NWRI GRADUATE FELLOW SEMI-ANNUAL 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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Background and Introduction

Research Needs

In some small towns across the United States, the three pillars of sustainability are impaired. Economies that once boomed have been left to bust. Communities that were or could be rich cultural hubs are withering. Environmental neglect has led to pollution of surface and ground water, affecting human health and putting the public at risk. These factors demand that innovative solutions be put forward to support these communities, including sustainable solutions to drinking water treatment that are cheaper, use less electricity, and use fewer hazardous materials than conventional technologies. My PhD research is part of the EPA funded DeRISK (Design of Risk-reducing, Innovative-implementable Small-system Knowledge) research center investigating innovative, risk-reducing solutions for sustainable water technologies for small systems in the US. Emerging sources of ultraviolet (UV) light that output specific wavelengths, including light emitting diodes (LEDs) and excimer lamps, have the promise to be a more sustainable solution for drinking water treatment in small communities like these.

Research Contributions

My research uses microbiological investigations to broaden understanding of the mechanisms of UV disinfection. By understanding how UV affects the molecules that make up microorganisms at different UV wavelengths, combinations of new and/or existing UV light sources can be optimized for more efficient drinking water disinfection. LEDs and excimer lamps are a more sustainable source of UV light than traditional UV lamps because they do not contain toxic mercury, are more compact, require less power, and are becoming more efficient as materials science advances. Because disinfection does not depend on the UV lamp type, these sources are as effective as traditional mercury UV lamps for inactivating bacteria, protozoa, and viruses for a given dose/wavelength combination[1]. By optimizing wavelength selection, reactor design, and operation of these new UV

sources, the same disinfection performance can be achieved with less electricity, improving sustainability of UV disinfection for small systems.

Additionally, regulations of UV disinfection technology in the United States are based on viruses, which tend to be the most resistant microbes to UV disinfection[1]. Studies that inform current regulations used traditional low pressure (LP) mercury lamps that emit a single UV wavelength. Because viruses are resistant to this wavelength, doses needed to achieve required 4-log viral inactivation are so high that they can be prohibitive for implementation in small systems. However, many microorganisms have varying sensitivity to different UV wavelengths[1]. For example, adenovirus is extremely resistant to monochromatic LP UV disinfection, but is very susceptible to disinfection by polychromatic medium pressure (MP) UV, which emits many different UV wavelengths.

The mechanistic microbiology studies of my PhD research can inform new regulations so that when optimized wavelengths are used, lower UV doses will be required, increasing the attainability of this technology for small systems.

Progress

Experimental Design

A tailored UV reactor would ideally combine wavelengths from peak DNA absorbance (250-280 nm) with peak protein absorbance (< 240 nm) to achieve optimal possibility for microbial inactivation. This combination would simulate the advantages previously identified for polychromatic MP UV emissions[2], yet be more efficient and targeted for inactivation. UV LEDs emitting various wavelengths from 255-285 nm will be tested to target peak DNA absorbance and the secondary peak of protein absorbance. A benchtop UV LED system capable of emitting at these wavelengths is being supplied through an industry partnership. A KrCl excimer lamp emitting at 222 nm will be used to target maximum protein absorbance, and is being supplied through another industry partnership.

These novel, non-mercury UV sources will be tested when illuminated individually, sequentially, or simultaneously to determine the optimum disinfection wavelength combination(s) for these UV sources. These sources will also be tested in conjunction with a traditional monochromatic low pressure (LP) mercury UV lamp to determine if wavelength-specific sources targeting proteins can enhance LP disinfection, and decrease dose requirements.

Studies have shown that operating UV sources in pulsed mode provides the same level of disinfection at lower electrical requirements than continuous mode[3–8]. After optimizing wavelengths, we will test the UV source(s) in pulsed mode to explore further optimization of disinfection to achieve the same level of disinfection at lower electrical requirements.

The ability to disinfect will be measured via cellular survival, viral infectivity assays, and molecular assays to assess damage of nucleic acids and proteins. Disinfection efficacy will be normalized to UV dose (fluence) and energy use, enabling comparisons between UV source combinations and modes of operation.

After optimization, a flow-through reactor will be designed and evaluated at bench-scale for verification of performance. The reactor will then be installed and piloted at a test facility in partnership with researchers at the DeRISK center, where performance will be verified using standard UV validation protocols. Data on electrical and maintenance requirements will be collected for life cycle sustainability analyses performed by partner DeRISK researchers.

Additionally, biofilm will be collected downstream of the installed pilot UV reactor over time, and downstream of the disinfection reactor currently used by the test facility. DNA sequences in biofilm that develops on 1-inch pipe sections downstream of the disinfection reactors will be analyzed to compare microbial communities resulting from different disinfection strategies.

Experimental Results

- Research for this project builds on previous work in the Linden Lab evaluating UV LEDs for their efficacy in inactivating the common water-borne pathogens, fecal indicators, and surrogates *E. coli,* MS2 coliphage, adenovirus 2, and *Bacillus pumilus* spores. This work explored UV inactivation and molecular biological analysis by individual wavelengths and simultaneous exposures of multiple wavelength. The research was just published. Other work done to set the stage for this NWRI-funded research looked at virus inactivation and the role of protein damage using methods such as SDS-PAGE (sodium dodecyl sulfate polyacrylamide gel electrophoresis)

- In this research the use of other novel UV sources is being examined, such as the KrCl excimer lamp emitting UV light at a wavelength of 222 nm, for inactivating the common water-borne pathogen surrogate MS2 coliphage. The inactivation dose-response is being evaluated compared to LP UV lamp and in combination with other light sources. We expect to determine the most effective lamp and lamp combinations and the mechanisms by which that effectiveness is generated. Preliminary results indicate possible MS2 inactivation synergy from simultaneous exposure of the LP UV and excimer lamps.

- Damage to MS2 proteins resulting from exposure to the LP and excimer lamps is being assessed using the SDS-PAGE method. We will evaluate the different UV lamp sources and determine the contribution of protein damage to inactivation.

Conclusions

Novel Aspects

Synergies between wavelength-specific excimer lamps, LEDs, and traditional LP lamps have not been investigated to determine how molecular protein and nucleic acid damage contributes to increased UV disinfection efficiency (especially at low wavelengths). Use of a simple viral surrogate, MS2 coliphage, to assess protein damage is a novel technique for evaluation of performance of these UV sources.

Implications

- LEDs were demonstrated to successfully inactivate pathogens, indicators, and surrogates. This provides proof of concept that these emerging sources can be an effective drinking water disinfection technology.
- The extent of protein damage is being investigated. This is important for the design of a reactor using tailored wavelengths that will be equally or more effective at lower doses than provided by LP UV.
- Mechanistic understanding of how surrogate and pathogenic microorganisms are inactivated can contribute to more informed regulatory decision-making, especially when mechanisms for the surrogate (like MS2) match the target pathogen (like adenovirus).

Next Steps

Future bench-scale research plans include sequential and simultaneous UV exposures, combining LEDs tested with Excimer lamp and/or LP UV, to optimize molecular damage and cellular inactivation. The best wavelength combination(s) will be tested in pulsed mode to determine if further electrical optimization is possible. As for adenovirus, MS2 will be exposed to wavelengths across the germicidal spectrum to determine the spectral protein damage response. It is expected that the protein damage spectrum for MS2 will resemble that for adenovirus, just as their inactivation action spectra are similar.

Additionally, an industry partner has developed with input from the Linden Lab the first commercially available UV LED disinfection flow-through reactor. We have begun bench testing to evaluate this reactor, and plan to subject it to further bench testing before implementation at a field site for sustainability analysis. Work with the excimer lamp also demonstrates promise for design and evaluation of a reactor combining it with either LEDs or LP UV to obtain enhanced disinfection from low wavelengths.

References

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