

# Comparison of Byproduct Formation in Waters Treated with Chlorine and Iodine: Relevance to Point-of-Use Treatment

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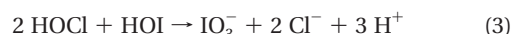
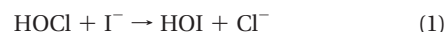
Due to their efficacy in deactivating a range of microbial pathogens, particularly amoebic cysts, iodine-based disinfectants have been a popular option for point-of-use (POU) drinking water disinfection by campers, the military, and rural consumers in developing countries. Recently, concerns regarding the formation of cytotoxic and genotoxic iodinated disinfection byproducts (I-DBPs) have arisen during chloramine disinfection of iodide-containing waters in the developed world; similar concerns should pertain to iodine-based POU disinfection. Because there are alternative POU disinfection techniques, including chlorine-based disinfectants, this paper compared disinfection byproduct formation from a range of iodine-based disinfectants at their recommended dosages to chlorination and chloramination under overdosing conditions. Just as chloroform was the predominant trihalomethane (THM) formed during chlorination or chloramination, iodoform was the predominant THM formed during iodination. Conditions fostering THM formation were similar between these treatments, except that THM formation during chlorination increased with pH, while it was slightly elevated at circumneutral pH during iodination. Iodoform formation during treatment with iodine tincture was higher than during treatment with iodine tablets. On a molar basis, iodoform formation during treatment with iodine tincture was 20–60% of the formation of chloroform during chlorination, and total organic iodine (TOI) formation was twice that of total organic chlorine (TOCl), despite the 6-fold higher oxidant dose during chlorination. Based upon previous measurements of chronic mammalian cell cytotoxicity for the individual THMs, consumers of two waters treated with iodine

tincture would receive the same THM-associated cytotoxic exposure in 4–19 days as a consumer of the same waters treated with a 6-fold higher dose of chlorine over 1 year. Iodoacetic acid, diiodoacetic acid, and other iodo-acids were also formed with iodine tincture treatment, but at levels <11% of iodoform. However, testing of a Lifestraw Personal POU device, which combines an iodinated anion exchange resin with activated carbon post-treatment, indicated minimal formation of I-DBPs and no iodine residual. Although *N*-nitrosamines have been associated with oxidant contact with anion exchange resins, *N*-nitrosamine formation rapidly declined to low levels (4 ng/L) using the Lifestraw device after the first few flushes of water.

## Introduction

To meet lower regulatory limits on chlorine- and bromine-containing trihalomethanes (THMs) and haloacetic acids (HAAs) in the Disinfection By-Products Rules of the U.S. Environmental Protection Agency, drinking water utilities increasingly are incorporating chloramination for secondary disinfection. Free chlorination oxidizes bromide to hypobromous acid (HOBr), while chloramination of bromide-containing waters forms bromamines. Chloramines and bromamines are significantly less potent halogenating agents than free chlorine (HOCl) and HOBr. Although chloramination dramatically lowers the formation of regulated THMs and HAAs, there are concerns regarding its propensity to promote the formation of iodinated byproducts (I-DBPs) (1, 2), and *N*-nitrosamines (3).

While both free chlorination and chloramination are capable of oxidizing iodide to hypiodous acid (HOI), chlorination, but not chloramination, rapidly converts HOI to iodate (IO<sub>3</sub><sup>-</sup>) (eqs 1–3 and (4)). The persistence of HOI during chloramination of iodide-containing waters promoted the formation of iodinated THMs (I-THMs) from model organic precursors (eq 4), particularly phenols (1), and natural organic matter (NOM) in source waters (1, 2). During chlorination of iodide-containing waters, formation of I-THMs was observed only at low chlorine dosages, due to incomplete oxidation of HOI to iodate (1). Although chloramination reduced the formation of total organic chlorine (TOCl), total organic bromine (TOBr), and overall total organic halogen (TOX), it promoted the formation of total organic iodine (TOI) when applied to both natural waters (5) and NOM isolates (6, 7).



Formation of I-DBPs has caused concern, because I-THMs cause taste and odor issues (8, 9), and because I-DBPs are generally significantly more cytotoxic and/or genotoxic in mammalian cell assays than their chlorinated and brominated analogues (2, 10). Their promotion during chloramination, like the formation of carcinogenic *N*-nitrosamines, has caused concern regarding the increased utilization of chloramination. Due to its rapid reduction to iodide by glutathione in vivo, iodate formed during chlorination is unlikely to be toxic (11).

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Concerns over HOI-mediated I-DBP formation during chloramination of iodide-containing waters raises questions regarding I-DBP formation during iodine-based disinfection. Iodine-based disinfectants include saturated aqueous solutions of elemental iodine ( $I_2$ ), and tetraglycine hydroperiodide (globaline) tablets that liberate  $I_2$ . However, formulations often employ mixtures of  $I_2$  and iodide ( $I^-$ ) to enhance the low solubility of  $I_2$  by forming tri-iodide ( $I_3^-$ ). Tri-iodide-based formulations include an aqueous solution (Lugol's solution), an aqueous/alcohol mixture (tincture of iodine), and  $I_3^-$  solubilized by complexation to weak cationic polymers (povidone or iodophor). Lastly, filters containing cationic resins complexed with  $I_3^-$  have become popular options for point-of-use (POU) disinfection, particularly in developing world applications (e.g., the Lifestraw Personal) (12); such resins often include activated carbon postfilters to reduce iodine residuals (13).

Iodine-based disinfectants feature several advantages. Although disproportionation of  $I_2$  can form HOI,  $I_2$  predominates at pH < 8 (14), the pH regime relevant to most source waters. While iodination is approximately as effective as chlorination for deactivation of bacterial and viral pathogens, it is far more effective against amoebic cysts, such as *Entamoeba histolytica* (15), likely due to the ability of nonpolar  $I_2$  to pass through cyst walls. Iodine-based disinfectants maintain residuals longer than chlorine-based disinfectants (16). The lower oxidant demand from NOM encountered by iodine-based disinfectants (13, 17) may arise because the standard reduction potentials of  $I_2$  (+0.62 V) and  $I_3^-$  (+0.54 V) are significantly lower than those of HOCl (+1.65 V) and HOI (+1.45 V) (14).

Following the development of iodine-based globaline tablets during World War II, iodine gained prominence for POU water disinfection by the U.S. military (13, 17). The U.S. Public Health Service approved the use of iodination for pool disinfection in 1962 (18). Iodophor is commonly used to disinfect glassware in restaurants and bars. However, use of iodination for full-scale water disinfection has been rare, due to the high cost of elemental iodine (17). Various human health evaluations focusing on thyroid impacts, including a small, but full-scale, iodination trial at prisons in the 1960s, indicated that iodination was effective for disinfection and that thyroid-associated complications were not significant at iodine dosages <5 mg/L, except for individuals prone to thyroid disorders (13, 17).

Although lingering concerns regarding thyroid impacts have led the World Health Organization and the U.S. Environmental Protection Agency to recommend that iodination be restricted to emergency or other short-term uses (13), iodine-based disinfectants have been suggested for prolonged use for POU disinfection by the military and in developing country applications (e.g., the Lifestraw Personal) (12). However, previous studies have not evaluated the risk of I-DBPs. Although pathogen deactivation is of primary concern in these situations, alternative POU options exist, including chlorine-based options (e.g., halazone tablets). Because alternative POU disinfectants are available, the health risks posed by I-DBP formation from iodine-based POU treatments should be evaluated. Given concerns regarding the cytotoxicity of I-DBPs, this paper compares I-THM, iodo-acid, and TOX formation from chlorination, chloramination and iodination of raw source waters. Because nitrosamine formation has been associated with the reaction of disinfectants with quaternary amines (19), particularly the quaternary amine-based resins employed in anion exchange resins (20), nitrosamine formation was evaluated for the Lifestraw Personal, in which  $I_3^-$  is bound to an anion exchange resin, followed by activated carbon postfilters. Additionally, factors contributing to byproduct formation are evaluated.

TABLE 1. Water Quality Characteristics<sup>a</sup>

| samples           | DOC<br>mg/L | UV <sub>254</sub><br>cm <sup>-1</sup> | SUVA L<br>mg <sup>-1</sup> m <sup>-1</sup> | pH  | bromide<br>μg/L |
|-------------------|-------------|---------------------------------------|--------------------------------------------|-----|-----------------|
| Mill River 1      | 5.1         | 0.0784                                | 1.53                                       | 7.4 | 18              |
| Mill River 2      | 9.3         | 0.0732                                | 0.79                                       | 7.1 | 12              |
| Lake Wintergreen  | 7.7         | 0.1393                                | 1.81                                       | 7.4 | 19              |
| Ripley Creek      | 16.0        | 0.5041                                | 3.16                                       | 6.4 | 9               |
| Lake Damariscotta | 5.1         | 0.1263                                | 2.47                                       | 6.7 | <5              |

<sup>a</sup> All samples <150 μg/L iodide.

## Materials and Methods

**Natural Water Collection.** Natural waters were collected in fluorinated high-density polyethylene containers. Except where noted, the waters were filtered through 0.7-μm nominal pore size borosilicate microfiber filters (Environmental Express, Mt. Pleasant, SC) and stored at 4 °C; the glass fiber filters had been baked at 400 °C to remove any organic contaminants prior to use. Dissolved organic carbon (DOC) analyses were conducted using a Shimadzu TOC-VCSH total organic carbon analyzer. Table 1 provides water quality characteristics of the waters examined in this study.

**Materials.** Free chlorine stock solutions (20 mM) were standardized by UV absorbance at 292 nm (21). Preformed monochloramine stock solutions (20 mM) were constituted by mixing free chlorine and ammonium chloride at a 1:1.2 molar ratio and standardized by UV absorbance at 245 and 295 nm, as described previously (21). A tincture of iodine stock solution was formulated as a mixture of 72 mM elemental iodine (Acros resublimed, Fair Lawn, NJ) and 172 mM potassium iodide (Acros, Greel, Belgium) in 50% deionized water and 50% methanol, and was standardized by titration against sodium thiosulfate. A Lifestraw Personal POU treatment unit was obtained from Vestergaard Frandsen (Lausanne, Switzerland); note that Vestergaard Frandsen has recently changed the design of the Lifestraw from an iodinated resin to a hollow-fiber filter system. Fisher Scientific iodoform (99%) and a 0.2 mg/mL standard mix of the four regulated THMs (THM4; chloroform, bromodichloromethane, dibromochloromethane, and bromoform) in methanol (AccuStandard, New Haven, CT) were employed as standards. The remaining I-THMs and iodoacid standards were purchased at the highest level of purity from Orchid Cellmark (New Westminster, BC, Canada), CanSyn Chem. Corp. (Toronto, ON, Canada), and Sigma-Aldrich.

**Reactions.** Reactions for analysis of THM4 and iodoform were performed in duplicate in 25 mL headspace-free vials with PTFE-lined septa, and were initiated by injection of 36 μM oxidant of tincture of iodine or 200 μM hypochlorite stock solutions via syringe injection through the septa. Triplicate reactions were conducted similarly in 100 mL headspace-free vials for the analysis of 6 I-THMs (dichloriodomethane, bromochloriodomethane, dibromiodomethane, chlorodiodomethane, bromodiodomethane, and iodoform) and 6 iodo-acids (iodoacetic acid, bromoiodoacetic acid, diiodoacetic acid, (*Z*)-3-bromo-3-iodopropenoic acid, (*E*)-3-bromo-3-iodopropenoic acid, and (*E*)-2-iodo-3-methylbutenedioic acid). At the 36 μM total oxidant dose of iodine tincture employed, calculations indicate that the initial iodine speciation was 32.7 μM  $I_2$  and 3.3 μM  $I_3^-$  (22). Reactions using 6 g iodine tablets (Potable Aqua Purification Technology; 16.7% tetraglycine hydroperiodide) employed two tablets per liter of solution in 1 L amber jars. The initial total residual iodine concentration measured after dissolution of the tablets into deionized water was 3.4 mg/L as  $Cl_2$ . After injection of the disinfectant, reaction vials were shaken for 1 min and then stored in the dark.

For treatments using the Lifestraw Personal, water was pumped from the Teflon sample jar through Teflon tubing

and through the Lifestraw via a peristaltic pump at 1.4 mL/sec. The Lifestraw contains an iodinated resin followed by activated carbon post-treatment, all contained within a ~170 mL cylinder (empty bed contact time = 2 min). Samples were collected into either 500 mL volumetric flasks for nitrosamine analysis, or in 25 mL headspace-free vials for trihalomethane analysis.

A more limited number of samples were analyzed for total organic chlorine (TOCl), total organic bromine (TOBr), and total organic iodine (TOI). Samples were treated with oxidants in 500 mL amber glass bottles under headspace-free conditions.

**Analyses.** One sample aliquot was analyzed for total oxidant residual by the DPD colorimetric method (23). Oxidants in other aliquots were quenched after 24 h with either 200  $\mu$ M ascorbic acid (for THM4, iodoform, and NDMA measurements), 220  $\mu$ M sodium sulfite (for 6 I-THMs and 6 iodo-acids), or a stoichiometric concentration of sodium sulfite for total organic halogen measurements. THMs and iodo-acids were extracted by liquid-liquid extraction with methyl *tert*-butyl ether (MTBE) within 5 min after quenching the disinfectant residual. THMs (including I-THMs) were analyzed by gas chromatography (GC) with electron capture detection or electron ionization-mass spectrometry (MS) against standards spiked into 20 mM phosphate buffered water and extracted and analyzed as for the samples. Iodo-acid measurements were carried out using diazomethane derivatization, and detection by GC/negative chemical ionization (NCI)-MS, also against standards spiked into buffered water and extracted as for the samples. Samples (500 mL) were analyzed for nitrosamines by EPA Method 521. TOCl, TOBr, and TOI analyses were conducted in triplicate using a previously published procedure (24, 25), with minor modification. A Mitsubishi AQF-100 precombustion station (Cosa Instruments, Norwood, NJ) was interfaced to an ion chromatography (IC) system (LC30 chromatography oven, AD25 absorbance detector, Dionex), which was used to separate and detect the halide ions. The relative standard deviation of replicate analyses was generally <25%. Further details on these methods are available in the Supporting Information (SI).

## Results and Discussion

**Byproduct Formation under Standard Conditions.** Although byproduct formation during chlorination and chloramination have been studied for many years, these treatments were included to enable comparison with iodination. As a conservative comparison of the disinfectants, we compared the recommended 36  $\mu$ M oxidant dose (2.6 mg/L as Cl<sub>2</sub>) of iodine tincture (13) to chlorine or monochloramine doses of 200  $\mu$ M (14.2 mg/L as Cl<sub>2</sub>), representative of an overdosing situation; although a conservative comparison, overdosing raw waters with free chlorine may be fairly common for POU treatment in the developing world. Although not generally used for POU treatment, preformed monochloramine was evaluated because chloramination is more prone to I-DBP formation than chlorination (1, 2).

Initially, we evaluated the formation of all 10 THMs, 6 iodo-acids, as well as TOCl, TOBr and TOI from treatment of raw waters with 36  $\mu$ M as oxidant of iodine tincture, iodine tablets, 200  $\mu$ M free chlorine, 200  $\mu$ M preformed monochloramine, or the Lifestraw (Table 2 and SI Table SI-1). The waters included the unspiked Mill River 1, Lake Damariscotta, and Lake Wintergreen samples, as well as the Ripley Creek sample spiked with 300  $\mu$ g/L bromide and 50  $\mu$ g/L iodide (Table 1). The latter sample represented a "challenge" water, featuring the highest DOC, specific UV absorbance, and bromide and iodide concentrations at the high end of those observed previously in a survey of I-THMs in treated drinking waters (2). Raw source waters without disinfectant did not contain

detectable levels of THMs or other DBPs. Chloroform was the dominant THM during both chlorination and chloramination, although formation during chloramination was an order of magnitude less than during chlorination. After 24 h, formation of chloroform during application of 200  $\mu$ M free chlorine was 85–167  $\mu$ g/L, except for Lake Wintergreen, where the chloroform concentration reached 358  $\mu$ g/L. Lower concentrations of some iodo-THMs were occasionally observed, particularly for dichloriodomethane, and bromochloriodomethane; lower detection limits were obtained for these two THMs using GC-MS, although most of the THMs were quantified using GC-ECD due to chromatographic interference during GC-MS analysis. For the Ripley Creek water, formation of chloroform during chlorination and chloramination dominated, but the 300  $\mu$ g/L bromide spike fostered the formation of detectable concentrations of bromine-containing THMs. With the exception of Ripley Creek, where the residual chlorine was 0.6 mg/L as Cl<sub>2</sub>, residual chlorine concentrations were ~11 mg/L as Cl<sub>2</sub>. Coupled with the high DOC and specific UV absorbance, the low pH of the Ripley Creek sample likely fostered its high chlorine demand, as HOCl is the more active oxidant.

During treatment with iodine tincture, iodoform was the dominant THM, and was substantial, at roughly 20–60% on a molar basis of the chloroform formation observed during treatment of the same waters with a 6-fold higher oxidant concentration. Iodoform formation was always highest for the iodine tincture treatment, ranging from 114  $\mu$ g/L for Ripley Creek to 268  $\mu$ g/L for Mill River 1. Iodine residuals ranged from 0.2 mg/L as Cl<sub>2</sub> for Ripley Creek to 1.9 mg/L as Cl<sub>2</sub> for Lake Wintergreen. The reasons for the lower iodoform formation at Ripley Creek are unclear, but the lower iodine residuals indicate that iodine decay occurred by other pathways than those leading to THM formation. Despite the higher iodine residuals, iodoform formation during treatment with iodine tablets was lower, ranging from 74–132  $\mu$ g/L. Although both chlorodiiodomethane and dichloriodomethane were detected, their concentrations were more than an order of magnitude lower than for iodoform. Iodoacetic acid (IAA), bromoiodoacetic acid, diiodoacetic acid (DIAA), (E)-3-bromo-3-iodopropenoic acid, and (E)-2-iodo-3-methylbutenedioic acid were also formed with iodine tincture treatment (SI Table SI-1). DIAA and IAA were the dominant iodo-acids, but were present at levels <11% of iodoform. The iodine residuals were not measurable during treatment with the Lifestraw. Low concentrations of some I-THMs were occasionally detected during treatment with the Lifestraw, which contains an iodinated resin. The only iodoform detection with the Lifestraw was 23  $\mu$ g/L for treatment of the Mill River 1 sample, a concentration among the lowest measured following treatment with iodine-based disinfectants.

TOX analyses revealed similar trends (Table 2). TOI dominated during treatment with the iodine tincture, while TOCl dominated during chlorination and chloramination. During chlorination and chloramination, TOBr increased in importance for the Ripley Creek sample spiked with 300  $\mu$ g/L bromide, but remained significantly lower than TOCl. Concentrations of TOCl, TOBr, and TOI were relatively low during treatment with the Lifestraw. Interestingly, TOI concentrations during iodination exceeded TOCl concentrations during chlorination on a molar basis for both waters, despite the lower oxidant dose. Although iodine incorporation into NOM may be very efficient during iodination, I-THMs accounted for a lower fraction of the TOI pool. While I-THMs accounted for 18% and 3% of the TOI pool for the Mill River 1 and Ripley Creek waters, respectively, chlorine-containing THMs accounted for 68% and 38% of the TOCl pool for the same waters.

**TABLE 2. Trihalomethane and Total Organic Halide Concentrations and Trihalomethane-Associated Cytotoxicity**

|                                         | CHCl <sub>3</sub> μM | CHBrCl <sub>2</sub> μM | CHBr <sub>2</sub> Cl μM | CHBr <sub>3</sub> μM | CHCl <sub>2</sub> I <sup>a</sup> μM | CHBr <sub>2</sub> I <sup>a</sup> μM | CHCl <sub>2</sub> μM | CHBrI <sub>2</sub> μM | CHI <sub>3</sub> μM | total THM toxicity <sup>b</sup> | TOCl <sub>3</sub> μM | TOBr μM | TOI μM |
|-----------------------------------------|----------------------|------------------------|-------------------------|----------------------|-------------------------------------|-------------------------------------|----------------------|-----------------------|---------------------|---------------------------------|----------------------|---------|--------|
| (C1/2) <sup>-1</sup> (M <sup>-1</sup> ) | 104                  | 87                     | 187                     | 253                  | 242                                 | 413                                 | 415                  | 714                   | 15152               |                                 |                      |         |        |
| iodine tincture                         | <0.005               | <0.005                 | <0.005                  | <0.005               | 0.00051                             | <0.0005                             | 0.0091               | <0.005                | 0.684               | <b>10372</b>                    | 0.06                 | 0.01    | 11.6   |
| free chlorine                           | 0.68                 | 0.16                   | <0.005                  | <0.005               | 0.0008                              | <0.0005                             | <0.005               | <0.005                | <0.005              | <b>85</b>                       | 6.63                 | 0.15    | <0.039 |
| monochloramine                          | 0.022                | <0.005                 | <0.005                  | <0.005               | 0.0006                              | <0.0005                             | <0.005               | <0.005                | <0.005              | <b>2.4</b>                      | 2.37                 | 0.09    | 0.11   |
| lifefraw                                | <0.005               | <0.005                 | <0.005                  | <0.005               | 0.0036                              | 0.0006                              | 0.146                | <0.005                | 0.057               | <b>932</b>                      | 0.06                 | <0.013  | 0.29   |
| iodine tincture                         | <0.005               | <0.005                 | <0.005                  | <0.005               | 0.0055                              | <0.0005                             | 0.005                | 0.045                 | 0.290               | <b>4422</b>                     | 0.49                 | 0.03    | 31.4   |
| free chlorine                           | 1.40                 | 0.74                   | 0.095                   | <0.005               | 0.0105                              | 0.0021                              | <0.005               | <0.005                | <0.005              | <b>231</b>                      | 15.6                 | 0.65    | 0.05   |
| monochloramine                          | 0.101                | 0.066                  | 0.014                   | <0.005               | 0.0032                              | 0.0009                              | <0.005               | <0.005                | <0.005              | <b>20</b>                       | 6.20                 | 0.31    | 0.05   |
| lifefraw                                | <0.005               | <0.005                 | <0.005                  | <0.005               | <0.0005                             | <0.0005                             | <0.005               | <0.005                | <0.005              | <b>0</b>                        | 0.69                 | 0.10    | 0.15   |
| iodine tincture                         | <0.005               | <0.005                 | <0.005                  | <0.005               | <0.005                              | <0.005                              | 0.027                | <0.005                | 0.663               | <b>10060</b>                    | NM <sup>d</sup>      | NM      | NM     |
| iodine tablet                           | <0.005               | <0.005                 | <0.005                  | <0.005               | <0.005                              | <0.005                              | 0.012                | <0.005                | 0.396               | <b>6008</b>                     | NM                   | NM      | NM     |
| free chlorine                           | 1.05                 | <0.005                 | <0.005                  | <0.005               | <0.005                              | <0.005                              | <0.005               | <0.005                | <0.005              | <b>109</b>                      | NM                   | NM      | NM     |
| iodine tincture                         | <0.005               | <0.005                 | <0.005                  | <0.005               | 0.0022                              | 0.00053                             | 0.024                | <0.005                | 0.678               | <b>10283</b>                    | NM                   | NM      | NM     |
| iodine tablet                           | <0.005               | <0.005                 | <0.005                  | <0.005               | <0.005                              | <0.005                              | 0.0061               | <0.005                | 0.328               | <b>4966</b>                     | NM                   | NM      | NM     |
| free chlorine                           | 3.00                 | 0.108                  | <0.005                  | <0.005               | 0.0014                              | <0.0005                             | <0.005               | <0.005                | <0.005              | <b>322</b>                      | NM                   | NM      | NM     |
| monochloramine                          | <0.005               | <0.005                 | <0.005                  | <0.005               | 0.00078                             | 0.0011                              | 0.099                | <0.005                | 0.032               | <b>528</b>                      | NM                   | NM      | NM     |
| lifefraw                                | <0.005               | <0.005                 | <0.005                  | <0.005               | 0.0016                              | <0.0005                             | <0.005               | <0.005                | <0.005              | <b>0</b>                        | NM                   | NM      | NM     |

<sup>a</sup> Measured by GC-MS except for Lake Damariscotta samples and the iodine tablet samples for Lake Wintergreen. <sup>b</sup> Total trihalomethane toxicity = Σ([THM] × (C1/2)<sup>-1</sup> × 10<sup>6</sup>).

<sup>c</sup> Ripley Creek water was spiked with 300 μg/L bromide and 50 μg/L iodide. <sup>d</sup> NM = not measured.

Because nitrosamine formation has been associated with oxidant contact with quaternary amine-based anion exchange resins (20), nitrosamine formation was evaluated during passage of Mill River 1 water through the Lifeflow Personal; the Lifeflow employs an iodinated resin in which  $I_3^-$  is bound to an anion exchange resin. None of the EPA Method 521 nitrosamines were detected when deionized water was passed through the peristaltic pumping apparatus without the Lifeflow. To evaluate first flush effects, an initial liter of deionized water was passed through a new Lifeflow. Only *N*-nitrosodimethylamine (NDMA) was detected at 11 ng/L ( $\pm 2$  ng/L, 85% percent confidence interval;  $n = 2$ ). Next, 1 L of Mill River 1 water was passed through the Lifeflow, resulting in 30 ng/L ( $\pm 0.1$  ng/L, 85% percent confidence interval;  $n = 2$ ). After 8 L of Mill River 1 water passed through the Lifeflow, the NDMA concentration was 3 ng/L ( $\pm 0.6$  ng/L, 85% percent confidence interval;  $n = 2$ ). To evaluate whether nitrosamine formation was continuous or solely a result of first flush effects, multiple waters were passed through the filter. After  $\sim 40$  L, treatment of a liter of Mill River 2 water yielded 4 ng/L ( $\pm 0.7$  ng/L, 85% percent confidence interval;  $n = 2$ ). Therefore, it is evident that NDMA levels are greatly reduced after the initial flush of source water through a new Lifeflow Personal.

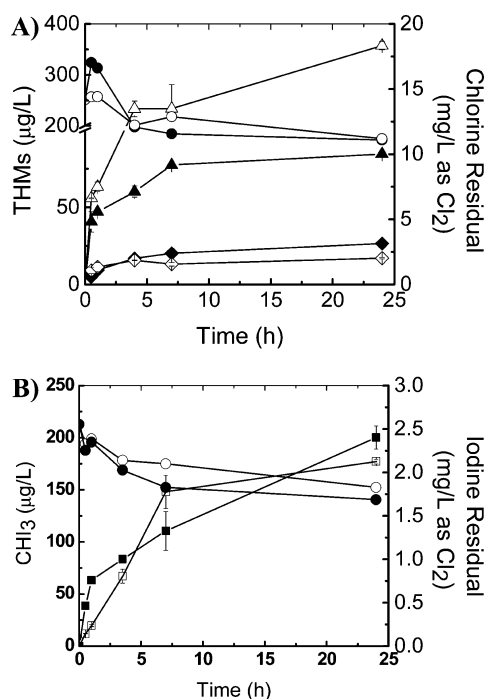
**Factors Contributing to THM Formation.** Further experiments evaluated factors contributing to THM formation during chlorination or iodine tincture POU treatment. These experiments focused on the formation of chloroform and bromodichloromethane, the most prevalent THMs to form during treatment with 200  $\mu$ M free chlorine, and iodoform, the most prevalent THM to form during treatment with 36  $\mu$ M oxidant of iodine tincture.

An initial experiment compared iodoform formation in unbuffered, filtered vs unfiltered waters (SI Figure SI-1). Iodoform formation was comparable whether Mill River 2 ( $4.7 \pm 1.1$  mg/L total suspended solids (TSS) standard deviation;  $n = 3$ ) and Lake Wintergreen ( $4.2 \pm 0.8$  mg/L TSS;  $n = 3$ ) waters were filtered or unfiltered. Previous research indicated that THM4 concentrations after chlorination were correlated with turbidity, but the treated waters were highly turbid, featuring turbidities up to 305 NTU (26). All remaining experiments employed filtered waters.

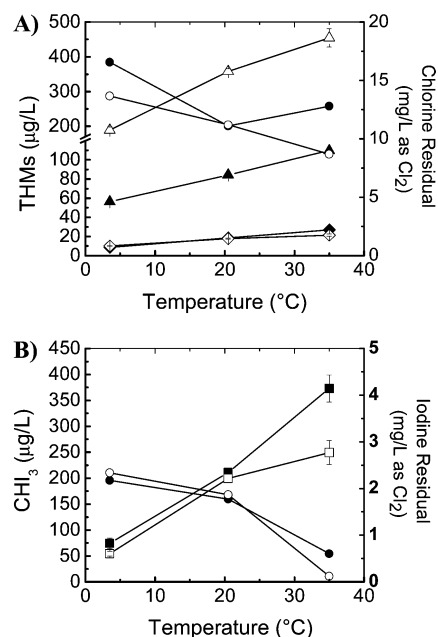
Formation of chloroform and bromodichloromethane during chlorination and iodoform during iodination were compared over time for filtered, unbuffered Mill River 1 and Lake Wintergreen waters (Figure 1). Chloroform and bromodichloromethane formed rapidly, achieving 68% of the concentration formed after 24 h within 4 h. Chlorine residuals remained above 11 mg/L as  $Cl_2$  over 24 h. Like chloroform, iodoform formation was initially rapid, but then leveled off. However, after 4 h, iodoform formation was only 40% of the total formed after 24 h. Iodine residuals remained above 1.5 mg/L as  $Cl_2$  after 24 h.

To capture the range of temperatures potentially relevant to POU treatment, chloroform and bromodichloromethane formation during chlorination were compared to iodoform formation during treatment with iodine tincture at 3.5, 20.5, and 35  $^{\circ}C$  (Figure 2). Formation of all three THMs increased with temperature, while disinfectant residuals declined.

To evaluate the influence of pH, filtered water samples were buffered at pH 5.5–9.5 with 20 mM phosphate buffer. Chloroform concentrations increased with pH, and disinfectant residuals remained above 10 mg/L as  $Cl_2$  (Figure 3A). Iodoform formation exhibited less of a trend with pH, although iodoform formation was slightly higher near circumneutral pH (Figure 3B). The iodine residual declined precipitously above pH 7.5. While  $I_2$  predominates below pH 8, hypiodous acid (HOI) predominates between pH 8 and 12 (14). As the standard reduction potential of HOI (+1.45 V) is substantially higher than those of  $I_2$  (+0.62 V) and  $I_3^-$

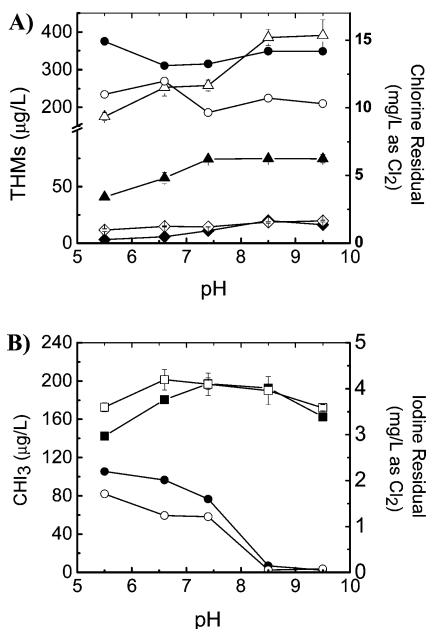


**FIGURE 1.** (A) Formation at 20.5  $^{\circ}C$  over time of chloroform (triangles) and bromodichloromethane (diamonds) and total chlorine residual (circles) from application of 200  $\mu$ M free chlorine or (B) formation of iodoform (squares) and total iodine residual (circles) from application of 36  $\mu$ M iodine tincture to filtered, unbuffered Mill River 1 (filled symbols) or Lake Wintergreen (open symbols) water. Error bars represent 85% percent confidence interval of experimental duplicates.



**FIGURE 2.** (A) Formation after 24 h vs temperature of chloroform (triangles) and bromodichloromethane (diamonds) and total chlorine residual (circles) from application of 200  $\mu$ M free chlorine or (B) formation of iodoform (squares) and total iodine residual (circles) from application of 36  $\mu$ M iodine tincture to filtered, unbuffered Mill River 2 (filled symbols) or Lake Wintergreen (open symbols) waters. Error bars represent 85% percent confidence interval of experimental duplicates.

(+0.54 V) (14), reactions between HOI and natural organic matter may have rapidly formed iodoform. However, above



**FIGURE 3.** (A) Formation vs pH after 24 h at 20.5 °C of chloroform (triangles) and bromodichloromethane (diamonds) and total chlorine residual (circles) from application of 200  $\mu\text{M}$  free chlorine or (B) formation of iodoform (squares) and total iodine residual (circles) from application of 36  $\mu\text{M}$  iodine tincture to filtered Mill River 2 (filled symbols) or Lake Wintergreen (open symbols) waters buffered with 20 mM phosphate buffer. Error bars represent 85% percent confidence interval of experimental duplicates.

pH 8, rapid disproportionation of HOI to iodate and iodide also occurs (17), consuming the disinfectant residual.

**Toxicity Evaluation.** As an initial evaluation of the relative toxicity of disinfected waters, we compared the chronic cytotoxicity associated with the THMs detected in four waters treated with different disinfectants as discussed above (Table 2). Previous research evaluated the reduction in cell density of Chinese Hamster Ovary (CHO) cell cultures treated for 72 h with varying concentrations of each of the 10 pure THMs compared to the untreated controls (2, 10). From the concentration–response curves, concentrations of each THM resulting in a 50% reduction in cell density (%C1/2 values) were determined. The toxicity exerted by byproducts is a function of their concentration and their innate toxicity. To compare the THM-associated toxicity of chlorinated and iodinated waters, we multiplied the concentrations of each THM detected by its (%C1/2)<sup>-1</sup>. Summing these values for each disinfected water (Table 2) provides a comparison of THM-associated toxicity for different disinfection techniques, although the units are arbitrary.

The results indicate that the THM-associated toxicity of the waters was 19–92 times higher for treatment with iodine tincture than for chlorination, despite the 6-fold higher oxidant dose used for chlorination. Pearson's Correlation analyses demonstrated that total THM toxicity was driven by TOI for both the Mill River 1 ( $r = 0.99$ ,  $P > 0.002$ ) and Ripley Creek ( $r = 0.99$ ,  $P > 0.001$ ) samples. The THM-associated toxicity of waters treated with iodine tablets was roughly 40% lower than for treatment with iodine tincture. In exposure terms, the THM-associated toxicity from consumption of the waters treated with 200  $\mu\text{M}$  free chlorine over 1 year would be achieved by consumption of the same waters treated with 36  $\mu\text{M}$  as oxidant of iodine tincture over 4–19 days. Combined with the elevated TOI concentrations observed during treatment of these waters with iodine tincture, these results indicate that chlorination, even under overdosing conditions, may be preferable to iodination as a

long-term POU disinfectant. Additionally, use of iodine-based disinfectants has been associated with taste and odor issues (8), potentially reducing disinfectant usage in the developing world. However, as pathogen inactivation is a primary concern for POU treatment, chlorination should be favored over iodination only where comparable degrees of disinfection are achieved.

While iodoform was the dominant DBP formed by treatment with iodine tincture (up to 0.684  $\mu\text{M}$ ), the importance of the detection of iodoacetic acid and other iodo-acids should not be minimized. While DIAA and IAA (the dominant iodo-acids) were formed at levels <10% of iodoform (up to 0.075 and 0.023  $\mu\text{M}$ , respectively), IAA is >2 $\times$  more cytotoxic (in mammalian cells) than iodoform, and is highly genotoxic, whereas iodoform is not genotoxic (2). And, in general, the iodo-acids are much more cytotoxic than I-THMs. Therefore, it is important to consider all of these I-DBPs when evaluating potential risks.

For treatment with the Lifestraw, the THM-associated toxicity of the Mill River 1 sample was  $\sim$ 10% of that of the iodine tincture, but 6-fold higher than for chlorination, due to the low concentrations of iodoform and chlorodiiodomethane detected in this sample. However, no THMs were detected during Lifestraw treatment of the other water samples (Table 2), and iodine residuals were not detected in any sample. Finally, although NDMA reached 30 ng/L during treatment of the first few liters of water, likely due to the iodinated resin, the concentrations rapidly decreased to 3–4 ng/L. Although currently unregulated by the U.S. EPA, this low concentration is likely not a significant concern, as California has a 10 ng/L drinking water Notification Level for NDMA (27). Although the World Health Organization and the U.S. Environmental Protection Agency recommend iodination only for short-term usage (13), the Lifestraw combines the advantages of iodine-based disinfectants for pathogen deactivation while minimizing byproduct exposure by placing activated carbon after the iodinated resin. However, the activated carbon also eliminates a disinfectant residual, allowing for recontamination by pathogens in stored water between treatment and use.

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## Supporting Information Available

Additional details of the materials and methods, and additional figures and tables. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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