Chemical disinfection preceding UV treatment: An assessment of microbial regrowth in a model distribution system

Jennie L. Rand and Graham A. Gagnon

ABSTRACT

The goal of this study was to compare disinfection strategies for controlling microbial growth in distribution systems from a blended water source in a warm climate. This research compared the efficacy of chlorine (Cl_2) to monochloramine (NH_2Cl) with and without post-treatment with ultraviolet (UV) light for heterotrophic bacteria control. Two influent streams were pre-treated with either chlorine or monochloramine, and consisted of a blend of groundwater, surface water and desalinated water. Annular reactors (ARs) containing coupons made of PVC material were used to simulate common operating conditions in a distribution system. Two ARs acted as controls and received the chlorinated water or water treated with monochloramine. The remaining two ARs received water that was additionally treated with UV light. The data presented show that treatment with Cl_2 alone was the most effective disinfection strategy against suspended heterotrophic (HPC) bacteria in influent and effluent samples and also against attached HPC bacteria. Chlorine with or without post-UV treatment was more effective than monochloramine at removing suspended and attached HPC bacteria. Levels of free chlorine concentration were reduced following treatment with UV light, which resulted in the increased bacteria counts in the AR. UV treatment also appeared to enable nitrification in the AR treated with NH_2Cl, as ammonia was completely converted to nitrate in the NH_2Cl/UV-treated AR whereas concentrations less than 0.2 mg l^{-1} of nitrate or nitrite were detectable in the NH_2Cl-treated AR.

Key words | chloramines, chlorine, disinfection synergy, nitrification, UV light

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INTRODUCTION

Treatment of drinking water in warm climates can be challenging considering the degradation of free chlorine residual leading to increased microbial growth (Moore *et al.* 2006) and the relatively low biostability that exists in warm climates even following advanced physicochemical treatment (Escobar *et al.* 2001; Liu *et al.* 2007). Chloramines are often considered as an alternative to chlorine since they have been shown to persist longer in a distribution system (Norton & LeChevallier 1997). Martel *et al.* (2002) found that chloramines improved water quality in storage facilities in a warm climate where chlorination resulted in residual loss and increased bacteria counts. However, when considering a switch to chloramines, utilities must consider other possible issues that may arise in warm climates, primarily the potential for nitrification (Wilczak *et al.* 1996). It has been reported in literature that conditions that favour nitrification include warm climates or high temperatures in summer months (Pintar & Slawson 2003; McGuire *et al.* 2006). Pryor *et al.* (2004) found that a switchover to monochloramine at a utility in Florida resulted in lower *Legionella* but increased total coliforms, nitrification and heterotrophic (HPC) bacteria.

One potential way to address regrowth concerns in distribution systems is to evaluate sequential disinfection. Previous studies have shown synergistic benefits with sequential disinfection (e.g. Koivunen & Heinonen-Tanski

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2005; Dykstra *et al.* 2007). Koivunen & Heinonen-Tanski (2005) described synergy as when the 'efficiency of combined disinfection methods is greater than the efficiency achieved when summing the effects of individual disinfectants'. Their research showed synergistic benefits when using UV in combination with peracetic acid for treatment of wastewater, and specifically for inactivating *Escherichia 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 at the bench-scale when the application of UV treatment preceded the chemical disinfectant. Among the few studies that have investigated UV synergy, most have considered chemical disinfection downstream of primary treatment.

Kouame & Haas (1991) demonstrated synergistic benefits between chlorine and monochloramine for inactivating *E. coli* at the bench-scale in a completely stirred tank reactor (CSTR). Straub *et al.* (1995) showed synergism existed in the inactivation of both *E. coli* and MS2 coliphage with significantly shorter required contact times using a combined chloramines–copper system. Rennecker *et al.* (2000) investigated the inactivation kinetics of *Cryptosporidium parvum* oocysts with ozone/free chlorine and ozone/monochloramine disinfection combinations. The current study found that there was enhancement in the rate of inactivation with secondary disinfection when pre-treated with ozone (O_3) and a reduction in lag times for secondary disinfection. Li *et al.* (2004) tracked morphological changes in *Giardia lamblia* cysts following treatment with ozone, free chlorine and a combination of both disinfectants. They found that preconditioning of the cell wall by the first oxidant allowed for easier penetration and more damage by the second oxidant, showing synergistic effects.

This study examines the potential for synergistic effects with chemical disinfection upstream, followed by UV treatment and chemical residual downstream. This disinfection strategy would be conceivable where UV light is implemented in the treatment process at the point of entering the distribution system. A potential concern related to the implementation of UV treatment is the interaction between UV light and chemical disinfection. Some studies have shown that free chlorine or monochloramine in water exerts demand on the UV light through absorbance of UV irradiation, and conversely that the UV light destroys the chemical disinfectants reducing the available residual for inactivation of microbial cells. In particular, Ormeci *et al.* (2005) found that, although UV absorbance of free chlorine and monochloramine was relatively small, they may affect the effectiveness of UV light toward targeted microorganisms. This study also found that chlorine and monochloramine in potable water decay steadily in the presence of UV light, especially chlorine in poorer water quality.

The focus of this study was to determine whether the addition of UV light to the treatment process post-chemical disinfection would enhance the ability of disinfectants to suppress biofilm growth and control microbial growth in simulated drinking water distribution systems. In addition this work compared the following treatment strategies: chlorine (Cl_2), chlorine and UV light (Cl_2/UV), monochloramine (NH_2Cl), and monochloramine and UV light (NH_2Cl/UV). Heterotrophic and coliform bacteria were used to compare disinfection treatments for bacteria within the systems.

MATERIALS AND METHODS

Description of field location

The Keller Water Treatment Plant is located in Pinellas County, Florida, and collects water from sources that are regionally managed by the Tampa Bay Water supplier. The source for Keller is a blended mixture of groundwater, treated surface water and desalinated seawater. Separate streams treated with chlorine or monochloramine are directed into the Keller treatment facility, which has various processes for hydrogen sulphide removal, corrosion control, pH adjustment, addition of fluoride and, finally, disinfection for residual protection in the distribution system. In 2002, the utility switched from chlorination as the final disinfection step to adding monochloramine.

Field experiment set-up

Annular reactors (ARs) containing coupons made of PVC material were used to simulate the distribution system in Pinellas County. The hydraulic retention time (2.0 h) was

controlled by the volumetric flow rate of the influent entering the AR and was established based on a relationship between surface areas and volumes in ARs and pipes, as described by Gagnon & Huck (2001). The influent water stream was maintained at approximately 8.1 ml min^{-1} for each AR. The ARs operated at a rotational speed of 50 rpm which translates into a shear stress of 0.25 N m^{-2} (Camper 1996). A shear stress of 0.25 N m^{-2} corresponds to a flow of approximately 0.30 m s^{-1} (1fps) in a 100 mm (4 in) diameter smooth pipe which is similar to shear conditions of other pilot and bench scale investigations. Two ARs acted as controls and received raw source water containing free chlorine or chloramine residual. Two more ARs received water initially disinfected with either Cl_2 or NH_2Cl and then were additionally treated with UV light. Since water sources for this experiment were pre-treated with chlorine or monochloramine, there was no acclimation period as in most other AR studies. UV treatment was applied following chemical disinfection at a dose of approximately 100 mJ cm^{-2}. Disinfectant residual was the result of the concentration within the source waters as no additional chemical disinfectant was fed to the experimental system. The study ran over a seven-month period from April to November 2005.

All non-opaque exposed surfaces of the ARs were covered to reduce the potential of phototrophic growth in the field systems. Before each experimental trial, all ARs were cleaned with antibacterial soap and disinfected using a 70% ethanol solution. In addition all tubing and clearwells used within the set-up were disinfected with ethanol for a period of 24 hours. This was followed by rinsing with Milli-Q water and the source water.

Two streams, one containing monochloramine and one with free chlorine, were the primary source waters for the model distribution systems. Chemical disinfection was provided offsite prior to entering the plant. Original chlorination was accomplished using a sodium hypochlorite solution; monochloramine through the addition of ammonia to a chlorinated stream at a pH of approximately 9.4. No additional chemical disinfection was added to the feed streams. The water collected from each stream was directed into separate raw water (RW) clearwells. The flow pumped from each of these clearwells was split to feed both a UV unit and one AR. Each water stream had a separate UV system. Once water streams passed through the UV treatment they were directed towards two additional separate clearwells which fed the remaining two ARs.

The ARs were monitored once weekly for heterotrophic bacteria counts (suspended and biofilm), pH, temperature, turbidity, disinfectant residual, total organic carbon (TOC), coliforms, nitrite, nitrate, free ammonia and total ammonia. In addition, weekly checks of flowrates throughout the system and the rotational speeds of the ARs were performed to ensure consistent operating conditions.

Low-pressure UV light was delivered using a Trojan UVMax® system (Trojan Technologies, London, Ontario). The reduction equivalent dose (RED) delivered by the UV reactor was determined by biovalidation with MS2 phage as the challenge and ranged from 90 to 100 mJ cm^{-2}. Methods for the biovalidation procedure followed Bolton & Linden (2003) for the collimated beam work.

Sample collection and analysis

All sampling and testing protocols were carried out as described in the *Standard Methods for the Examination of Water and Wastewater* (1998). No additional chemicals were added for disinfection of the ARs. Free and total chlorine were measured using the DPD colorimetric method and a HACH DR/890 spectrophotometer. Monochloramine was measured using a HACH DR/890 spectrophotometer and the Indophenol Method 10200.

Microbial analysis

To evaluate the effectiveness of disinfectant strategies on regrowth in the simulated distribution systems, samples were collected for biofilm bacteria and suspended bacteria. Biofilm forms on pipe walls in a distribution system and can lead to headloss and promote regrowth in the system. Bacteria suspended in bulk water can often be the result of sloughing of the biofilm bacteria; therefore both biofilm and bulk samples indicate the effectiveness of a disinfectant. For suspended heterotrophic bacteria analysis, influent and effluent samples were collected in sterile, 100 ml IDEXX bottles containing 10% w/v sodium thiosulphate to quench disinfectant residual. These samples were used for the heterotrophic plate counts. Biofilm samples were collected when coupons were removed aseptically, in sequence, from the AR. Once taken out, they

were transferred into sterile 50 ml glass bottles containing PBS and 0.1% w/v sodium thiosulphate. The attached cells were removed by the scraping method as described by Gagnon & Slawson (1999) and plated on agar to be analysed for heterotrophic plate counts. Following sampling, the coupons were cleaned with soap and water, and treated with ethanol before being returned to the AR.

Heterotrophic plate counts

Suspended and attached bacteria samples collected as described above were enumerated with heterotrophic plate counts. The process involved a standard spread plate technique as described in *Standard Methods for the Examination of Water and Wastewater* (1998) on R2A agar (Difco Laboratories). Sterile glass test tubes containing 9 ml phosphate buffer saline solution (PBS) were used in series to obtain dilutions from 10^{-1} to 10^{-5}, depending on concentration. Dilutions were used to target a microbial yield of 30 to 300 colonies per plate per 1 ml of sample. Duplicate plates were spread for each dilution and generally 2 to 3 dilutions were plated for each sample for quality assurance. All equipment used was sterilized and work was completed on a clean surface near a flame to prevent contamination. Plates were incubated upside down in the dark for 7 days at room temperature, after which time colonies were counted.

Coliforms and *Escherichia coli*

Bulk influent and effluent water samples were collected to analyse for coliforms and *E. coli*. Coliforms were enumerated using the IDEXX Colilert® Quanti-tray® system. Sterilized glass vials were used to collect the 100-ml samples required for the analysis, which during disinfection were quenched with 100 μl sterile sodium thiosulphate (10% w/v) solution. One Colilert® reagent packet was added to each vial within 24 hours of collection and the sample was shaken to dissolve the package. The samples were then immediately transferred into the IDEXX Quanti-trays® and sealed using the Quanti-tray® Sealer. The trays were incubated at 37.5°C for 24 hours during which a colour change would occur to indicate presence/absence. Coliforms use the enzyme β-galactosidase to metabolize the substrate ONPG, which changes to yellow in the test kits. Coliforms are then counted using a most probable number (MPN) table provided by IDEXX. To determine presence/absence of *E. coli*, the Quanti-trays® were placed under a blue light. If *E. coli* was present the wells would fluoresce and could be enumerated with the MPN table.

Water quality

Over the 30-week study period water samples were collected from the influent and effluent water streams to analyse for several parameters including pH, temperature, turbidity, TOC and disinfectant residual. In addition, samples were monitored both onsite and in a laboratory for ammonia and nitrate. Finally samples were taken to be analysed for the disinfection by-product (DBP) total trihalomethanes (TTHMs) three times over the course of the experiment.

pH and temperature readings were measured using a pH meter (Oakton Instruments). Meters were calibrated as samples were taken on a weekly basis. Turbidity was measured throughout the experiments using a HACH 2100P turbidimeter (HACH Company, Loveland, Colorado) following Standard Method 2130 B (*Standard Methods* 1998).

For TOC analysis, samples were poured headspace free into clean 40 ml glass vials. Four drops of pure phosphoric acid was added and then the vials were covered with Teflon-lined and septum-free plastic caps. The TOC samples were refrigerated at 4°C until analysis was performed using a TOC-V CHP analyser (Shimadzu Corporation, Kyoto, Japan).

Nitrite, nitrate and ammonia

Nitrite and nitrate concentrations were measured in the Pinellas County Water Utilities laboratory using EPA Method 300 and ion chromatography with the Dionex Model IC25A. Free and total ammonia were measured in the Pinellas County laboratory using an ion-selective probe (Denver 250) and *Standard Methods* (1998) 4500NH_3F-Total and 4500NH_3F-Free. Free ammonia was measured in the field using a DR/890 HACH spectrophotometer and the indophenol method 10200.

Statistical analysis

Statistical tests were repeated for the various combinations of disinfectant type. In addition, statistical tests compared the significant differences between the average influent and

effluent values for the water quality parameters measured. The level of significance that was used for all tests was $\alpha = 0.05$ and confidence intervals are presented with all data. Statistical procedures followed were an analysis of variance (ANOVA) test, as described by Box *et al.* (1978).

RESULTS AND DISCUSSION

Unlike many other AR studies, the annular reactors for this study went through no acclimation period in which biofilm is established during a non-disinfection period (Ollos *et al.* 2003; Gagnon *et al.* 2004). Therefore average counts include every sample throughout the 30-week study. For this reason, unlike other AR studies, no information regarding average influent, effluent or biofilm samples for all ARs prior to disinfection is presented. Samples for HPC bacteria included the influent to each AR, the effluent of each AR as well as biofilm samples from the coupons of each AR.

Comparison of disinfectants on microbial growth

Heterotrophic bacteria

The most effective disinfectant option for the influent suspended bacteria was Cl_2 alone with an average count over the course of the experiment of $4.20 \times 10^2 \pm 1.37 \times 10^3$ CFU ml^{-1}, which was a statistically significant difference compared with all other ARs ($p < 0.001$). The highest average count was observed in the AR treated with NH_2Cl alone at $1.09 \times 10^6 \pm 1.17 \times 10^6$ CFU ml^{-1} but this did not differ significantly from the NH_2Cl/UV AR with an average count of $8.33 \times 10^5 \pm 7.17 \times 10^5$ CFU ml^{-1} ($p = 0.674$).

The suspended heterotrophic bacteria counts increased over the course of the experiment in the influent of the AR treated with Cl_2 and UV. Specifically, the average count of $6.00 \times 10^0 \pm 5.21 \times 10^0$ CFU ml^{-1} in the first eight weeks of the project increased to $8.90 \times 10^5 \pm 6.59 \times 10^5$ CFU ml^{-1} for the final 20 weeks in the Cl_2/UV AR. In comparing the initial 8-week period with the last 20-week period, it was found that the average numbers of heterotrophic bacteria in the influent of the Cl_2/UV AR were statistically different from each other. The increase in heterotrophic bacteria directly corresponded to a decrease in free chlorine in the AR influent to a concentration level that was below the method detection limit (Figure 1). However, the free chlorine level was approximately 0.45 mg l^{-1} in the influent to the UV reactor. Therefore the potential explanation for the loss of chlorine residual was that chlorine demand in the UV influent line was exceeded owing to degradation of chlorine from exposure to UV. Rand & Gagnon (2007) found the UV demand for chlorine in this water was approximately 0.28 mg l^{-1}.

The decrease in chlorine residual did not occur in the AR receiving water treated with Cl_2 only. Although there was scatter in the data for the Cl_2 only AR, which has been reported in field studies (e.g. Camper 1996), the overall chlorine residual and heterotrophic bacteria concentrations remained fairly constant in this reactor (Table 1). Consistent with previous studies (LeChevallier *et al.* 1996; Huck & Gagnon 2004; Baribeau *et al.* 2005), maintaining chlorine residual was essential for the control of heterotrophic bacteria.

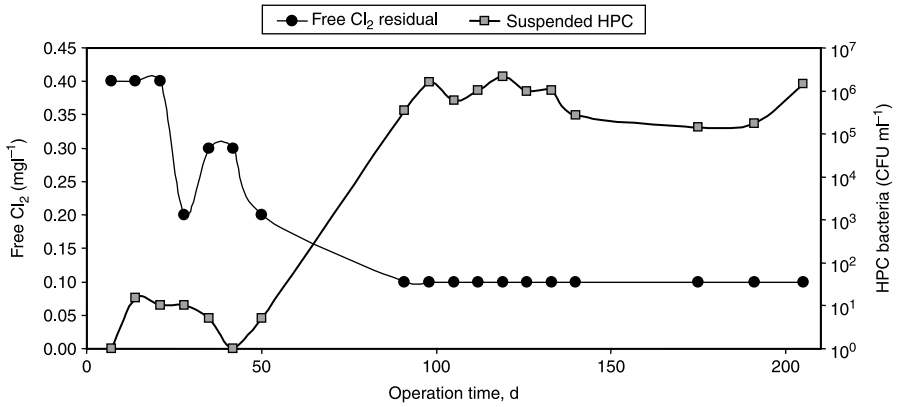

Figure 1 | Free chlorine residual with corresponding HPC bacteria in the influent of the AR receiving water treated with UV and Cl_2.

Table 1 | Disinfectant residual concentrations

	Measured residual concentration (mg l^{-1})			
Disinfectant	**Cl_2 AR**	**Cl_2/UV AR**	**NH_2Cl AR**	**NH_2Cl/UV AR**
Influent NH_2Cl	–	–	1.67 ± 0.74	0.90 ± 0.66
Effluent NH_2Cl	–	–	0.87 ± 0.60	0.62 ± 0.65
Influent free Cl_2	0.53 ± 0.26	0.17 ± 0.11	–	–
Effluent free Cl_2	0.32 ± 0.17	0.11 ± 0.03	–	–
Influent total Cl_2	0.68 ± 0.32	0.27 ± 0.10	2.13 ± 0.80	1.30 ± 1.16
Effluent total Cl_2	0.43 ± 0.18	0.20 ± 0.02	1.33 ± 0.83	0.86 ± 0.86

Similar to the influent data, the AR treated with Cl_2 alone had the lowest average number of heterotrophic bacteria for effluent samples. The AR receiving chlorine-treated water only had an average number of heterotrophic bacteria of $8.19 \times 10^2 \pm 9.38 \times 10^2$ CFU ml^{-1}, which differed significantly from all other ARs ($p < 0.001$) (Figure 2).

The Cl_2/UV AR had higher bacterial counts in effluent samples than was observed in its influent with an overall average of $3.53 \times 10^5 \pm 4.40 \times 10^5$ CFU ml^{-1}.

The highest average effluent count was observed in the NH_2Cl/UV AR at $1.00 \times 10^6 \pm 1.19 \times 10^6$ CFU ml^{-1} which was significantly different from the NH_2Cl AR ($p = 0.005$) which had an average count of $2.61 \times 10^5 \pm 2.51 \times 10^5$ CFU ml^{-1}. Overall for bulk samples of the effluent, ARs treated with UV in addition to the chemical disinfectants had higher average counts compared with ARs with no UV treatment. As is presented below, this is most likely due to a decrease in the chemical residual following UV treatment. These results indicate that UV light following chemical treatment was less effective owing to the lowering of the residual, which resulted in increased bacteria levels in the ARs.

In biofilm data the AR treated with Cl_2 had the lowest level of attached bacteria with an average count of $4.11 \times 10^5 \pm 7.38 \times 10^5$ CFU cm^{-2} (Figure 3) over the course of the experiment. This was a significantly lower count compared to all other ARs ($p = 0.000 - 0.005$), but there was no statistically significant difference among average counts for the remaining three ARs. The AR treated with UV and Cl_2 had the highest average count overall at $2.49 \times 10^6 \pm 2.43 \times 10^6$ CFU cm^{-2}. The AR that received NH_2Cl-treated water had an average count of $1.86 \times 10^6 \pm 2.40 \times 10^6$ CFU cm^{-2} and the

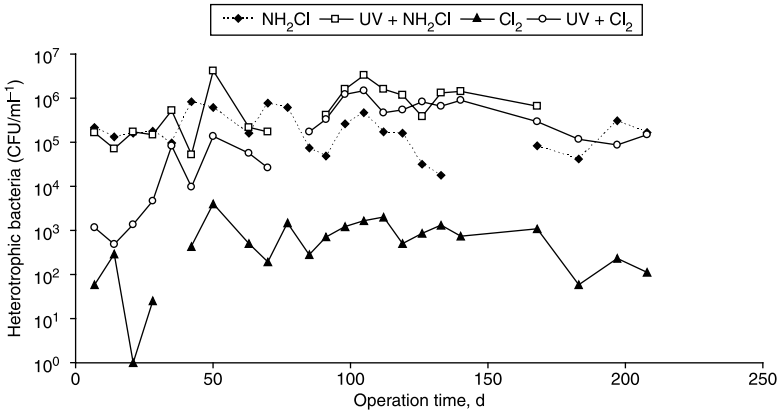

Figure 2 | Suspended heterotrophic bacteria in the effluent of each AR.

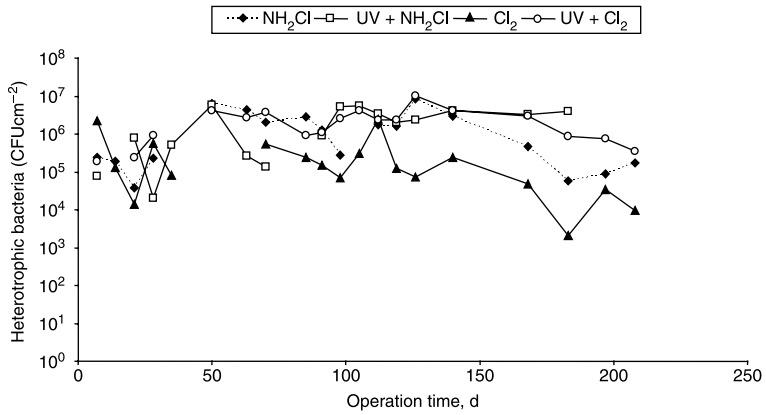

Figure 3 | Attached heterotrophic bacteria from PVC coupons.

NH_2Cl/UV AR averaged $2.41 \times 10^6 \pm 2.11 \times 10^6$ CFU cm^{-2} for attached heterotrophic bacteria. Similar to the effluent samples, the ARs with the additional treatment of UV had higher overall average counts than the ARs that had no UV treatment. This finding is contrary to other UV studies (e.g. Dykstra *et al.* 2007) that have reported the benefits of sequential disinfection with UV followed by chlorine. In contrast, the data in this study point to some potential limitations of chlorine or chloramines preceding UV, most likely due to the reduction of residual through UV treatment, which would have practical importance to utilities that are considering the application of UV disinfection in the distribution system or following water storage.

Total coliforms and *Escherichia coli*

Samples were taken for total coliform and *E. coli* analysis six times over the course of the project (Figure 4). For influent samples, the water treated with UV and NH_2Cl was positive for total coliforms once out of the six sample dates, resulting in an average concentration of 1.03 MPN 100 ml^{-1} over the course of the project, and the NH_2Cl-treated water was positive twice resulting in an average concentration of 0.87 MPN 100 ml^{-1}. These occurrences were negative for *E. coli*. The chlorinated influent water streams had no positive occurrences for total coliforms. There were positive occurrences in all AR effluents. Furthermore, all of the effluent samples were higher in number than the influent coliform counts, which indicated that significant regrowth conditions existed in the ARs. The effluent for the NH_2Cl and NH_2Cl/UV ARs each tested positive five out of six times resulting in average total coliform concentrations of 11.8 MPN 100 ml^{-1} and 5.98 MPN 100 ml^{-1}, respectively. The Cl_2 AR tested positive three out of six times resulting in an average concentration for total coliforms of 6.77 MPN 100 ml^{-1}. The Cl_2/UV AR had four positive occurrences which resulted in an average concentration of 6.75 MPN 100 ml^{-1}. No occurrences in any samples tested positive for *E. coli* throughout the experiment.

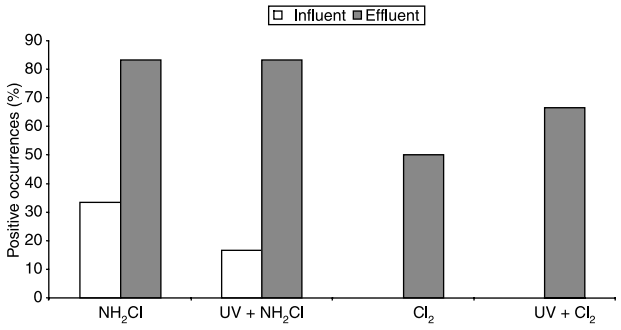

Figure 4 | Positive occurrences of coliforms in the influent and effluent of the ARs.

Water quality analysis

Disinfectant residual

For both chlorine and monochloramine, the presence of UV treatment appeared to decrease disinfectant residuals in both influent and effluent water streams. This indicates that UV light quenches chemical residual, allowing for an increase in HPC bacteria and potential *E. coli* occurrences. A subsequent study was conducted that investigated the

effect of UV light on Cl_2, NH_2Cl and ClO_2 at varying concentrations under varying water conditions which verified this phenomenon (Rand & Gagnon 2007). It was evident from HPC bacteria analysis that a concentration of chlorine must be maintained to control bacterial regrowth in distributions systems, which coincides with the concept of a critical concentration (C_{crit}) as described by Huck & Gagnon (2004). Similarly, Escobar *et al.* (2001) experimentally demonstrated for water with similar temperatures and very low levels of biodegradable organic matter (i.e. AOC less than 50 $\mu g\ l^{-1}$) that the presence of a disinfectant residual was critical for maintaining biological stability. Therefore the addition of UV treatment lowered disinfection concentrations, which in turn decreased the stability of the water in the AR.

The average residual NH_2Cl in the influent of that AR (Table 1) was $1.67 \pm 0.74\ mg\ l^{-1}$ compared with $0.90 \pm 0.66\ mg\ l^{-1}$ for the NH_2Cl/UV AR influent. Similarly, the NH_2Cl residual was lower in the NH_2Cl/UV effluent with an average of $0.62 \pm 0.65\ mg\ l^{-1}$ compared with $0.87 \pm 0.60\ mg\ l^{-1}$ in the effluent of the AR receiving water treated only with NH_2Cl.

Similarly, free and total chlorine residuals were lower in the combined UV/Cl_2 system than the Cl_2 only system. The average influent free Cl_2 residual for the AR also treated with UV was $0.17 \pm 0.11\ mg\ l^{-1}$ compared with $0.53 \pm 0.26\ mg\ l^{-1}$ in the Cl_2 alone AR. Also, the average effluent residual concentration was $0.11 \pm 0.03\ mg\ l^{-1}$ in the Cl_2/UV AR and $0.32 \pm 0.17\ mg\ l^{-1}$ in the Cl_2 AR. As previously mentioned, free chlorine residual concentration in the Cl_2/UV AR influent and effluent streams was below the detection limit of $0.10\ mg\ l^{-1}$ for the majority of the experiment. Total chlorine levels in the influent streams were also lower in ARs treated with UV (Cl_2/UV $= 0.27 \pm 0.10\ mg\ l^{-1}$, $Cl_2 = 0.68 \pm 0.32\ mg\ l^{-1}$, NH_2Cl/UV $= 1.30 \pm 1.16\ mg\ l^{-1}$, $NH_2Cl = 2.13 \pm 0.80\ mg\ l^{-1}$), which was also observed in effluent streams (Cl_2/UV $= 0.20 \pm 0.02\ mg\ l^{-1}$, $Cl_2 = 0.43 \pm 0.18\ mg\ l^{-1}$, NH_2Cl/UV $= 0.86 \pm 0.86\ mg\ l^{-1}$, $NH_2Cl = 1.33 \pm 0.83\ mg\ l^{-1}$).

pH, temperature and turbidity

The average pH for all ARs was 7.76 ± 0.04 in the influent water streams and 7.84 ± 0.02 in the effluent streams. The ARs operated at an average temperature of 25.2 ± 0.16°C during the experiment, and the average influent temperature was slightly higher at 26.3 ± 0.23°C.

The average turbidity for the NH_2Cl influent water streams was higher than the Cl_2 influent water streams. In addition, water treated with UV had lower turbidity on average than water that was not treated with UV. The average turbidity for the NH_2Cl/UV influent was 1.58 ± 1.75 NTU and 2.12 ± 3.45 NTU for the NH_2Cl influent. For effluent samples, the average turbidity in the NH_2Cl/UV AR was 0.73 ± 0.35 NTU and 0.89 ± 0.81 NTU in the NH_2Cl AR. Average influent turbidity values for the Cl_2/UV and Cl_2 ARs were 0.45 ± 0.29 NTU and 0.50 ± 0.26 NTU, respectively, and for effluent the average turbidity for the Cl_2/UV was 0.31 ± 0.12 NTU and 0.38 ± 0.21 NTU for the Cl_2 AR.

Organic content

Total organic carbon was similar without significant changes over the course of the study and the presence of UV light did not appear to affect TOC levels. The average influent TOC concentration in all ARs was $3.81 \pm 0.08\ mg\ l^{-1}$ with $3.92 \pm 0.20\ mg\ l^{-1}$ in the effluent of all ARs.

Evidence of nitrification

Nitrate and nitrite were measured in the Pinellas County laboratory for the entire study period. Nitrification was suspected to occur in water streams treated with NH_2Cl only. Samples collected from the Cl_2 streams and corresponding chlorinated ARs had nitrite and nitrate concentrations that were below the detection limit for all sample dates. The average nitrate concentration for the NH_2Cl influent stream measured in the lab was $0.07 \pm 0.05\ mg\ l^{-1}$ as N and $0.09 \pm 0.05\ mg\ l^{-1}$ as N for the NH_2Cl/UV influent. The effluent of the NH_2Cl AR had an average nitrate concentration of $0.12 \pm 0.07\ mg\ l^{-1}$ as N and the average concentration was $0.30 \pm 0.34\ mg\ l^{-1}$ as N for the effluent of the NH_2Cl/UV AR.

Nitrite concentrations were also measured for AR influent and effluent streams. The influent of the NH_2Cl AR had an average nitrite concentration of $0.12 \pm 0.10\ mg\ l^{-1}$ as N in lab analysis and the NH_2Cl/UV stream averaged $0.19 \pm 0.15\ mg\ l^{-1}$ as N. The effluent of the NH_2Cl AR averaged $0.18 \pm 0.15\ mg\ l^{-1}$ as N and the NH_2Cl/UV AR

had an average nitrite concentration of $0.13 \pm 0.19\,mg\,l^{-1}$ as N in lab analysis of the effluent stream. Observing the data, the influent UV-treated water had higher concentration levels of nitrate and nitrite compared with the AR with NH_2Cl disinfection only, indicating that photolysis of NH_2Cl may have occurred as well as nitrification.

Free ammonia for water streams treated with NH_2Cl was measured at the Pinellas County laboratory and in addition in the field from June 2005 to the end of the experiment as a check for lab analysis. Field and lab results were fairly consistent; therefore only lab analysis results are reported. The average free ammonia concentration in the influent treated with NH_2Cl alone was $0.44 \pm 0.14\,mg\,l^{-1}$ as N, and for the NH_2Cl/UV influent the average was $0.46 \pm 0.15\,mg\,l^{-1}$ as N in the lab analysis.

Total ammonia was measured in the lab alone for all water streams including the chlorinated ARs. Average influent concentrations were slightly higher than effluent concentrations and ARs that were not treated with UV had slightly lower total ammonia levels. The average ammonia concentrations for the NH_2Cl and the NH_2Cl/UV influent streams were $0.89 \pm 0.26\,mg\,l^{-1}$ as N and $0.69 \pm 0.30\,mg\,l^{-1}$ as N, respectively. The effluent of the NH_2Cl AR had an average ammonia concentration of $0.73 \pm 0.32\,mg\,l^{-1}$ as N and the average was $0.50 \pm 0.41\,mg\,l^{-1}$ as N for the NH_2Cl/UV AR. The Cl_2 ARs all measured close to the detection limit for free and total ammonia.

Free ammonia, nitrite and nitrate concentrations were all measured as nitrogen for analysis, and in order to determine whether nitrification occurred in the ARs treated with monochloramine, the variation in concentration of each in the effluent over the course of the experiment was analysed. Figure 5 shows that free ammonia, nitrate and nitrite concentration in the NH_2Cl AR varied although the average nitrate concentration in the NH_2Cl reactor was less than $0.2\,mg\,l^{-1}$ as N.

Nitrification did appear to occur in the AR receiving NH_2Cl and UV-treated water (Figure 6). Nitrification is a process that can take up to several weeks in a distribution system and occurs when free ammonia is oxidized into nitrite, which is additionally oxidized to form nitrate (McGuire *et al.* 2006). From Figure 6 it can be observed that a reduction in free ammonia concentration occurred in the 12th week of the study, which corresponded to an increase in nitrite

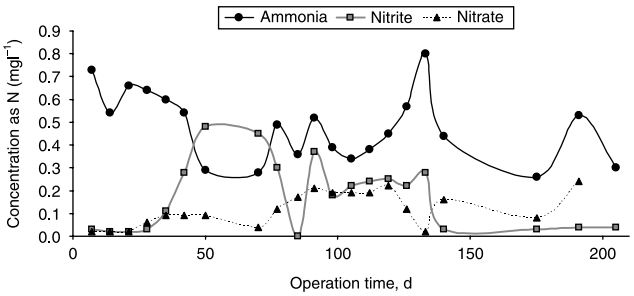

Figure 5 | Ammonia, nitrite and nitrate concentrations in the effluent of the AR treated with NH_2Cl only.

concentration. This was followed by a decrease in nitrite levels and a corresponding increase of nitrate concentration in the 16th week. Accelerated nitrification in systems with UV light disinfection following monochloramine has not yet been reported in literature. Ammonia (NH_3) concentrations in the first 11 weeks of the experiment were similar in both ARs ($NH_2Cl = 0.50 \pm 0.15\,mg\,l^{-1}$ as N and $NH_2Cl/UV = 0.55 \pm 0.16\,mg\,l^{-1}$ as N). Therefore, nitrification did not initially occur in the NH_2Cl/UV AR due to a higher level of excess NH_3 compared with the NH_2Cl AR. However, the average nitrate concentration in the UV-NH_2Cl AR was greater than $0.6\,mg\,l^{-1}$ as N, which clearly shows increased chemical or biological nitrification in the UV-NH_2Cl AR.

A possible explanation could be similar to that for increased HPC counts in Cl_2 and NH_2Cl ARs with UV treatment, where UV light increases the bacterial regrowth potential of natural organic matter (NOM) (Parkinson *et al.* 2003), thereby causing elevated levels of ammonia oxidizing bacteria (AOB) which leads to oxidation of ammonia into nitrite. In addition, Mack & Bolton (1999) established OH· radicals are the result of photolysis of nitrate and nitrite, which could be achieved with the UV lamp. Gagnon *et al.* (2004) suggested that OH· radicals react with humic

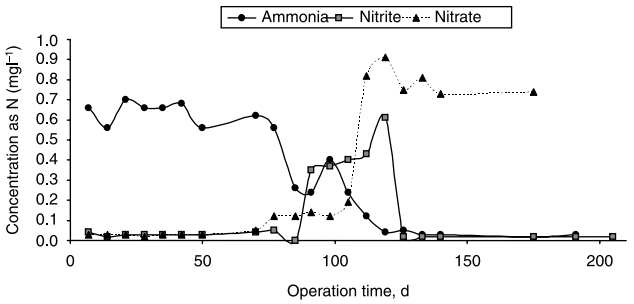

Figure 6 | Ammonia, nitrite and nitrate concentrations in the effluent of the AR treated with UV and NH_2Cl.

material in water to form biodegradable organic matter, which acts as a nutrient source for bacteria in distribution systems. This would create a stronger biofilm community where AOB were able to thrive in the UV-treated AR, which would eventually lead to the occurrence of nitrification. Also, photolysis caused by UV light would have increased degradation of NH_2Cl and released more ammonia, which would also allow AOB to proliferate (McGuire *et al.* 2006). The degradation of NH_2Cl due to UV light may have also allowed for a stronger biofilm community of potentially nitrifying bacteria, and more research should be conducted on the biofilm community. It is possible that without the potential for elevated levels of AOB in the AR receiving water treated only with NH_2Cl nitrification was not accomplished. However AOB was not enumerated in this study therefore this is an area that requires further research.

CONCLUSIONS

It was found in this study that, in comparing disinfection strategies, the AR that was treated with chlorine alone showed significantly lower concentrations of suspended heterotrophic bacteria in influent and effluent samples and attached HPC bacteria compared with other treatments. Chlorinated influent maintained a low bacteria count and this trend was repeated in the AR effluent and samples taken from the PVC coupons. Monochloramine was not effective against the HPC bacteria and had the highest counts in the influent water. Contrary to other studies mentioned above where synergistic benefits were observed between disinfectants, UV treatment after chemical disinfection hindered removal of HPC bacteria. It can be concluded that, although pre-treatment with UV light may lead to enhanced bacterial reductions, post-UV treatment potentially reduces residual protection allowing for an increase in bacteria levels. Therefore utilities must consider placement of UV light in the treatment train and understand that UV light may decrease residual concentration if implemented after the chemical dosing point.

It was observed that a lower chlorine and monochloramine residual was maintained in the ARs that were treated with UV light compared with those with no UV treatment, and this contributed to the higher HPC levels in those ARs additionally treated with UV light. An increase in HPC bacteria in the influent of the chlorinated AR with UV treatment directly corresponded to a drop in chlorine residual. It is believed that the UV light degraded the chemical residual allowing for increased growth of heterotrophic bacteria. There is a clear need for higher Cl_2 residuals through the UV system in order to control HPC bacteria, which could lead to pressure on DBP control. This indicates that UV light should not be implemented post-chemical disinfection, because although in cases where UV light precedes chemical disinfection there is an enhanced reduction of bacteria, UV light following chemical application reduces the residual and leads to increased bacteria levels.

Several studies have shown that NH_2Cl is removed by sunlight or UV light, and that photolysis of NH_2Cl by UV light produces nitrate. It was observed in this study that nitrate levels were significantly higher in the influent treated with UV and NH_2Cl compared with treatment with NH_2Cl only. Nitrification occurred in the 12th week of the experiment in the NH_2Cl/UV AR, which could have contributed to lower residual concentrations, increased bacterial counts and higher levels of nitrite and nitrate. No nitrification was observed in the AR treated with NH_2Cl alone, and more research is needed to understand reactions between UV light and NH_2Cl and why this combination may lead to nitrification.

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