus of current studies as a safer alternative that can be utilized to kill pathogens as they establish in populated areas. Does it have the same efficacy as GUV light? How is it safer? How can it be incorporated into products for commercial and clinical use?

3.1.1 Physics of UVC Light*

UVC light consists of light that produces wavelengths in a range of 200-280 nm. This corresponds to a frequency range of 1.1e9 - 1.5e9 MHz and an energy range of 427-598 kJ/mole. GUV light is the main source of disinfectant used currently with a wavelength of 254 nm. This generates a frequency of 1.2e9 MHz at 471 kJ/mole. On the other hand, Far-UVC light has a wavelength of 222 nm, coming in at a frequency of 1.4e9 MHz and 539 kJ/mole [10].

3.1.2 UVC Light as a Disinfectant* (Biological Interaction)

The wavelength of GUV light and Far-UVC light is long enough to penetrate through cells and emits radiation with high enough energy to disrupt these cells. Radiation kills cells through the disruption, damage, or removal of DNA. As cell DNA is required for cell division or binary fission (prokaryotes), a disruption of this DNA can lead to disruption of cell division and thus become potentially fatal to an organism [11]. As the wavelength of these lights is able to easily penetrate through at least one cell, its radiation is successful at killing microorganisms, specifically viruses, as most of these microbes are only one cell in size. They are unicellular organisms. Thus, penetration and radiation is able to kill a full microorganism, allowing it to act as a successful disinfectant on target areas. For example, GUV light has been determined to be 99.9% effective at inactivating various pathogens at low doses of 1.7 and 1.2 mJ/cm2 [12].

3.1.3 UVC Light Safety*

Although GUV light has been proven as an effective source of killing microorganisms, its safety concerns only allow the light to disinfect areas when humans are not present. Due to its longer wavelengths, it is able to penetrate through the human stratum corneum (epidermis), the ocular tear layer, or even the cytoplasm of individual human cells, creating skin or eye damage for humans [12]. In instances of prolonged direct exposure, temporary eye and skin damage may occur, such as cornea injury. This generally heals after a couple of days. Short-term effects may also include redness or ulceration of the skin. At high levels of exposure, these burns can be serious. For long-term exposures, there is also a cumulative risk of premature aging of the skin and skin cancer [13].

On the other hand, despite Far-UVC light's higher energy and frequency, its shorter wavelengths make it a safer alternative as a disinfectant. Far-UVC light has a range in biological materials of less than a few micrometers, and thus it cannot reach living human cells in the skin or eyes. This range is due to its strong absorption by proteins through the peptide bond, and other biomolecules, resulting in severely limiting its ability to penetrate biological materials. Therefore, it cannot penetrate the 15 to 20 layers of corneocytes and 10 and 40 μm thickness of the human stratum corneum (the outer dead-cell skin layer), the ocular tear layer, nor even the cytoplasm of individual human cells. However, as viruses and bacteria are extremely small, Far-UVC light can still penetrate and kill them [12]. Far-UVC light is thus a safe alternative to GUV light and should be able to remain permanently on in settings even with humans present.

3.1.4 Far-UVC Studies*

There have been two current case studies performed with Far-UVC light that proves that it has the same efficacy as GUV light at killing pathogens and is thus a sufficient option in replacement of GUV light disinfectant.

The first study was by the Columbia Medical Center of Research. They tested the effectiveness of Far-UVC light on HCoV-229E (VR-740) and HCoV-OC43 (VR-1558) by propagating human diploid lung cells with the virus. These cells were kept in a MEM standard cell culture medium. The tests were performed with excimer lamps at distances 22 cm away from the virus, spanning back and forth across a 26 cm × 25.6 cm × 254 μm UV-transmitting plastic window. The results concluded that beta-HCoV-OC43 and alpha HCoV-229E was ~90% inactivated in ~8 minutes, 95% in ~11 minutes, 99% in ~16 minutes and 99.9% inactivation in ~25 minutes. Based on the data, inactivation of the two human coronavirus by 222-nm light followed a typical exponential disinfection model, with an inactivation constant for HCoV-229E of k = 4.1 cm2/mJ (95% C.I. 2.5–4.8), and k = 5.9 cm2/mJ (95% C.I. 3.8–7.1) for HCoV-OC43. These values imply that 222 nm UV light doses of only 1.7 mJ/cm2 or 1.2 mJ/cm2 respectively produce 99.9% inactivation (3-log reduction) of aerosolized alpha HCoV-229E or beta HCoV-OC43. Both of the studied coronavirus strains have similar high sensitivity to far-UVC inactivation. As all human coronaviruses have similar genomic sizes which is a primary determinant of UV sensitivity, it is reasonable to expect that far-UVC light will show similar inactivation efficiency against all human coronaviruses, including SARS-CoV-2 [12].

The second study was performed by Hiroshima University and included cell culture of SARS-CoV-2. Tests were conducted with a 100 microliter solution containing the virus (ca. 5 × 106 TCID50/mL) spread onto a 9-cm sterile polystyrene plate [14]. The researchers allowed it to dry in a bio safety cabinet at room temperature before placing the Far-UVC lamp 24 cm above the surface of the plates. This in vitro experiment showed that 99.7% of the SARS-CoV-2 viral culture was killed after a 30-second exposure to 222 nm UVC irradiation at 0.1 mW/cm2 [15].

Both tests were conducted using the Ushio Care222TM krypton-chloride excimer lamp[16] and both proved that this Far-UVC light source was effective in killing microorganisms, specifically viruses, with 99.9% effectiveness. Unfortunately, the light source is only a part of a light stand causing it to have limited maneuverability, range, and coverage.

Therefore, a design that will be able to use Far-UVC light across a full room and kill 99.9% of the viruses is needed.

3.2 Client Information

Our client is Dr. Ernesto Brauer, a Critical Care Physician at Aurora St. Luke's Medical Center. As he is exposed to diseases and viruses at work, he created a mini Far-UVC disinfectant room for himself. Based on its effectiveness, he would like further research done in order to determine how safe it is as well as a product designed that could become widespread to help disinfect clinical settings.

3.3 Design Specifications

Our goal is to perform a meta-analysis to further investigate the effectiveness of Far UVC light in preventing viruses from existing on surfaces and in the air. We will determine its efficacy at different light intensities, dosages, distances, and durations by utilizing literature, probability models, and research. Based on these findings, we will design a product that will use Far-UVC light to kill airborne and surface based viruses in a fully furnished typical patient clinical setting, such as a 29.7 square meter patient room or a 3.72 square meter bathroom, with 99% effectiveness across the whole room. This design will consist of a 120 Volt Far-UVC light that must have a shelf life of 50,000 hours. It will not cause harm to human skin or eyes even after prolonged exposure and will adhere to current safety standards; the current regulatory exposure limit of 222 nm light to the public is ~3 mJ/cm2/hour with a maximum regulatory limit of 23 mJ/cm2 per 8-hour exposure [17]. Our design will then be available for others to implement in public settings. The full product design specifications can be found in section 8.1 of the Appendix.

4. Preliminary Designs

4.1 General Concept

The following designs were created through brainstorming sessions with the entire team and inspired by previous research of far-UVC light and existing products that produce far-UVC. Our designs also aimed to please our client and our problem statement. The main focus was to implement our design in a medical environment where the spread of viruses is extremely common and must be contained. Especially during times of a pandemic, the use of disinfecting light that is safe on skin can easily prevent the spread of these airborne pathogens.
Each design will include a detailed drawing/rendering of the desired concept along with a summary of the overall functions of each respective design.

4.2 Preliminary Designs

4.2.1 Design 1: Far-UVC Light Emitting Diode (FULED)

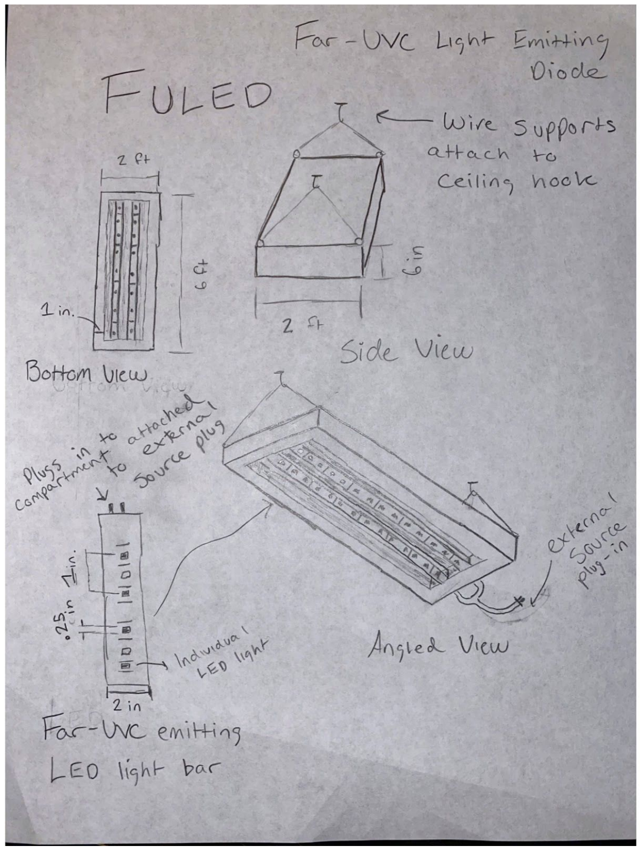


Figure 6: Sketches and dimensioned drawings of the FULED solution. It is 2’ wide and 6’ long and has a 6” thickness, attached to the ceiling by hooks with wire supports.

The FULED design is a mixture of an overhead light along with LED lights to create a more efficient product that emits far-UVC light. The overhead light is a 61 × 183 cm frame that is 15.48 cm deep to hold the individual bars of LED lights. There are wires that can attach to ceiling fixtures that allow for easy installation and moving of the light fixture itself. The frame will be made of ¼ inch thick steel that will protect the lights incase of any accidents. The LED light bars are made of plastic and are hollow rectangular shapes. Inside the rectangle are the wires and resistors that connect to each LED light. The LED lights on the outside of the bar are spaced 1 inch apart from each other and are .645 cm thick.

This design's main focus and/or goal is to implement far-UVC wavelength in LED lights. There are existing UV-LED lights on the market but little-to-no documentation on far-UVC LED lights. The problem with creating far-UVC LED's is that the LED light can only produce so much energy. Smaller wavelengths require more energy to produce and more energy to stabilize that wavelength.

Implementing far-UVC into LEDs will not just allow for products like an overhead light, but allow the light to be much more universal and applied in many products. LED lights are also more energy efficient and will allow for longer run-time than standard fluorescent bulbs that produce far-UVC.

4.2.2 Design 2: 2-in-1 Air Purifier and Far-UVC Sanitation

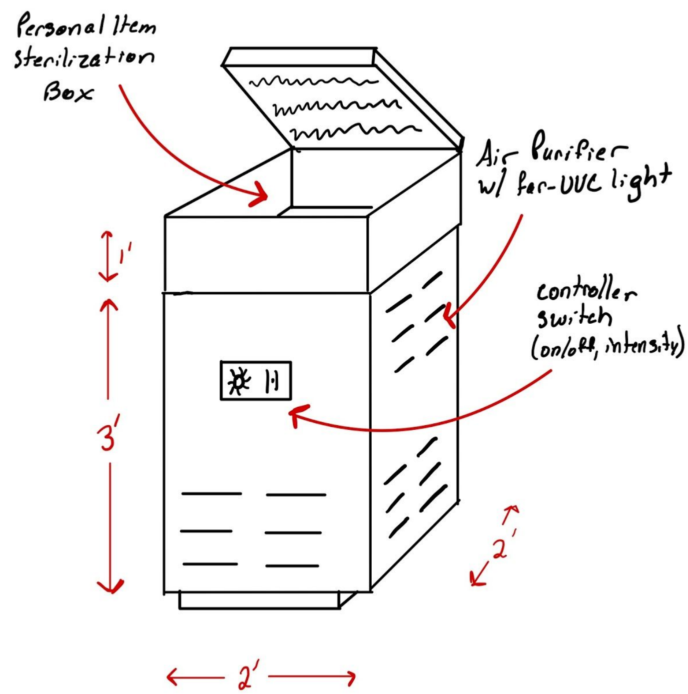
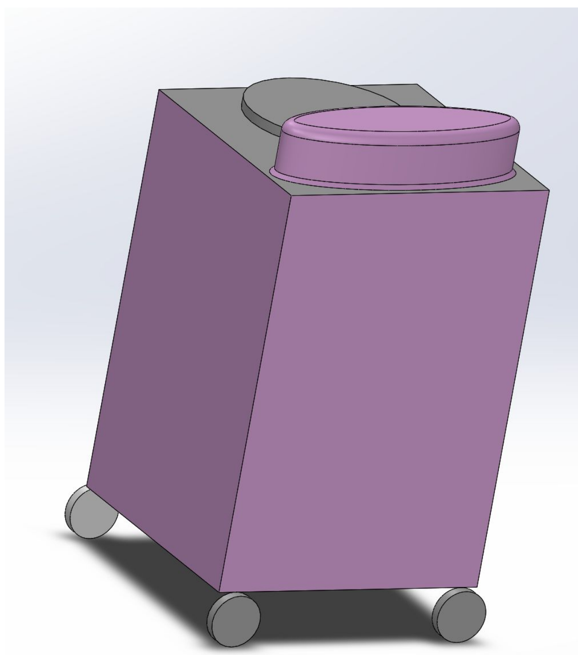


Figure 7: Annotated hand drawing with dimensions showing the main features of the 2-in-1 Air Purifier and Far-UVC Sanitation solution. The entire unit has a 2' by 2' base and a 4' height, with a 4ft^2 personal item sterilization box.

The 2-in-1 solution features an air disinfection unit and a box to disinfect personal items. The entire unit is a 122 × 61 × 61 cm stationary box. The air disinfection portion acts like an air purifier, filtering air into the unit to be effectively cleaned by far-UVC light. This passive unit can remain on throughout the day to clean the local air. The personal item sterilization box makes up the top 30.5 cm of the unit, giving the box a 30.5 cm depth. This box is targeted for high contact items that easily transport germs, such as phones, pens, stethoscopes, and other related items. The user can place these items for an effective amount of time in the enclosed box and can be disinfected periodically throughout the day. The enclosed box feature allows for the entire surface area of an object to be exposed to the far-UVC light.

This design heavily considers safety, considering possible health warnings [6]. The user would only ever be exposed to far-UVC light minimally because the far-UVC light shines internally. However, the 2-in-1 solution is a much larger design and would likely require more unique and possibly complex components. This would require developing both an air filtering system and light system.

4.2.3 Design 3: Mobile Light Cart - Easy Access



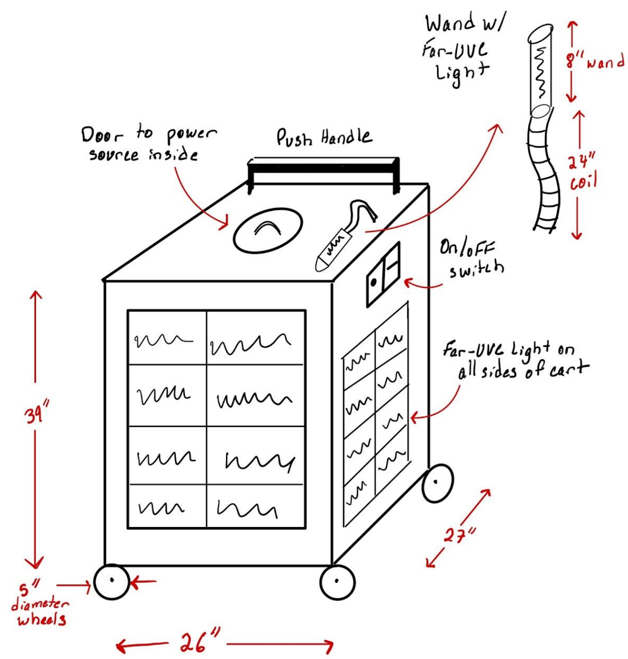


Figure 8 (left): SolidWorks rendering showing the general shape and external physical characteristics of the Mobile Light Cart.
Figure 9 (right): Annotated hand drawing with dimensions showing the main features and components of the Mobile Light Cart. The cart has a 26" by 27" base with a 39" height with a 24" extendable coil with an 8" handheld wand that can be removed for use.

The Mobile Light Cart solution is a transportable cart which features passive and active solutions for airborne and surface disinfection using far-UVC light. The main cart is a 70 × 67.1 × 101 cm rectangular cart with 12.9 cm diameter wheels for transportability and far-UVC light on all outward sides of the cart. There is also a 62 cm extendable coiled, handheld shower head-like wand with far-UVC light for the user to hold and allows the user to focus the far-UVC light on shadowed areas or high contact surfaces such as doorknobs. The far-UVC light that shines from the sides of the cart will not be able to reach every area of a room or bathroom, for example. There will be shadowed areas and surfaces that the far-UVC light from the cart cannot effectively disinfect, so the handheld wand becomes especially useful because the user can actively use the more directional light from the wand to reach these areas. The safety of far-UVC light makes it safe for the user to actively disinfect shadowed areas while the cart lights are continuously on. There is also a handle on the top of the cart to push the cart with ease and protruded edges on the sides of the cart protect the far-UVC light on the sides of the cart. The cart also features a compartment in the middle holding the power source with a hatch in the middle of the top side to access it.

Currently, far-UVC light production is limited and very expensive[12]. This solution is able to utilize the technology and valuability of far-UVC light in healthcare by being transportable and versatile. The versatility makes the cost of far-UVC light worth the investment. The cart can be moved from room to room for active work, or left in a room where it may be necessary.

5. Preliminary Design Evaluation

5.1 Design Matrix

Far-UVC Device Designs							
Design Criteria	**Weight**	Mobile Light Cart - Easy Access		FULED Overhead Light		2-in-1 Air Purifier and Far-UVC Sanitation	
Efficacy*	25	4/5	20	5/5	25	4/5	20
Coverage	20	4/5	16	4/5	16	2/5	8
Safety	15	4/5	12	2/5	6	4/5	12
Ease of Fabrication	15	3/5	9	3/5	9	4/5	12
Cost	10	3/5	6	3/5	6	2/5	4
Energy Usage	5	4/5	4	3/5	3	2/5	2
Durability	5	4/5	4	5/5	5	2/5	2
Ease of Use	5	3/5	3	5/5	5	4/5	4
Total (100)	**100**		74		75		64

Table 1: Far-UVC Device design matrix.

***The eight design criteria on the far-most left column were evaluated for each preliminary design. Each design was given a number score out of 5 for each category. Finally, each design's ratings were totalled to determine which design was best (described under each design section below). Light red shaded blocks indicate the highest ranking in each category. The lighter shaded red blocks indicate a tie in the category. The FULED was the highest scoring, and thus winning design

The design matrix above consists of 8 criteria: efficacy, coverage, safety, ease of fabrication, cost, energy usage, durability, and ease-of-use. The efficacy rating is determined by the device's ability to effectively kill 99.9% of microbes within a reasonable timeframe. This has currently been established at a dosage of 1.7 mJ/cm^2 in 25 minutes or at a dosage of 3.6mJ/cm^2 in 30 seconds. This category has the highest weight of 25 in the design matrix because the main goal of our problem statement is to determine an effective method to kill these microbes. The coverage or square footage criteria is how much area the product can effectively disinfect. The more area the design can cover, the more efficient and effective the design will be. The optimal coverage would be over 29.7 square meters. This goes in hand with the efficacy criteria since greater coverage would allow for less lights to perform the same job thus it is given the second highest weight with 20.

Another important goal is to limit potential harm from exposure to light. Safety is an important criterion because even though Far UVC is believed to not cause any harm to people who come in contact with the light it has not been tested as thoroughly so these designs will be evaluated in a cautious manner. While safety is an important subject, each of these devices can only cause harm if the light comes in direct contact with human tissue, so all of these designs can be made safer by only having them on when people are not around, the overall weight of the category is lower than efficacy and coverage with a weighted score of 15.

Ease of fabrication is about how much time and effort it will take to manufacture the product to make it readily available. If many hospitals in public places need access to these lights, manufacturing has to happen efficiently and easily in order to make the lights affordable and widely available. Thus the weight of this category is the same as safety. The price of manufacturing and materials is used to determine how we scored the cost criteria of each of the designs. Since we do not know hard numbers at the moment, the cost criteria is rated at only 10 and the goal is to be as inexpensive as possible while maintaining a high quality product

Energy usage is the amount of energy it is going to require to operate the device. Durability relates to how long the device will last given the amount of time the customer uses the device. Lastly, ease of use relates to the accessibility and ease of set-up of the light source. These three categories are all weighted at 5 because they are not the main focuses of the project, but still hold some sway in the decision of which design would be best.

5.2 Design Matrix Evaluation

2-in-1 Air Purifier and Far-UVC Sanitation:

The 2-in-1 scored 64/100 overall. For efficacy, the 2-in-1 scored 20/25 because this unit would disinfect the air around it as well as provide a space for users to disinfect personal, frequently used items such as phones which can be modes of transportation for germs but it would not be consistently shining on different areas of the room, it cannot fully get rid of bacteria and viruses like the FULED light so it did not receive the full 5/5 score. The coverage of the 2-in-1 is scored at 8/20. Although ideally this design would be placed in many areas, it is a single air purification system and the disinfecting box for personal items would only disinfect smaller items instead of the surrounding area. The 2-in-1 is rated at 4/5 for safety because the unit contains the possible dangers within it, including the far-UVC light. The box would not, however, expose users to the light so it is tied for the least dangerous. We rated the 2-in-1 at the highest score of a 4/5 for ease of fabrication because a design like this is already on the market with regular UV light so mimicking the design with the Far UVC light would not be all that difficult. Even though the 2-in-1 would require many parts for the air purification system and the light system, once the parts are acquired it should not be too difficult to fabricate in comparison to the other designs.

The cost is rated a 2/5 because the 2-in-1 is a larger, more complex unit than the other designs. Creating the air purification system will incur more costs and complexities because of the parts that are required since it is not just a simple lamp light. In addition, replacing filters and installing this system could be costly. Energy usage received the lowest score of a 2/5 because this unit would remain on, requiring power to bring air in and push it out, in addition to the energy used by the light. For durability, the 2-in-1 also received the lowest score of a 2/5 because it is a large unit and the air purification system will require many moving parts. If this unit is implemented on a large scale, it could be rather difficult to maintain all units, in addition to having the Far-UVC light which could come with possible dangers. The 2-in-1 scored a 4/5 for ease of use because the unit would be simply operated. There would be controls for intensity of the air-purifier which could be left alone after initial settings are inputted. Furthermore, the box would require a user to simply place their items in for a specified amount of time. All in all this design ranked the lowest because it is a more difficult, inconvenient and less effective design overall.

Mobile Light Cart - Easy Access:

The Mobile cart design scored 74/100 with the top scores in energy usage and tying scores in coverage, safety, and cost. The mobile light cart would be effective because you can move it around to certain areas you want to disinfect, however, it is not going to be present 24/7, so the efficacy rating is 20/25 . The cart may also miss aerosolized viruses if the user does not hold the wand long enough in specific locations that may be missed by the cart itself. The mobile would be able to cover quite a lot of space because it can move around and get all the parts of the room. However, the cart itself if put in the room would not cover as much as the FULED as the area covered by the cart will not extend out as much as a permanent overhead light. Although the wand tries to account for this disadvantage, it will not be as efficient with its coverage because it will not provide continuous light in the area it is moved over. Even with the ability to reach every crevice in the room, the fact that its coverage over a given timeframe is not as vast and efficient as the FULED, it will not kill as high a percentage of viruses over a specific duration, putting it behind the FULED in the rankings. The safety of this design is relatively safe because you can use the mobility of the product to keep it from pointing directly at people at a high intensity. LED lights will not be used so the light intensity also decreases. However, patients and users will still be exposed to this light, and as we do not have enough evidence to determine the long term effects of exposure to Far-UVC light, we can not give this design a full (5/5) score.

The mobile design received a relatively low score on ease of fabrication because being able to make a light that also has a movable component to it so it would potentially be harder to manufacture and not be as easily able to produce in high quantities. The cost for the mobile light would be relatively high because it would take more work to manufacture. However, the light would not cost much money to install and since there is not as much of the light as there would be in a ceiling light, it would be cheaper. Additionally, it would be relatively affordable for a hospital to has a few of these that could move around rather than purchasing and installing the lights in every room. However, they might not last as long because there is no LED component in them so the "lifespan" of the lights are shorter. The energy usage of the mobile design would be relatively low because it would not be on all the time. Additionally, there is less overall light being used for a few mobile carts as compared to the amount of lights you would need for a whole room. The durability of the mobile light would be moderate because it might not last as long as the FULED because it would be being manually used and moved around every day. However, a Far UVC lamp generally still has quite a long shelf life. Lastly, ease of use for the mobile light would be the lowest of the three design options because it actually requires someone to manually move around the light.

FULED Overhead Light:

The final design we invented during our design process is the FULED design. FULED stands for Far-UVC and LED as it is a combination of disinfectant far-UVC light and the typical illuminating LED light in an overhead lamp compartment. This design will be installed in an overhead manner because it will be attached to the ceiling and shine down on the room. This design is meant to illuminate large spaces and rooms while disinfecting them at the same time. Therefore, it can be easily inferred that the FULED would have large coverage, convenience, and high efficacy due to its constant usage and high intensity of the LED component.

The FULED design scored 75/100 in our design matrix evaluation. It received the highest scores in efficacy, coverage, durability, and ease of use. This overhead LED design allows for the light source to be farther away while maintaining the needed intensity to effectively disinfect a room. It can cover a larger area because of its ability to act from a distance with an increased intensity that is brought about by incorporating the LED aspect. Additionally, this design idea would have the LED light and Far-UVC light attached to an ordinary light switch. This would increase the ease of use in particular because all one has to do is flip a switch and the room will automatically begin disinfecting. The durability is also increased in this design because the users would not have to directly handle the device so there's less interaction with the device and less chance of damage. In addition, it can be easily shut off to save some energy. The FULED was on the lower end in the ease of fabrication category because the installation of the light fixture should remain similar to putting in a standard light which is relatively simple, but the combination of the Far-UVC light with the LED lights could pose a challenge during fabrication because there currently is no product on the market that combines the LED light and the Far UVC light. However, once the LED lights are designed they should not be too hard to fabricate because normal LED lights are not harder to fabricate than regular lights. In addition LED lights are more efficient meaning you will get more power and energy out of it so not as many would need to be fabricated to have the same amount of total efficiency.

In the design matrix, this design tied with the mobile design in the cost and ranked lower than the mobile design in energy usage. The FULED device would be on as much as a normal LED light would be, thus it would be constantly using energy in order to continually disinfect the area of interest. Since, an LED/Far-UVC hybrid light source is not currently available commercially, the cost is expected to be similar if not more compared to a standard Far-UVC light of the same size but because LED lights last for so long, the cost would be worth it in comparison. Lastly, the FULED design received the lowest score in the safety category due to the lack of research (short and long-term) on the effects on humans after increasing the intensity of the Far-UVC wave. Overall, this design received the highest score on the design matrix due to its high scores in the categories directly involved in solving the problem statement.

5.3 Proposed Final Design

Our final design proposal will include the best aspects of the proposed preliminary designs in order to achieve the most optimal product. As debriefed in the design matrix evaluation, efficacy, coverage and safety are the top 3 crucial criteria for the optimal design. Therefore, for our final design we will incorporate aspects of designs that may improve certain criteria but mainly stick to the FULED design because of its highest overall ranking and high rankings in the 3 most important categories. Our idea is to incorporate a mobile aspect to the Far UVC LED design to increase the coverage and make the device safer so it can be pointed away from people to allow less exposure on the human cells. The final design we are planning on moving forward with is going to be attached to the ceiling of the room and will be made to be the LED Far UVC.

We have chosen to stick to including an LED component in our design as opposed to being a typical Far UVC lamp in hopes of creating a more energy efficient design with better intensity, coverage and efficacy. We also decided to keep the light attached to the ceiling because if we set up our design properly and target the lights throughout the room, the lights could be on all the time to consistently keep the room clean and will cover the full area of the enclosed space, allowing the efficacy to be the best. In addition, the ease of use of this design would be high because it could be as simple as flipping a switch.

In order to incorporate the mobile aspect into our design, we will make it so that a separate set of switches can control the movement of the lights on the ceiling. The idea is that you can angle the lights to direct it away from people and towards surfaces or lower/raise it to increase or decrease the intensity on respective surfaces. By incorporating the mobile aspect to our design, we can increase the level of safety and the overall coverage. Safety is increased with the mobile design due to different angling and height variance for which the light is at. Both types of mobility would mean less exposure in general, along with a decreased exposure if any exposure does occur. The coverage aspect of this design is also increased because of the easy installation that allows for moving the frame to different locations to be efficient.

We decided against using any aspects of the 2-in-1 design for our final design proposal because we felt that it was lacking in most of the criteria we had established, as well as the design not being entirely what our client wanted. Although the 2-in-1 design is relatively safe because it does not necessarily emit UV light on people, our client was hoping for us to use the Far UVC light in an area where it can be spread throughout a large room occupied with people while continuously disinfecting the area. Our client chose Far UVC light because he was hoping for us to use the fact that Far UVC light has already been proven relatively harmless when creating a design.

6. Fabrication/Development Process

6.1 Materials

Material we would hypothetically need in order to manufacture our design with the Far UVC light:
-Far UVC light with LED light combination
- We need to use a machine that could make the light at this wavelength as an LED)
-Adjustable pieces that can be added to our ceiling lights so that they can angle as well as be raised or lowered and be done automatically via a switch or a remote control
- The wiring and circuitry that will accompany the light and switch control
-Attachments for the lamp to go to the ceiling and wiring to connect it to a switch

If we perform in person testing with UV light and convert our measurements to Far UVC light we will need:
-Regular UVC light for testing
-Bacteria plates for testing of the UVC
-Bacteria samples to use on our plates - Home grown bacteria through agar
-Microscope to analyze the bacteria

6.2 Methods

- Going to model the setting that this design will be implemented in
- Doing this kind of modeling will help us evaluate the effectiveness of our design with the following categories:
    - Different materials
    - Absorbance through different air environments
    - Distance of light traveling
    - Ease of use of the design
- Will either do direct testing with UV light and convert it over to Far UVC light or will collect data others have done
- Will conduct more research in general and create a mini meta analysis of our results to further prove our design will be effective

6.3 Future Work (Fabrication and Testing, etc.)

-Will conduct more research on how we would go about incorporating the LED lights with the Far UVC light
-Will conduct more research on increasing intensity of lights and how that may make it more hazardous for humans
-Will conduct more research on how to convert from UVC to Far UVC if we do testing using the UVC light
-Will conduct more research on how to determine the coverage of the lights from a certain distance given different factors of absorption
-Will test our design using regular UV light
-Will fabricate a model of our design using a modeling software
-Will perform calculations using UV light or existing experimental processes found through research

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8. Appendix

8.1 Product Design Specifications (PDS)

Far-UVC Light in Healthcare Design Specifications

Client: Dr. Ernesto Brauer

Project Name: Far-UVC Light in Healthcare

Team Members:

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Date: October 6, 2020

Function (a general statement of what the device is supposed to do): The PDS should begin with a brief, concise paragraph describing (in words) the overall function of the device. In the initial stages, this will be the problem statement, and will become more specific as you decide on a final design.

Currently, UVC light, specifically germicidal ultraviolet light (254 nm) has been proven as an efficient source of killing pathogens, with 99.9% effectiveness. Unfortunately, due to the nature of this longer wavelength, UVC light can only be utilized in settings where no humans are present, as prolonged exposure to this light can cause temporary or permanent eye and skin damage. As an alternative, Far-UVC light (~220 nm) has been proposed to have little to no health risks due to less penetration into human skin from its shorter wavelength, but with the same effectiveness rate as germicidal UV light. As these results have only come from short term and limited empirical studies, our goal is to perform a meta-analysis to further investigate the effectiveness of Far UVC light in preventing viruses from existing on surfaces and in the air. We will determine its efficacy at different light intensities, dosages, distances, and durations by utilizing literature, probability models, and research. Based on these findings, we will design a product that will use Far-UVC light to kill airborne and surface based viruses in a fully furnished typical patient clinical setting, such as a 320 square foot patient room or a 40 square foot bathroom, with 99% effectiveness across the whole room. Our design will then be available for others to implement in public settings.

<u>Client requirements (itemize what you have learned from the client about his / her needs):</u> Briefly describe, in bullet form, the client needs and responses to your questions.

- Design a far-UVC product that can be implemented in a clinical setting and is able to safely disinfect objects/surfaces while people are present and exposed to this light.
- Perform a meta-analysis to prove that Far-UVC light is 99.9% effective in killing microorganisms in populated spaces using light.
- Determine dosage (exposure time), distance, and intensity of light required to kill microorganisms and that can disinfect a full 320 square foot fully furnished patient room

<u>Design requirements:</u> This device description should be followed by a list of all relevant constraints, with the following list serving as a guideline. (Note: include only those relevant to your project):

1. Physical and Operational Characteristics

a. **Performance requirements:** The performance demanded or likely to be demanded should be fully defined. Examples of items to be considered include: how often the device will be used; likely loading patterns; etc.

The product must be able to disinfect 99.9% of viruses in the air and on target surfaces. Ideally the light will be able to disinfect as much surface area as possible. It must not pose any safety risk to humans who could be exposed for any period of time. This light must also be able to be on constantly for periods of time on the scale of years. It must be prepared to be on 24 hours a day for 365 days a year over the course of 5.5 years.

b. **Safety:** Understand any safety aspects, safety standards, and legislation covering the product type. This includes the need for labeling, safety warnings, etc. Consider various safety aspects relating to mechanical, chemical, electrical, thermal, etc.

Use this light in a way that won't cause cancer (melanoma), damage eyes (cataracts), or any other kind of harm to anyone that is exposed to the light for any period of time. Studies must also be done to make sure the light still keeps the "beneficial microorganisms" in our bodies intact. In theory, this will be done by ensuring that the light has wavelengths that are short enough so they can not penetrate living human cells but is long enough to penetrate and damage the DNA in viruses, thus killing them.

c. **Accuracy and Reliability:** Establish limits for precision (repeatability) and accuracy (how close to the "true" value) and the range over which this is true of the device.

Accuracy includes ensuring that the light accurately targets the intended area(s) by covering 99% of the target area and killing, on average, 99.9% of the intended microbes in the area.

d. **Life in Service:** Establish service requirements, including how short, how long, and against what criteria? (i.e. hours, days of operation, distance traveled, no.of revolutions, no. of cycles, etc.)

A life in service greater than other types of light sources is required so that it remains effective in its disinfectant properties. Light will be built into a normal light emitting diode (LED) light source (3.3 forward voltage and a 120V power supply) that can be replaced with the normal light source, however, the far-UVC light should be expected to be on at all times (24/7).

e. **Shelf Life:** Establish environmental conditions while in storage, shelf-life of components such as batteries, etc.

The shelf life must be for 50,000 hours or about 5.5 years if the light is on 24 hours a day for 365 days. This is comparable to a normal LED light.

f. **Operating Environment:** Establish the conditions that the device could be exposed to during operation (or at any other time, such as storage or idle time), including temperature range, pressure range, humidity, shock loading, dirt or dust, corrosion from fluids, noise levels, insects, vibration, persons who will use or handle, any unforeseen hazards, etc.

This device is meant for use in a fully furnished typical patient clinical setting, such as a 320 square foot patient room or a 40 square foot bathroom, lead to very sterile environments. It will exist at room temperature (20-22 degrees Celsisus), low and stable humidity (40-50% relative humidity), will not encounter significant shock loading, dirt or dust. Must be resistant to other sterilizing chemicals used in the area. The housing must maintain stability when being built into/used in the operating environment (likely metal housing similar to those used in other lighting fixtures).

g. **Ergonomics:** Establish restrictions on the interaction of the product with man (animal), including heights, reach, forces, acceptable operation torques, etc..

Far-UVC light emission is safe for contact on human skin and eyes. People should not touch or bend lights otherwise they may break, however, the light will be in close proximity to humans and specialized equipment so it should not emit heat that could be damaging. Significant amounts of water should not be in contact with the lights as they can potentially explode.

h. **Size:** Establish restrictions on the size of the product, including maximum size, portability, space available, access for maintenance, etc.

A strip light overhead design should have dimensions of about 5ft in length x 2.5ft in width x 1ft depth* to ensure variable placement in clinical environments while not being bothersome. As an overhead light, one section of this rectangular housing will be exposed for emission to the rest of the room and access for maintenance.

i. **Weight:** Establish restrictions on maximum, minimum, and/or optimum weight; weight is important when it comes to handling the product by the user, by the distributor, handling on the shop floor, during installation, etc.

The weight of this product should be less than 10lbs* to ensure it can be easily installed with regard to installation hardware and wall supports.

j. **Materials:** Establish restrictions if certain materials should be used and if certain materials should NOT be used (for example ferrous materials in MRI machine).

Materials should be safe and consistent with other materials that would be considered safe and usable in a hospital setting.

k. **Aesthetics, Appearance, and Finish:** Color, shape, form, texture of finish should be specified where possible (get opinions from as many sources as possible).

A clean, smooth, simplistic finish and uniform shape are required in clinical settings to not interfere with procedures and movements occurring below/around.

2. **<u>Production Characteristics</u>**

a. **Quantity:** number of units needed

There is a current issue with the rate of production. This design needs to be able to be mass produced for uses in clinical settings around the world.

b. **Target Product Cost:** manufacturing costs; costs as compared to existing or like products

Existing products range from about $500 to multiple thousands of dollars depending on the design. Manufacturing costs for simple products such as ours should be limited to $500.

3. **Miscellaneous**

a. **Standards and Specifications:** international and /or national standards, etc. (e.g., Is FDA approval required?)

FDA approval would be required. Once approved by FDA, international standards would likely be met. As of March 2020 there is an specific document for "Sterilizers, Disinfectant devices, and Air Purifiers" during the Covid-19 Pandemic. (https://www.fda.gov/media/136533/download)

- Current regulatory exposure limit of 222 nm light to the public is ~3 mJ/cm2/hour with a maximum regulatory limit of 23 mJ/cm2 per 8-hour exposure

b. **Customer:** specific information on customer likes, dislikes, preferences, and prejudices should be understood and written down.

Customers prefer simple, efficient products and lights that are easy to install and control. The light would be able to sterilize the area within a reasonable time and work consistently.

c. **Patient-related concerns:** If appropriate, consider issues which may be specific to patients or research subjects, such as: Will the device need to be sterilized between uses?; Is there any storage of patient data which must be safeguarded for confidentiality?

Those sensitive to light may experience discomfort when using far-UVC. Those with other conditions that might be more sensitive to light such as:

-Being pregnant
-The elderly
-People with cancer
-People with large open wounds
-Babies / toddlers
-Animals

d. **Competition:** Are there similar items which exist (perform comprehensive literature search and patents search)?

- Air filters with Far-UVC light
- Portable wand design
- Vertical light lamps
- Architectural sanitation lights
- Overhead doorway
- Medical equipment with built in lights on high contact areas
- Sanitation boxes
- Mounted track/swivel
- UVC lights in general that are used to disinfect objects after put in a container for a few minutes