NWRI GRADUATE FELLOW FINAL PROGRESS REPORT

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Project Title: Mechanisms and Sustainability of Wavelength-Tailored Ultraviolet Drinking Water Disinfection for Small Systems

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Introduction

This research was part of the EPA-funded DeRISK (Design of Risk-reducing, Innovative-implementable Small-system Knowledge) research center investigating solutions for sustainable water treatment technologies and strategies that are appropriate for small systems in the U.S. I investigated novel sources of ultraviolet (UV) light that output specific wavelengths, including light emitting diodes (LEDs) and excimer lamps, for drinking water disinfection. My research uses fundamental molecular biology investigations to expand understanding of how UV disinfection works, so that we can optimize based on wavelength specific responses. This research expands existing knowledge beyond the understanding that genome damage causes UV disinfection. Growing evidence indicates that protein damage also causes UV disinfection[1]. My research also evaluated and piloted a novel mercury free UV-LED reactor to prove how this research translates in to the field.

LEDs and excimer lamps are new UV sources that can be designed to emit specific wavelengths, as shown in Figure 1. These new sources could be more sustainable than traditional UV lamps because they do not contain toxic mercury, have lower power requirements, are more compact, and are becoming more efficient as materials science advances. Because disinfection does not depend on the UV lamp type, these sources disinfect bacteria, protozoa, and viruses just as well as traditional mercury UV lamps for a given dose and wavelength[2].

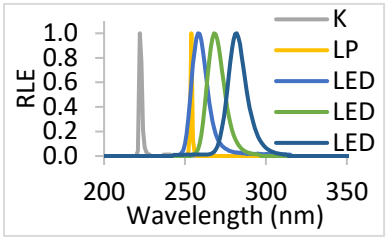

Figure 1 - Relative Lamp Emission (RLE) spectra for the KrCl excimer lamp (K), low pressure mercury lamp (LP), and light emitting diodes (LEDs) used in this study.

U.S. EPA guidance for UV disinfection of drinking water is governed by virus inactivation using traditional low pressure (LP) mercury lamps that emit a single UV wavelength[3]. Because viruses are resistant to this wavelength, the UV dose needed to achieve required 4-log viral inactivation (99.99% reduction) is high enough to sometimes be cost-prohibitive for small systems. However, microorganisms vary in their sensitivity to different UV wavelengths[4]. For example, adenovirus is resistant to single-wavelength (monochromatic at 254 nm) LP UV disinfection, but is more susceptible to multi-wavelength (polychromatic) medium pressure (MP) UV disinfection[5]. This varying wavelength sensitivity offers an opportunity to optimize UV disinfection. Additionally, draft regulatory guidance will allow future UV disinfection to be credited for disinfection at all wavelengths across the UV-C spectrum.[6]

Hypotheses:

(1) By optimizing wavelength selection, reactor design, and operation of mercury-free UV sources, we can achieve equivalent or better disinfection performance with less electricity, thereby improving the sustainability of the UV disinfection process.
(2) When optimized wavelengths are used, lower UV doses will be required, increasing the attainability (affordability and feasibility of implementation) of this technology for small systems.

Objectives:

(1) Determine wavelength-specific protein damage, genome damage, and inactivation for indicator organisms and pathogens using single or sequential exposures of mercury-free (LED and excimer lamp) and/or traditional UV sources.
(2) Validate disinfection performance at the bench and implement in a local small system the first commercially available LED flow-through reactor to study sustainability, robustness, and disinfection performance over time.

Progress

Approach:

A benchtop UV LED system emitting various peak wavelengths from 255 – 285 nm shown in Figure 1 was supplied to our lab through an industry partnership. A KrCl excimer lamp emitting at 222 nm was also supplied through another industry partnership. We tested these wavelengths to more efficiently target absorbance of DNA and proteins, to simulate the disinfection advantages previously identified for polychromatic MP UV emissions[7]. We are testing these novel, non-mercury UV sources when illuminated individually or in sequence to determine the optimum disinfection wavelength or combination(s) of wavelengths. These UV sources were also tested with a traditional LP lamp to determine if wavelength-specific sources targeting DNA and proteins can enhance LP disinfection to lower the required dose to achieve 4-log virus disinfection for regulatory compliance. The ability to disinfect was being measured by viral infectivity assays molecular assays for protein and nucleic acid damage. The effectiveness of disinfection was normalized to UV dose (fluence) and energy use, enabling comparisons between UV source combinations and modes of operation.

A flow-through LED reactor was designed using input from previous studies from our lab. We evaluated it at bench-scale and it is being piloted at a local small system. Over the course of 1 year as shown in Figure 2, the UV transmittance (UVT) in the UV reactor influent was measured daily, and correlated with temperature, pH, and turbidity. Bi-weekly samples were collected in the treatment plant influent, slow sand filter effluent, and existing chlorine disinfection effluent for comparison to the pilot UV LED disinfection effluent, as shown in the water treatment plant schematic in Figure 2. Analytes for these bi-weekly samples included ATP, total coliform, *E. coli*, and TOC. Continued disinfection performance was monitored using quarterly indicator virus challenge tests. Data on electrical and maintenance requirements were collected for life cycle sustainability analyses performed by partner DeRISK researchers.

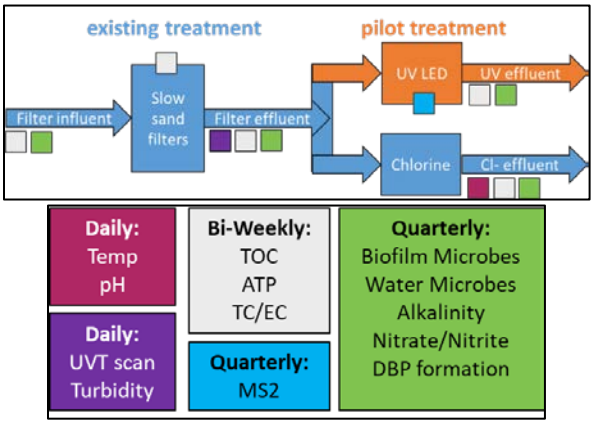

Figure 2 Schematic of existing treatment and pilot UV LED disinfection, showing color-coded sampling locations and schedule for the pilot study.

Results:

Research for this project built on our lab's previous evaluation of UV LEDs for inactivating *E. coli* bacteria, MS2 coliphage (nonpathogenic surrogate virus), adenovirus 2 (pathogenic virus), and *B. pumilus* bacterial spores[8], and studies of the contribution of wavelength-specific protein damage to adenovirus inactivation[1]. My study used the same techniques to measure wavelength-specific damage to MS2 proteins and demonstrated that protein damage similarly contributes to MS2 inactivation, likely because both viruses rely on protein integrity to attach to and infect their host cell. I also used a novel enzyme-linked immunosorbent assay (ELISA) to directly quantify wavelength-specific contribution of genome damage to both adenovirus and MS2 inactivation to complement previous research in our lab using indirect (enzyme based) methods to quantify wavelength specific genome damage to MS2 and adenovirus[9,10]. These mechanistic studies demonstrated that the viral surrogate MS2 has similar molecular disinfection response to the target pathogen adenovirus.

The KrCl excimer lamp was tested to determine MS2 inactivation dose-responses for the first time. The excilamp and LEDs were tested alone and when combined sequentially together or with an LP UV lamp. We found the excilamp to be most effective based on a given UV dose, and that disinfection was improved over LP alone when combining the LP and excilamps in sequential exposures. We also found synergy from the order of exposure when MS2 was exposed to either the excimer or the LP lamp before LEDs. When considering electricity requirements for a given level of disinfection, the excilamp is already competitive with LP UV, and all sequential exposures are competitive with MP UV.

The MS2 disinfection performance of the flow-through UV LED reactor was measured at various flowrates and UVTs measured at 285 nm (the wavelength emitted by the LEDs) at the bench in dechlorinated tap water. MS2 disinfection was measured in slow sand filter effluent water after installation at the local small system in January (Figure 3), and once per quarter over the course of one year. Experimental results of MS2 disinfection upon installation, and in November and the following January aligned well with the novel approach of combined variable model[11] predictions from bench testing. In May and August, MS2 was disinfected more effectively than predicted, possibly due to light scattering or photosensitization. The UV-LED reactor was resilient for one year with zero maintenance to maintain disinfection performance. The LEDs lost only 25% power after continuous operation, and the unit cost an estimated <$25 to run, treating 0.5 lpm at an MS2 reduction equivalent dose of at least ~40 mJ/cm^2 all year.

Figure 3 (a) UV-LED at Jamestown, CO drinking water treatment plant.

Conclusions

This research increased knowledge of how different UV wavelengths damage the molecules that make up infectious agents. Molecular studies of viral surrogate and pathogen contribute confidence to validations and test results for novel wavelength combinations using this viral surrogate. Use of a simple viral surrogate, MS2 coliphage, to assess genome and protein damage is a novel technique for evaluation of performance of these UV sources, and could be useful after further method development for on-site analysis of UV-induced damage for faster and more accurate UV validations. These molecular tools may also eventually prove useful for on-site or even online monitoring of UV disinfection system performance.

This research also showed that synergy can be achieved to minimize electricity requirements and maximize disinfection, when using a tailored wavelength combination of these novel mercury free sources. This could increase sustainability of UV disinfection for systems of all scales, including small systems. This is new and exciting because synergies between wavelength-specific excimer lamps, LEDs, and traditional LP lamps have not previously been investigated to determine how molecular protein and nucleic acid damage contribute to increased UV disinfection efficiency (especially at low wavelengths). Future research should investigate whether simultaneous exposure to these various types of UV sources results in synergy, and whether operation of these sources in pulsed mode (excilamps and LEDs but not LP lamps) results in increased disinfection and/or electrical efficiency.

This first longitudinal evaluation of a flow-through UV LED system provides data necessary for practical operation, life cycle analyses, design improvements, and scale-up, allowing faster adoption of wavelength tailored UV disinfection systems in the future. Future studies should examine scaled-up systems implemented at scaled suitable for meeting full municipal flow needs. Future studies should also optimize reactor design for lower water qualities to prove efficacy of wavelength tailored disinfection for reclaimed and waste water.

References

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Relevant Presentations and Publications

Hull NM and Linden KG (Feb 2018, conference presentation). Sequential LED and excimer lamp exposures for viral UV disinfection. IUVA Americas, Redondo Beach, CA.
NMH won 1st place student presentation

Linden KG, **Hull NM** (presenter), Sholtes KA, and Beck SE (Oct 2017, conference presentation). UV LEDs for small systems: a revolution in robust and effective disinfection? International IWA S2Small Conference on Sustainable Solutions for Small Water and Wastewater Treatment Systems, Nantes, France.

Hull NM and Linden KG (Oct 2017, invited presentation). Mechanisms and Sustainability of Wavelength-Tailored Ultraviolet Drinking Water Disinfection for Small Systems. Environmental Engineering Seminar, CU Boulder, CO.

Hull NM and Linden KG (Sep 2017, conference presentation). Longitudinal Disinfection Performance of a UV LED Reactor Piloted at a Drinking Water Plant. IUVA World Congress, Dubrovnik, Croatia.
NMH tied for 2nd place student presentation

Hull NM, and Sholtes KA (co-first authors) (Feb 2017, invited presentation). UVC LEDs and Disinfection. UVC LED Review Workshop for IUVA Americas, Austin, TX.

Hull, NM and Linden KG (Jan 2017, webinar). UV Wavelength-Specific Damage and Inactivation of MS2. DeRISK Center Drinking Water Webinar, Hosted in Boulder, CO.

Hull, NM, Linden KG (Nov 2016, conference presentation). Ultraviolet Wavelength- and Dose-Dependent Inactivation and Molecular Damage of MS2 Coliphage. WQTC, Indianapolis, IN.

Beck SE, **Hull NM** (presenter), and Linden KG (Feb 2016, conference presentation). Ultraviolet Wavelength- and Dose-Dependent Damage of Adenovirus Proteins. IUVA World Congress, Vancouver, BC, Canada.
NMH won 2nd place student presentation

Beck SE, **Hull NM**, Poepping C, and Linden KG (2017). Wavelength-Dependent Damage of Adenovirus Proteins Across the Germicidal UV Spectrum. *ES&T* 52(1):223-229.

Hull NM, Beck SE, and Linden KG (manuscript in preparation 2018). Molecular Damage of MS2 and Adenovirus Across the Germicidal UV Spectrum.

Hull NM, and Linden KG (manuscript in preparation 2018). Validation and Small-System Implementation of the First Commercial UV-C LED Water Treatment Reactor.

Hull NM and Linden KG (submitted to *Water Research*). Combining Novel UV Sources for Viral Disinfection Compliance at Lower Doses than Conventional Mercury Lamps.