Refinement of an Ultraviolet Light Sanitation Device for Central Lines

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Abstract: Central line-associated bloodstream infections are a critical concern in hospital settings, causing an estimated 250,000 infections annually in the U.S. and resulting in high patient mortality and financial costs. These infections are often linked to lapses in sterility during medication or fluid administration. While current prevention strategies emphasize proper insertion and hygiene protocols, these are not always feasible in high-stress environments. This project addresses this challenge by developing a UV light sanitation device that irradiates fluids before they enter a patient's bloodstream, minimizing intraluminal contamination without disrupting clinical workflows. Building on prior research demonstrating a 4-log reduction in *S. aureus* and *E. coli* following UV exposure and design of an initial prototype, this work focused on decreasing the prototype's size, improving thermal management, and ensuring seamless clinical integration. The final design consists of a reusable housing containing 2 UV-C lights and a power supply, and a disposable cartridge with a Luer lock connector for seamless attachment to central lines. Iterative CAD modeling refined the layout to support optimal light exposure and fluid flow, while circuit and heat testing confirmed the device's safety, keeping temperatures below 42°C using passive heat sinks. Although bacterial and drug compatibility testing remain ongoing due to delays, the prototype is prepared for these validations. Future steps include completing these tests, developing a scalable manufacturing process, conducting simulated clinical use evaluations, and initiating IRB-approved clinical trials. By preventing CLABSI at the point of entry, the device reduces reliance on antibiotics and limits the spread of drug-resistant bacteria, particularly *S. aureus* and *E,* without compromising the medical efficacy of medications such as insulin and epinephrine. This innovation holds strong potential to enhance patient safety, reduce healthcare costs, and provide a proactive solution to a persistent clinical challenge, ultimately contributing to broader efforts against antimicrobial resistance.

Keywords: Central Line, UV-C Light, UV Sanitation, Infection, Clinical Workflow, Central Line-Associated Bloodstream Infection, Medical Device

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Introduction:

A central line-associated bloodstream infection (CLABSI) is defined as the recovery of a pathogen from a blood culture in a patient who had a central line at the time of infection or within 48 hours before the development of infection. The placement of a central line is a common procedure, with 5 million inserted annually in the United States. Central lines are used when patients require prolonged or multiple infusions of medications, fluids, or blood products. An estimated 250,000 CLABSI occur per year, carrying a significant financial burden of around $46,000 per infection and a mortality rate of up to 25%. Infections involving gram-positive microorganisms are most common, and are most often associated with non-tunneled catheters, which are temporary central venous catheters inserted by passing through the skin directly into the vein (Haddadin et al., 2024). The current protocol for CLABSI prevention emphasizes following proper sterile insertion practices, such as pre-insertion hand hygiene and sterile preparation of the insertion site, which is not always fully achieved in high-stress environments. Treatment of these infections requires immediate removal of the central line, followed by a regimen of intravenous antibiotics that are tailored to the specific pathogen (CDC, 2024; Marschall et al., 2014).

These infections can theoretically be eliminated by irradiating all fluids and medications with ultraviolet (UV) light using a device attached to the central line. Research conducted by Dr. Thiele of the UVA Health Department of Anesthesiology, along with Dr. Marie of the UVA Health Department of Infectious Diseases revealed a 4-log reduction of *S. aureus* and *E. coli* bacteria

after 10 seconds of exposure to UV light and no degradation of medications commonly used with central lines. The initial prototype of the device involves a commercial off-the-shelf mini-UV unit from AquiSense coupled with a custom 3D printed cartridge that is designed and used for the sanitation of water (Figure 1).

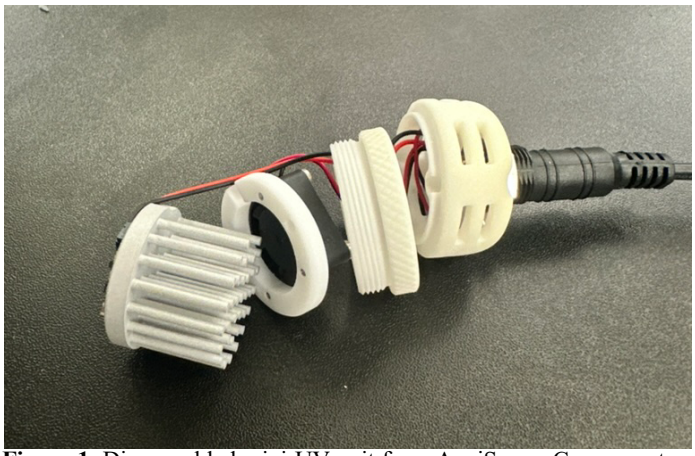

Figure 1. Disassembled mini-UV unit from AquiSense. Components from left to right are UV light attached to heat sink, fan, and connection to power supply.

For the device to be implemented in a clinical setting, it requires refinement to ensure ergonomic suitability for ICU nurses and a power supply that does not interfere with intravenous tubing or poses a risk of overheating and harming patients. Improving the existing prototype of the device will enhance its usability, ensure safer integration into clinical workflows, and increase its effectiveness in treating infections without compromising patient safety, while also reducing the financial burden associated with treating CLABSI. Completion of these aims will result in a working prototype that can be used to prevent CLABSIs in a clinical setting. Development of this device would be able to prevent hundreds of millions of dollars in healthcare expenses.

Design Specifications

The goal of this project is to improve and build on top of the current design for the disposable cartridge that Dr. Thiele and his team have created, (Appendix B). This new prototype should be roughly the size of an AA battery and should include a reusable component that houses two UV lights and the power source, and a disposable cartridge through which medications and other fluids will flow, which will be inserted into the reusable housing. The disposable cartridge should have a Luer lock

Figure 2. Dr. Thiele's original prototype for the disposable cartridge through which the fluid will flow.

system implemented that will allow the device to connect directly to the central line tubing and integrate seamlessly into the clinical environment. The device will be attached distal to the central line injection site. The lights utilized should emit 285nm UV-C light, chosen for its optimal wavelength in achieving medical-grade sanitation. The temperature generated by the lights should not exceed 42°C, the threshold for thermal injury to the skin, which will require the use of metal heat sinks to disperse heat.

Results

Circuit Design

The circuit was one of the more challenging aspects of the design process. While it was established early on that the lights needed to emit 285 nm UV-C light, the specific brand, shape, and connection type of the lights remained initially uncertain. Given the need for compactness, the smallest and flattest available UV-C lights were chosen. Their low profile was especially beneficial for integrating heat sinks without compromising space. The next hurdle was the electrical connection. Initially, we attempted to power the new UV-C lights using the original AquiSense device, simply replacing the original light. However, this approach proved incompatible with the CAD model constraints and physical layout, prompting a switch to a secondary power connector. This new connector still utilized the same 12V DC wall outlet power supply from the AquiSense system but allowed for more flexible integration. The choice between a series or parallel circuit configuration was resolved through prototyping both configurations. The parallel setup caused flickering, likely due to uneven voltage distribution across the lights (Appendix A). The series configuration proved more stable and reduced wiring complexity, aligning with the project's goal of miniaturization (fig. 1). The final implementation used a series circuit with lights soldered directly into place with three heatsinks attached to the back to mitigate the heat output of the lights, discussed at length below.

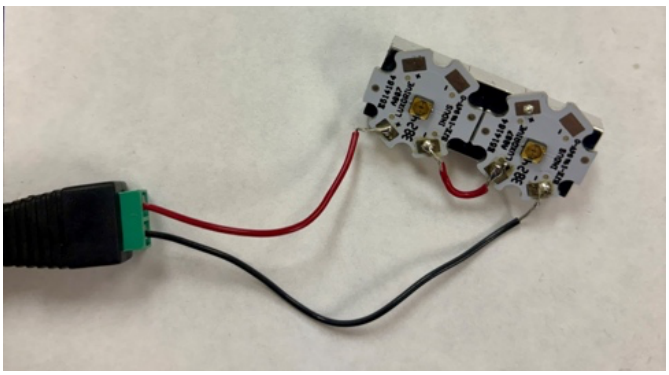

Figure 3. UV-C lights connected in series.

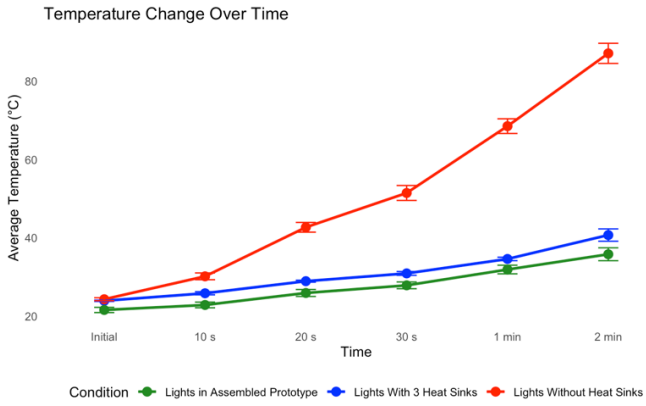

Figure 4. Results of heat testing conducted on 3 different lighting configurations.

Heat Testing

From the beginning of the project, managing heat was a critical design concern. The original AquiSense device featured a large heatsink and fan, indicating that thermal regulation was essential to device functionality. In early experiments, removing these components from the AquiSense light led to significant overheating. This experience prompted the team to prioritize heat testing in the development of the new prototype. Once the UV-C lights were selected, initial tests were conducted without any heat sinks. These lights quickly reached temperatures around 80°C, confirming the necessity for effective thermal dissipation strategies. This data helped determine the magnitude of heat that needed to be mitigated through heat sinks and informed the physical layout and material decisions for the device. Further testing compared three configurations: (1) lights without heat sinks, (2) lights with three heat sinks, and (3) lights fully integrated into the assembled prototype. Using the FLIR TG56 Spot IR Thermometer, temperatures were recorded over a two-minute interval. Readings were taken from the rear of the lights (no heat sinks), the outermost heat sink surface (with heat sinks), and the external casing of the resin-printed prototype (assembled device). As shown in Figure 4, lights without heat sinks exhibited the most severe temperature rise exceeding 75°C. Lights with three heat sinks performed significantly better, remaining under 50°C. The assembled prototype demonstrated the best thermal performance, staying below 40°C throughout the test. These results validate the use of passive heat sinks and confirm that the finalized design effectively prevents overheating while supporting the project's miniaturization goals.

This performance meets the design objective of keeping surface temperatures below 42°C, thus ensuring user safety. In addition to short-term heat testing, the prototype was left continuously powered for one week to assess potential burnout. The lights remained fully functional, indicating the device's readiness for sustained use in clinical applications such as central line sanitation, where long-term reliability is essential.

CAD Design

Several iterations of the reusable housing unit and the disposable cartridge were designed throughout the development process. The first iteration of the two parts was crude, and its main purpose was to ensure that the rail system and bumps were correctly placed to keep the cartridge in a spot where the UV lights could consistently treat the system. This original design did not include any area to hold the lights or power supply and did not have the Luer lock mechanism needed to integrate our device into the clinical workflow (figs. 5A, 5C). The second iteration of the housing component was designed after completion of the circuit. Using the measurements taken from the completed light system, we created a model that would be able to hold the lights in place and ensure that the lights were positioned in a way where they would be emitting light to disinfect the fluid. This involved creating a larger chamber above the space that was designed for the cartridge. After taking the measurements for the lights, we also had to increase the length of the housing unit so that it could contain the full length of the circuit.

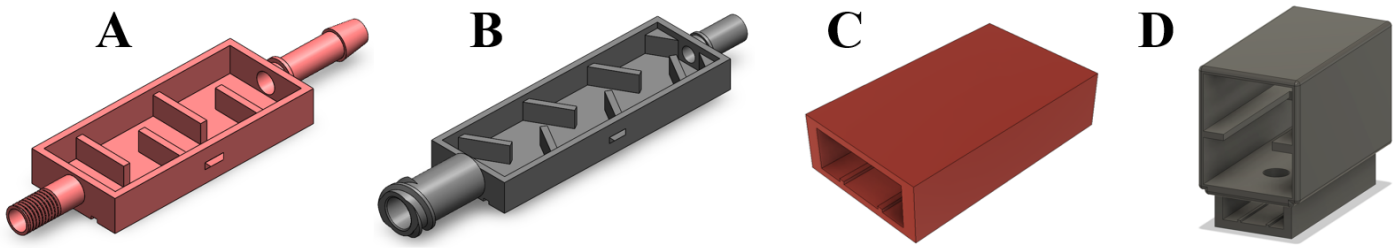

Figure 5. Iterative Prototype Design of Disposable Cartridge and Reusable Housing (A) Original Cartridge. (B) Final Cartridge. (C) Original Housing. (D) Final Housing

The second iteration of the cartridge changed the interior of the design so that instead of the baffling protruding 90° from the sides of the prototype, they were angled at 60° in order to ensure that the fluid flowed in the correct direction. Small, angled protrusions were also added to the floor of the cartridge at the end where the fluid flows out so that all of the fluid would be correctly removed from the device. Additionally, the length of the cartridge needed to be increased to match the increase in length of the housing unit. This increase in length also required us to increase the number of baffles from four to six to ensure that the fluid is contained in the device long enough to be treated by the UV exposure. Finally, in this iteration of the cartridge, the Luer lock threads were added to the front end to provide a seamless fit into the existing mechanisms of the healthcare system (fig. 5B). The final major iteration of the housing unit took place after additional heat testing was completed on the entire prototype. Our results showed us that there was not enough space provided inside the device to effectively dissipate heat through the heat sinks. To counteract this, we provided more space on the interior of the housing unit and added a shelf on which the power supply can sit. This shelf allowed for enough space above the heat sinks so that they could work effectively and keep the prototype below the threshold temperature (fig. 5D). The remaining iterations of the housing unit and cartridge were all minor updates to the design to provide a better fit between the two components and allow for more efficient treatment of the device by the UV lights. The final assembled prototype is shown in Figures 6 and 7.

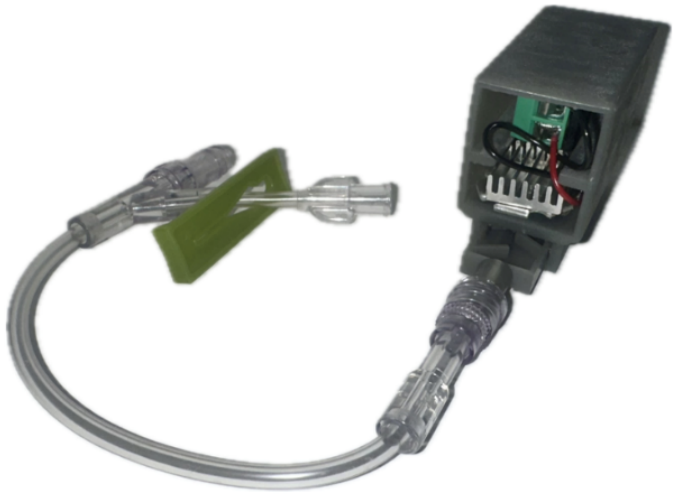

Figure 6. Final prototype of housing, cartridge, and circuit with connection to Luer lock shown.

Figure 7. Alternate view of final prototype of housing, cartridge, and power supply with other connection to central line tubing.

Discussion

Interpretation of Results

Overall, we were able to successfully miniaturize the conceptual foundation of the UV unit from AquiSense into a device aimed at reducing CLABSIs. The device consists of a two-part design, a reusable housing where

the circuit and lights reside and a disposable cartridge that allows for fluid flow. The prototype integrates seamlessly into the clinical workflow with the implementation of the Luer lock mechanism on the disposable cartridge, while maintaining essential design features previously shown to achieve significant bacterial reduction at clinically relevant flow rates.

Conclusions and Significance

Currently, the primary methods for preventing CLABSI include adherence to sterile procedures. According to the CDC's guidelines for infection prevention and control, these procedures revolve around proper hand hygiene, medication and injection preparation, environmental disinfection, and ensuring that providers have a strict set of rules they must adhere to concerning minimizing potential exposures (CDC, 2024; Chovanec et al., 2021). While these may appear to be effective infection prevention measures in theory, central lines are used in high stress environments, often as life-saving and sustaining measures. In these environments, it may be difficult for providers to adhere completely to these protocols. This device would lessen the burden of infection prevention that is placed on the provider, reducing the likelihood of human error and providing another layer of protection against infection for patients, ultimately saving lives.

The most common organisms linked with central line-associated bloodstream infections are gram-positive bacteria, making up approximately 75% of line infections. Based on the National Healthcare Safety Network *Staphylococcus aureus* are amongst the most common gram-positive bacteria, followed by gram-negatives which includes, *Escherichia coli* (Haddadin et al., 2024). Having chosen S. *aureus* and *E. coli*, two clinically significant pathogens to test the effectiveness of the UV light sanitation device, demonstrates the necessity of the device. The results showing successful elimination of both bacteria, highlights the device's strong potential as an additional preventative measure against CLABSIs in clinical settings. This accomplishment is highly significant for the healthcare system as it can reduce microbial colonization on central lines, lower infection rates and protect patient safety while being treated in the hospital. Additionally, this device as a preventative measure against line infections can substantially reduce the financial burden on health care institutions, as each case can cost tens of thousands of dollars in extended care, antimicrobial treatment, and complications.

By preventing CLABSI before the infection can occur, this device reduces the need for antibiotic use, which is vital for slowing the increase of antibiotic-resistant bacteria. These drug-resistant bacteria drive antimicrobial resistance (AMR), which was responsible for over 1.27 million deaths globally in 2019, and is expected to cost the United States over $1 trillion in healthcare costs by 2050. Notably, *S. aureus* and *E. coli* are becoming increasingly resistant. The median reported resistance rate from 76 countries is 42% for third-generation cephalosporin-resistant *E. coli* and 35% for methicillin-resistant *Staphylococcus aureus* (*Antimicrobial Resistance*, n.d.). These are the exact pathogens targeted in our testing, underscoring the clinical relevance of the device. By effectively eliminating these bacteria at the point of entry, the device offers a proactive strategy to reduce infection-related antibiotic use and mitigate the rise of resistant strains.

Limitations

At the beginning of the project, a key aim was to verify that the redesigned prototype maintains the same bacterial elimination efficacy as Dr. Thiele's original tests, which achieved a 4-log reduction in bacteria after just 2 seconds of exposure to UV light (Appendix 3). The testing planned to involve running fluid contaminated with E. coli and S. aureus through our assembled prototype and quantifying the number of bacteria remaining after exposure to the UV lights. It was originally anticipated that this testing would be time consuming, but after learning that Dr. Thiele's lab would be able to run the tests in a timely manner, it was decided to allocate more time to CAD and design iterations instead of preparing for bacterial testing. After facing setbacks involving 3D printing, and the usability of Dr. Thiele's lab due to maintenance issues, bacterial tests have yet to be completed. Additionally, Dr. Thiele performed tests with UV light on medications commonly used with central lines such as insulin and epinephrine, to determine if prolonged UV exposure caused degradation of the medications that would compromise effectiveness. It was also planned to run similar tests with the redesigned prototype, but these were not able to be completed.

One of the major limitations with the prototype itself is scalability. As of now, the design is made using SLA printing using resin printing. This current process takes approximately three hours to complete one prototype. With the goal of this product being mass production at a low cost, the current process cannot efficiently create the desired quantity. Additionally, the design is limited by the integration of the Topas plastic sheet. The current prototype uses glue to hold the Topas in place. However, for cost-effective mass production to be achievable, further iterations would require the plastic plate to be held in place in a way that prevents leakage without requiring the manual labor that is currently needed to attach the plate to the disposable cartridge.

Next Steps

Moving forward, future work on the development of the UV light sanitation device will focus on four key areas to ensure its effectiveness, usability and readiness to be integrated into clinical settings.

We were unable to collect data on the bacterial elimination efficacy and drug compatibility, the first step to accomplish would be performing these tests. Based off the proof of concept performed by Dr. Thiele and his team, we have a solid foundation of knowledge for how this device will perform when the fluid is exposed for two seconds. In order to test the efficacy of the device, the testing that should be performed should closely follow the original testing. The device should be tested on *S. aureus* and *E. coli* for common bacteria as well as insulin and epinephrine for the common medications as a minimum. We would expect to see similar results in this trial as Dr. Thiele found in his research which consisted of a 4-log reduction in bacterial reduction with no degradation of the drugs (Appendix B, C).

The second point would be to take into consideration steps for mass production, which would involve sourcing medical-grade materials that can be injection molded. Also, designing scalable manufacturing process that preserves the device's quality and sterility to be safe for clinical use. The following step would be to conduct clinical simulations before actual clinical trials that involve animal and human subjects. Possible simulations to conduct may include using mannequins to mimic central line insertion and maintenance by healthcare workers. Observing their interactions with the device, and taking notes on the ease of usability, and the incorporation of it into existing workflows will be collected for feedback. These simulations will help us evaluate the device's practicality, safety and usability. This step is essential because from there, the design can be iterated based on the feedback to improve comfort, functionality and integration into clinical practice further down the line.

Following improvement of the device based on professional assessment, preparation for clinical trials will proceed. This involves drafting a study protocol to be submitted to the Institutional Review Board (IRB) for approval and identifying partner hospitals and/or research institutions. Clinical trials will allow for further robust data to be gathered regarding the device's effectiveness in reducing CLABSI rates and further validate the safety and cost-effectiveness. Overall clinical trials will underscore the significance of UV technology being implemented into infection control protocols.

Materials and Methods

Creation of Prototype Designs and Physical Model

The circuit consists of two 285 nm UV-C lights connected in series with three aluminum heat sinks attached to the back. Our original testing of the lights utilized the power supply from the AquiSense UV light, while our final circuit design used a DC plug female screw post plug from GXILEE and a 12V 1A power supply.

The design iterations for the disposable cartridge piece were created using the computer-aided design software, SOLIDWORKS. The iterations of the housing unit were performed using Autodesk Fusion. The first 2 iterations were printed using Prusa fused deposition modeling (FDM) printers at the Shannon Library Makerspace using PLA. The later iterations were printed using FormLabs stereolithography (SLA) printers with resin material at both the Shannon Makerspace and the Stacey Hall BME Fabrication Space.

The plastic plate that was used to contain the fluid while still allowing UV light to penetrate and act on the fluid was Topas 8007S-04. This plastic, provided to us by Dr. Thiele, is a glass-clear amorphous polymer with high chemical resistance, high purity, and a non-reactive surface ("8007S-04," n.d.). Proper sizing of the plastic

was done using a Universal VLS6.60 laser cutter at the Stacey Hall BME Fabrication Space.

Heat Testing

Heat testing was conducted using an FLIR TG56-2 Spot Infrared Thermometer. Testing was performed on 3 different light configurations of two 285nm UV-C lights connected in series. These configurations are: (1) lights without heat sinks, (2) lights with three heat sinks, and (3) lights fully integrated into the assembled prototype. Temperatures were recorded over a two-minute interval. Readings were taken from the rear of the lights (no heat sinks), the outermost heat sink surface (with heat sinks), and the external casing of the resin-printed prototype (assembled device). The data was compiled in Microsoft Excel and then analyzed with R Studio.

End Matter

Acknowledgements

Thank you to Dr. Thiele for his guidance and support throughout the year.

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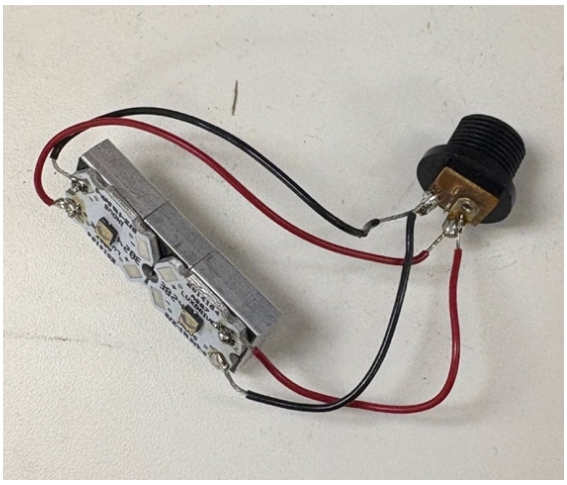
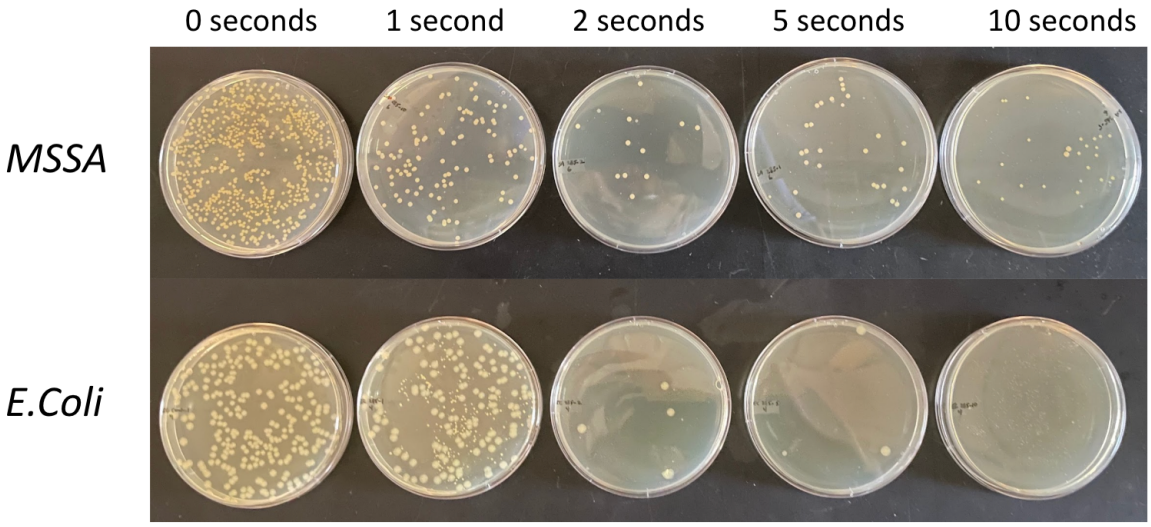
Appendix

Appendix A. UV-C lights connected in parallel. This configuration caused flickering of the lights instead of constant output.



Appendix B. Dr. Thiele's tests with *S. aureus* and *E. coli* bacteria exposed to UV light. CFU quantification showed a 4-log reduction in bacteria after 10 seconds.



Appendix C. Dr. Thiele's tests with epinephrine and insulin exposed to UV light. Minimal degradation was found, even after 1000 seconds.