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Sequential UV- and chlorine-based disinfection to mitigate *Escherichia coli* in drinking water biofilms

*H.M. Murphy, S.J. Payne, G.A. Gagnon**

Department of Civil & Resources Engineering, Dalhousie University, Halifax, Nova Scotia, Canada B3J 2X4

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ABSTRACT

This study was designed to examine the potential downstream benefits of sequential disinfection to control the persistence of *Escherichia coli* under conditions relevant to drinking water distribution systems. Eight annular reactors (four polycarbonate and four cast iron) were setup in parallel to address various factors that could influence biofilm growth in distribution systems. Eight reactors were treated with chlorine, chlorine dioxide and monochloramine alone or in combination with UV to examine the effects on *Escherichia coli* growth and persistence in both the effluent and biofilm. In general, UV-treated systems in combination with chlorine or chlorine dioxide and monochloramine achieved greater log reductions in both effluent and biofilm than systems treated with chlorine-based disinfectants alone. However, during UV–low chlorine disinfection, *E. coli* was found to persist at low levels, suggesting that the UV treatment had instigated an adaptive mutation. During UV–chlorine-dioxide treatment, the *E. coli* that was initially below the detection limit reappeared during a low level of disinfection (0.2 mg/L) in the cast iron systems. Chloramine was shown to be effective in disinfecting suspended *E. coli* in the effluent but was unable to reduce biofilm counts to below the detection limit. Issues such as repair mechanism of *E. coli* and nitrification could help explain some of these aberrations. Improved understanding of the ability of chlorine-based disinfectant in combination with UV to provide sufficient disinfection will ultimately effect in improved management and safety of drinking water.

1. Introduction

Coliforms bacteria are widely used as indicators of microbiological quality and safety of drinking water (Besner et al., 2002). Total coliforms and *Escherichia coli* are routinely monitored by drinking water utilities and their detection is often an indication of (a) inadequate treatment, (b) breech in distribution system integrity and/or (c) regrowth (e.g., Williams and Braun-Howland, 2003; Craun and Calderon, 2001; LeChevallier, 1990).

Once introduced into distribution systems, the presence of *E. coli* and, to an extent, total coliforms can become a concern of drinking water safety and public health (Hrudey et al., 2003). Several outbreaks worldwide have been associated with the presence of *E. coli* O157 in drinking water supplies such as Walkerton, ON, Canada; Highland Region, Scotland; and Cabool, MO, USA (Hrudey and Hrudey, 2004). In general, those who are most susceptible to significant health impacts as a result of consumption are the elderly, children and the immuno-compromised. Previous studies have shown that coliforms are capable of persisting in drinking water distribution system biofilms in the presence of disinfectants (Camper et al., 1999; Lisle et al., 1998; Williams and Braun-Howland, 2003; LeChevallier, 1990, Norton and LeChevallier, 1997).

*Corresponding author. Tel.: +1 902 494 3268; fax: +1 902 494 3108.
E-mail address: graham.gagnon@dal.ca (G.A. Gagnon).
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Consequently, the ability of coliforms to persist in distribution system biofilms is of high significance for ensuring water safety and is an issue that requires an improved understanding for the development of appropriate solutions and prevention measures.

Public health concerns over the presence of chlorine-based by-products have prompted many utilities to consider or switch to UV as a primary disinfectant. The use of UV has been shown to be an effective disinfectant for addressing concerns associated with *Cryptosporidium* during drinking water treatment (e.g., Qian et al., 2005; Shin et al., 2001; Clancy et al., 2000). However, UV does not provide a residual disinfectant effect in the water distribution system, which is required by regulations in some jurisdictions, particularly in North America.

One potential way to address regrowth concerns in distribution systems is to design sequential UV chlor(am)ine disinfection. Previous studies have shown synergistic benefits with sequential disinfection (e.g., Dykstra et al., 2007; Koivunen and Heinonen-Tanski, 2005). Koivunen and Heinonen-Tanski's (2005) research showed synergistic benefits when using UV in combination with peracetic acid for treatment of wastewater, and specifically for inactivating *E. coli*, *Enterococcus faecalis*, *Salmonella enteritidis* and coliphage MS2 virus. Dykstra et al. (2007) suggested that free chlorine and chlorine dioxide act synergistically with UV treatment to control heterotrophic bacteria in annular reactors (ARs) operated under drinking water conditions. Similarly, Rand et al. (2007) also demonstrated in ARs that a disinfectant synergy for controlling heterotrophic bacteria may exist between UV/free chlorine treatment (UV/Cl_2) and UV/chlorine dioxide (UV/ClO_2) treatment. Although there are only few studies that have investigated UV synergy, similar synergy has been demonstrated through chemical-to-chemical sequences. Kouame and Haas (1991) demonstrated synergistic benefits between chlorine and monochloramine for inactivating *E. coli* at bench-scale in a completely stirred tank reactor. Straub et al. (1995) showed that synergism existed in the inactivation of both *E. coli* and MS2 coliphage with significantly shorter required contact times using a combined chloramine–copper system.

This study was designed to examine the potential downstream benefits of sequential disinfection to control the persistence of *E. coli* under conditions relevant to drinking water distribution systems. Improved understanding of the ability of chlorine-based disinfectant in combination with UV to provide sufficient disinfection will ultimately effect in improved management and safety of drinking water.

2. Materials and methods

ARs (BioSurface Technologies Corps) were used to simulate conditions relevant to drinking water distribution systems. Eight ARs were setup in parallel to address various factors that could influence biofilm growth in distribution systems. Four ARs contained polycarbonate coupons, while the other four contained cast iron coupons. Four of the ARs were pretreated with low-pressure (LP) UV lamps (Trojan UV-Max-C, Trojan Technologies, London, ON), while four received no UV disinfection. All eight ARs were chemically disinfected (secondary disinfection) with chlorine, chlorine dioxide or monochloramine depending on the experimental trial. *E. coli* K12 was used as the model organism.

2.1. Bench-scale distribution system setup

For this study, eight ARs were operated in parallel. The experimental setup is shown in Fig. 1. They were operated at a rotational speed of 50 rpm, which approximately corresponded to a shear stress of 0.25 N/m^2 and is consistent with previously published studies (Gagnon et al., 2004; Sharp et al., 2001; Camper, 1996). The HRT for the reactors was 6 h, which translated into a total flow rate of 2.8 mL/min into the ARs. All glass surfaces and any exposed surfaces were covered with aluminum foil to reduce the potential for phototrophic growth within the system. All tubing feeding influent water, *E. coli* and disinfectant into the system were non-transparent. The experiments were conducted at a water temperature of $20 \pm 1\,^{\circ}C$. Before each experimental trial, the ARs were completely disassembled and cleaned with antibacterial soap. All the coupons were removed from the drums and individually cleaned. Once reassembled, the ARs were filled with 70% ethanol solution and allowed to soak for 24 h. All the tubing from the previous trial was discarded except the tubing used to feed disinfectant. New tubing that had been flushed with 70% ethanol, followed by de-ionized water, was used for feeding influent water throughout the experiment and for the *E. coli* inoculations.

Tap water from the Halifax Regional Water Commission was the primary source water for the model distribution systems. On average, the water quality of this source water leaving the plant has an alkalinity of 17.5 mg/L as $CaCO_3$, a pH of 7.2 and a total organic carbon (TOC) concentration of 1.5 mg/L. Prior to entering the ARs, tap water passed through a granular activated carbon (GAC) filter to neutralize any chlorine present in the source water. Then the water was passed through a biologically active GAC (BAC) filter, which provided an inoculum for the ARs. The water from the BAC filter was then directed into a clearwell. The flow from this clearwell was split to feed both the UV unit and four ARs. Once water passed through the UV system it was directed towards another clearwell that fed four ARs.

The UV treatment system is capable of treating up to 64 lpm (17 gpm) at a fluence of 16 mJ/cm^2 and a UV transmittance of 95%. Water was pumped through the lamp with a variable speed modular peristaltic pump (Masterflex) at a flowrate of 250 mL/min, which translated to a fluence of between 90 and 100 mJ/cm^2. Prior to the startup of each trial, the UV lamp was cleaned and soaked in 70% ethanol for 24 h. The fluence was determined by performing MS2 inactivation as described by Dykstra et al. (2002).

The water quality of the GAC/BAC water contained an average heterotrophic bacteria count of 3.57×10^4 CFU/mL, a pH of 7.1, DOC of 1.64 mg/L and free chlorine was not detected.

2.2. Experimental timeline

Four experimental trials (runs) were conducted over a period of 14 months. Each trial was conducted with a separate