

Factors controlling nitrosamine formation during wastewater chlorination

W.A. Mitch and D.L. Sedlak

Department of Civil and Environmental Engineering, University of California, Berkeley, 609 Davis Hall, Berkeley, California 94720, USA

Abstract Recent discoveries of the formation of low levels of the potent carcinogen *N*-nitrosodimethylamine (NDMA) during wastewater chlorination has caused concern where indirect potable water reuse is practiced. Experiments indicate that nitrosamine formation during chlorination of wastewater is consistent with a reaction scheme involving the slow formation of a hydrazine intermediate from a secondary amine and monochloramine, followed by its rapid oxidation to the corresponding *N*-nitrosamine. A survey of precursors indicates that secondary amines form their corresponding *N*-nitrosamines to the greatest extent. However, molecules containing the secondary amine as a functional group can also form the corresponding *N*-nitrosamine. NDMA is the predominant *N*-nitrosamine found in chlorinated wastewater. However, other nitrosamines are detected. These *N*-nitrosamines may be important if the summed risk posed by the exposure to all *N*-nitrosamines is considered.

Keywords Chlorination; NDEA; NDMA; nitrosamine; *N*-nitrosodiethylamine; *N*-nitrosodimethylamine; UDMH; unsymmetrical dimethylhydrazine; water reuse

Introduction

Several water agencies in California have recently reported the formation of NDMA after chlorine disinfection. Under conditions employed during chlorine disinfection of municipal wastewater effluent, NDMA formation can exceed 100 ng/L (Najm and Trussell, 2001). Chlorination of surface waters typically result in the formation of less than 10 ng/L of NDMA (Najm and Trussell, 2001).

The US EPA Integrated Risk Information Service (IRIS) database classifies NDMA as a probable human carcinogen and lists a drinking water concentration resulting in a 10^{-6} lifetime risk of contracting cancer of 0.7 ng/L for NDMA (US EPA, 2001). Responding to these recent detections of NDMA, the California Department of Health Services has set an action level of 20 ng/L for NDMA. Recent NDMA detections have been particularly disconcerting in locations where chlorinated wastewater effluent is used for indirect potable water reuse. Indeed, two drinking water production wells, under the influence of recharge water from the wastewater reclamation system of the Orange County Water District's Water Factory 21, recently suspended operations after failure to meet the 20 ng/L action level (Orange County Water District, 2000). While there is current interest in the use of ultraviolet treatment to remove the NDMA formed during chlorination, more cost-effective solutions may be possible by changing plant operations to reduce NDMA formation once the mechanism of NDMA formation during chlorination is understood.

Some researchers have hypothesized that NDMA formation during water and wastewater chlorination is attributable to a nitrosation reaction involving nitrite and dimethylamine (Kimoto *et al.*, 1981; Child *et al.*, 1996). This reaction was delineated by toxicologists concerned with nitrosamine formation in the stomach and was determined to have a maximum rate near pH 3.4 (Mirvish, 1975). In a recent article, we demonstrated that formation of NDMA during chlorination may be more consistent with a reaction scheme involving the slow formation of unsymmetrical dimethylhydrazine (UDMH) via a

nucleophilic substitution reaction between uncharged dimethylamine and monochloramine, followed by the rapid oxidation of UDMH to a variety of products, including NDMA (Mitch and Sedlak, submitted). Our previous research delineated the reaction scheme by using dimethylamine and monochloramine as model precursors in deionized water with the goal of determining the key factors promoting NDMA formation.

Our prior study indicated several key features of the reaction scheme (Mitch and Sedlak, submitted). First, monochloramine and dimethylamine are the ideal precursors for NDMA formation. While the reaction of hypochlorite and dimethylamine, and monochloramine and trimethylamine also formed NDMA, the NDMA formation rate was an order of magnitude lower than for monochloramine and dimethylamine. Application of hypochlorite in excess of the breakpoint to solutions of ammonia and dimethylamine in deionized water and to wastewater samples resulted in decreased NDMA formation, similar to that observed for chlorination with hypochlorite, as ammonia was removed from solution. NDMA formation occurred very slowly. A mixture of 1 mM dimethylamine and 1 mM monochloramine resulted in a yield of only 12% NDMA in relation to Cl₂/I₂ loss after one week. Other products measured in that study included dimethylformamide (DMF) and dimethylcyanamide (DMC), both of which were associated with NDMA formation and were observed at less than 20% yield with respect to Cl₂/I₂ loss. The oxidation of UDMH to a variety of products at low yields may be controlled by complex branching mechanisms that could not be determined by our study. However, NDMA formation was maximized between pH 7 and 8.

With the exception of three experiments in wastewater effluent designed to assess the effects of breakpoint chlorination, the previous study focused on reactions with model compounds in deionized water. The current study attempts to demonstrate that the features of the proposed reaction scheme observed in deionized water are also observed during chlorination of wastewater samples, and thus that this scheme can be useful for analyzing the system to determine methods to reduce NDMA formation. This study also assesses the importance of various potential precursors. Finally, this study assesses the formation of other nitrosamines during wastewater chlorination due to a reaction scheme analogous to that observed for NDMA.

Methods

Samples of secondary wastewater effluent were collected in Teflon-lined polyethylene containers and stored at 4°C. Samples collected from the San Francisco Public Utilities Commission's Southeast wastewater treatment plant in San Francisco, California, were filtered through 0.7 µm glass fiber filters the day of sample collection. Samples collected from the Truckee Meadows Water Reclamation Facility near Reno, Nevada were filtered through Whatman Polycap™ AS 0.2 µm pore-size nylon cartridge filters in the field. Samples collected from the West Basin Municipal Water District's Water Recycling Facility in El Segundo, California, which receives secondary wastewater effluent from the City of Los Angeles' Hyperion Treatment Plant in El Segundo, California, were unfiltered. Certain experiments were conducted using deionized water produced from a Barnstead Nanopure II water purifying system.

All glassware used during these experiments was rinsed with acetone and baked at 400°C for at least 4 hours prior to use. Reactions were conducted at 25°C in volumetric flasks placed in a temperature-controlled water bath shielded from light. Samples (1 L) were dosed with monochloramine stock solutions prepared fresh daily and standardized by iodometric titration (Standard Methods for the Examination of Water and Wastewater, 1998). Reactions were quenched by addition of excess ascorbic acid.

Some deionized water samples were extracted with methylene chloride using separatory

funnels as described previously (Mitch and Sedlak, submitted). Most samples were extracted for 6 hours with 100 mL methylene chloride by continuous liquid–liquid extraction using Corning Accelerated One-Step™ Extractor/Concentrators. Deuterated NDMA (100 ng d_6 -NDMA from Cambridge Isotope Laboratories, Andover, MA) was used as an internal standard. Samples were concentrated to 1 mL using a rotary evaporator and blowdown under nitrogen. Recoveries averaged 59% (\pm 11% standard deviation) for NDMA.

Sample analyses were performed on a Varian CP-3900 gas chromatograph coupled to a Saturn 2100T MS/MS. Temperature conditions were 200°C for the injection port, 250°C for the transfer line, and 150°C for the trap. Gas chromatography temperature conditions (Supelco SPB™-1701 capillary column, 30 m by 0.25 mm I.D. by 0.25 μ m) were 35°C held for 1 minute followed by ramping at 10°C/minute to 70°C, then ramping at 2°C/min. to 83°C, and ramping at 10°C/min. to 220°C held for 2.4 minutes. Tandem mass spectrometry was conducted using chemical ionization mode with methanol. The emission current was set at 60 μ A. Quantification ions are provided in Table 1.

Results and discussion

In our previous study we found that addition of increasing concentrations of monochloramine to solutions of dimethylamine in deionized water resulted in increasing rates of formation of NDMA and dimethylcyanamide and little effect on dimethylformamide formation (Mitch and Sedlak, submitted). In the current study, dimethylformamide concentrations in unchlorinated wastewater effluent samples were too high to accurately quantify the low concentrations formed during chlorination of wastewater samples. However, chlorination of wastewater effluent resulted in the formation of significant amounts of NDMA and dimethylcyanamide. For example, application of 0.48 mM monochloramine (34 mg/L as Cl_2) to filtered secondary wastewater effluent from the San Francisco Southeast Treatment Plant for 20 days (final chlorine residual of 12 mg/L as Cl_2), resulted in an increase in NDMA concentration from <10 to 1,420 ng/L. The dimethylcyanamide concentration increased from 38–131 ng/L. Application of 0.63 mM monochloramine (44 mg/L as Cl_2) to filtered secondary wastewater effluent from the Truckee Meadows Water Reclamation Facility for 7 days (final chlorine residual of 23 mg/L as Cl_2), resulted in an increase in NDMA concentration from 16–465 ng/L. The dimethylcyanamide concentration increased from <8 to 45 ng/L.

Figure 1 depicts the formation of NDMA over time following the application of 1 mM monochloramine (70 mg/L as Cl_2) to deionized water containing 1 mM dimethylamine (44 mg/L) (Mitch and Sedlak, submitted) and of monochloramine to unfiltered secondary wastewater effluent obtained from the West Basin Municipal Water District's Water Recycling Facility. In both cases, NDMA formed very slowly over one week and the yields of NDMA were only a fraction of the chlorine applied. In the case of wastewater

Table 1 Quantification ions used for GC/MS/MS analysis

Compound	Quantification ions <i>m/z</i>
<i>N</i> -nitrosodimethylamine (NDMA)	44, 47, 58
d_6 -NDMA	50, 64
Dimethylcyanamide (DMC)	42, 44
Dimethylformamide (DMF)	46
<i>N</i> -nitrosomethylethylamine (NMEA)	61
<i>N</i> -nitrosodiethylamine (NDEA)	75, 85
<i>N</i> -nitrosopyrrolidine (NPYR)	55
<i>N</i> -nitrosopiperidine (NPIP)	69

chlorination, where dimethylamine concentrations are anticipated to be $<500 \mu\text{g/L}$ (Hwang *et al.*, 1995), NDMA formation eventually halts, presumably because one of the precursors is exhausted (data not shown).

The maximum rate of NDMA formation was observed at circumneutral pH during chloramination of secondary wastewater effluent (Figure 2a), which is consistent with our previous study with monochloramine in deionized water containing dimethylamine (Figure 2b). Because NDMA formation via a reaction scheme involving nitrite is maximized near pH 3.4, this finding suggests that nitrite is not involved in the primary formation pathway during wastewater chlorination. In our proposed reaction scheme, the slow formation rate of the UDMH intermediate is maximized at high pH, where it is more stable. At circumneutral pH, UDMH is rapidly oxidized to NDMA and other products. In our previous study (Mitch and Sedlak, submitted), significantly higher concentrations of NDMA were measured when 1 mM dimethylamine and 1 mM monochloramine in deionized water were reacted at pH 11.6 for 70 minutes followed by acidification to 6.8 for 10 minutes before quenching the reaction, relative to experiments conducted at either pH 6.8 or 11.6 for the entire 80 minutes (Table 2, Experiment 1). Similarly, the application of 0.45 mM monochloramine (32 mg/L as Cl_2) to secondary wastewater effluent from the West Basin Municipal Water District's Water Recycling Facility resulted in higher concentrations of NDMA when the pH was held at 10.5 for 500 minutes followed by acidification to 6.6 for 10 minutes prior to quenching, relative to an experiment conducted at pH 10.5 for all 510 minutes (Table 2, Experiment 2). However, maintaining the reaction at pH 6.3 for the entire 510 minutes resulted in the highest NDMA concentration.

Experiments were conducted to assess the importance of different nitrogen-containing precursors for formation of NDMA during chloramination. Potential precursors were chosen to cover a wide range of chemical structures potentially present in wastewater. Monomethylamine (MMA), dimethylamine (DMA), trimethylamine (TMA) and tetramethylamine (QMA) were chosen to demonstrate the effect of the number of methyl groups surrounding the nitrogen atom. Dimethylethanolamine (DMEA) was chosen to represent compounds containing dimethylamine functional groups. Methylethylamine (MEA), diethylamine (DEA), and triethylamine (TEA) were chosen to represent simple aliphatic amines containing alkyl chains longer than a methyl group. One significant source of organic nitrogen in wastewater is protein and polypeptides (Confer *et al.*, 1995). Proline (Prol), asparagine (Asp) and histidine (Hist) were chosen to represent amino acid structures. Proline contains no nitrogen in the side chain. Asparagine contains one primary nitrogen functional group in the side chain. Histidine contains two secondary nitrogen groups in the side chain. Glutathione (Glut) was chosen to represent a polypeptide with secondary nitrogen functional groups. Albumin (Alb) was chosen to represent proteins. Albumin was

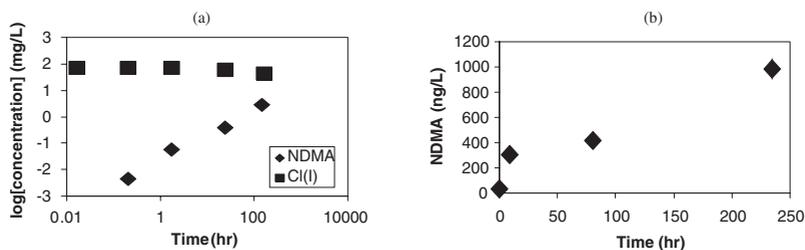


Figure 1 (a) Formation of NDMA and decline in Cl(I) over time for 1 mM monochloramine and 1 mM dimethylamine in deionized water at 25°C buffered at pH 6.8 with phosphate buffer (Mitch and Sedlak, submitted). (b) Formation of NDMA over time for a monochloramine residual $>10 \text{ mg/L}$ for unbuffered secondary effluent from the West Basin Municipal Water District's Water Recycling Facility at 25°C and pH 6.0

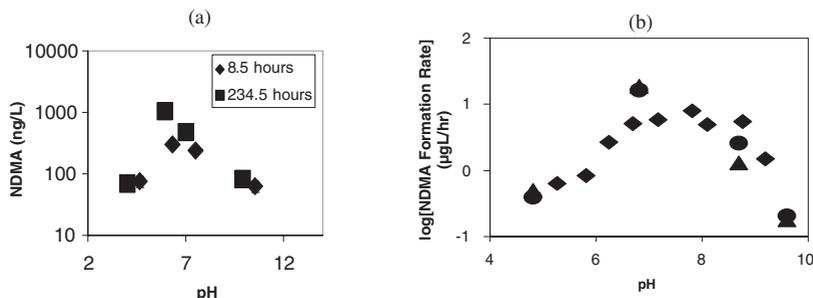


Figure 2 (a) NDMA formation for addition of monochloramine to secondary wastewater effluent from the West Basin Municipal Water District's Water Recycling Facility at 25°C. Adjustment of pH with HCl and NaOH. Monochloramine dosage was 31 mg/L as Cl₂ for 8.5 hours and 64 mg/L as Cl₂ for 235 hours. (b) NDMA formation rates from 1 mM NaOCl, 1 mM dimethylamine and 1 mM ammonia buffered at various pH values using 10 mM buffers (acetate buffer for pH less than 6, phosphate buffer for pH between 6 and 8, and borate buffer for pH greater than 8). Symbols depict results from different experiments with the following dates and reaction times: ◆ = 7/31/00 for 24 hours, ● = 7/7/00 for 17 hours, ▲ = 7/7/00 for 167 hours (Mitch and Sedlak, submitted)

Table 2 Experimental results

Experiment	Reaction	Reagent 1		Reagent 2		NDMA formation		Time min	pH
		Identity	mM	Identity	mM	µM	ng/L		
1	A	DMA ^a	1	NH ₂ Cl	1	0.30	–	80	6.8
	B	DMA	1	NH ₂ Cl	1	<0.24	–	80	11.6
	C	DMA	1	NH ₂ Cl	1	8.41	–	80	11.6–6.8 ^b
2	A	WW ^c	–	NH ₂ Cl	0.45	–	305	510	6.3
	B	WW	–	NH ₂ Cl	0.45	–	64	510	10.5
	C	WW	–	NH ₂ Cl	0.45	–	112	510	10.5–6.6 ^d
3	A	DMA	0.005	–	–	–	<4	75	6.8
	B	TMA ^e	0.0007	–	–	–	<4	75	6.8
	C	NH ₂ Cl	0.1	–	–	–	<4	75	6.8
	D	NH ₂ Cl	0.1	DMA	0.005	–	39	75	6.8
	E	NH ₂ Cl	0.1	TMA	0.0007	–	<4	75	6.8

^a DMA = dimethylamine

^b The pH was lowered from 11.6 to 6.8 by addition of hydrochloric acid during the last 10 minutes of the reaction

^c WW indicates that these experiments were conducted in a secondary wastewater effluent matrix with unknown concentrations of precursors

^d The pH was lowered from 10.5 to 6.6 by addition of hydrochloric acid during the last 10 minutes of the reaction

^e TMA = trimethylamine

also partially hydrolyzed by lowering the pH of the stock solution to 1.6 with hydrochloric acid 14 hours (Albhy). This partially hydrolyzed albumin was chosen to represent smaller proteins and polypeptides. All of these precursors were reacted individually with monochloramine in deionized water. Reaction conditions were chosen to mimic those of actual wastewater chlorination conditions (7 mg/L as Cl₂ monochloramine and 1.4 mg/L as N organic nitrogen) except that all of the organic nitrogen was comprised of the particular precursor. The reaction was quenched after 4 hours (Figure 3).

As expected, dimethylamine resulted in the highest NDMA formation. Reactions with trimethylamine and dimethylethanolamine resulted in approximately 30% of the NDMA concentrations observed for the dimethylamine reaction. No other precursor resulted in detectable concentrations of NDMA (NDMA concentrations were typically lower than 20 ng/L). Because not all of the organic nitrogen in wastewater consists of one of these precursors, and because chlorination is typically conducted for less than 4 hours, those precursors for which NDMA formation was not detectable in these experiments, are not

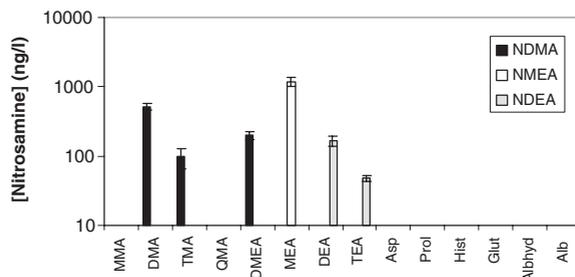


Figure 3 Nitrosamine formation from 1.4 mg/L as N precursor and 7 mg/L as Cl_2 monochloramine in deionized water at 25°C for 4 hours buffered at pH 6.8 with phosphate buffer. Error bars indicate one standard error

important precursors for NDMA formation during chlorination. Important precursors may be restricted to dimethylamine and compounds containing dimethylamine functional groups. Chlorination of these tertiary compounds, such as dimethylethanolamine, may result in cleavage of a carbon–nitrogen bond to leave a dimethylamine molecule that can then react to form NDMA.

Previous researchers have reported dimethylamine and trimethylamine concentrations of 230 $\mu\text{g/L}$ and 36 $\mu\text{g/L}$, respectively, in secondary effluent from a municipal wastewater treatment plant (Hwang *et al.*, 1995). Dimethylamine and trimethylamine at these concentrations were reacted with monochloramine in deionized water under conditions typical of wastewater treatment (Table 2, Experiment 3). The reaction of 0.005 mM (220 $\mu\text{g/L}$) dimethylamine with 0.1 mM monochloramine (7 mg/L as Cl_2) in deionized water for 75 minutes resulted in the formation of 39 ng/L NDMA. The reaction with 0.0007 mM (41 $\mu\text{g/L}$) trimethylamine resulted in the formation of <3.4 ng/L NDMA. These results suggest that dimethylamine is the organic nitrogen precursor responsible for a significant portion of the NDMA formed during chlorination of wastewater effluent.

Further experiments were conducted to assess the formation of other nitrosamines during wastewater chlorination. Table 3 presents drinking water concentrations of various nitrosamines that would result in a 10^{-6} excess risk of causing cancer if consumed over a 70 year lifetime according to the IRIS database. These data indicate that the cancer potency of *N*-nitrosomethylethylamine (NMEA), NDEA and NPYR are similar to that of NDMA (US EPA, 2001). The same precursors which were examined for the potential to form NDMA, were also examined for the potential to form NMEA and NDEA (Figure 3). While secondary amines form the maximum amount of the corresponding *N*-nitrosamine, compounds containing the secondary amine as a functional group may also form significant quantities of the corresponding *N*-nitrosamine. The formation pathway presumably follows a similar scheme of the formation and oxidation of a hydrazine intermediate.

A study of the excretion of secondary amines in urine and faeces indicates that pyrrolidine and piperidine are excreted in concentrations of the same order of magnitude as dimethylamine, while diethylamine concentrations are an order of magnitude lower

Table 3 Drinking water concentrations resulting in a 10^{-6} lifetime risk of cancer

Compound	10^{-6} cancer risk concentration
<i>N</i> -Nitrosodimethylamine (NDMA)	0.7
<i>N</i> -Nitrosodiethylamine (NDEA)	0.2
<i>N</i> -Nitrosomethylethylamine (NMEA)	2
<i>N</i> -Nitrosopyrrolidine (NPYR)	20

Table 4 Results from the measurement of four *N*-nitroso compounds during wastewater chlorination (ng/L \pm standard error)

Wastewater plant	Reaction	NDMA	NDEA	NPYR	NPIP
San Francisco	Effluent	13 \pm 6	<9	NM ^a	NM
Southeast	20 day formation ^b	1420 \pm 39	17 ^c \pm 9	71 \pm 11	5 ^c \pm 3
Reno	Effluent	16 \pm 3	<9	4 ^c \pm 3	<4
Truckee Meadows	7 day formation	256 \pm 18	15 ^c \pm 9	64 \pm 10	6 ^c \pm 3
Los Angeles	Effluent	110 \pm 21	17 \pm 11	<3	<4
West Basin	10 day formation	1060 \pm 259	114 \pm 29	41 \pm 5	<4

^a NM = not measured

^b Formation tests performed by allowing secondary effluent to react with sufficient concentrations of monochloramine to maintain a 10 mg/L residual for the stated duration

^c Compound was detected but was below the practical quantitation limit.

(Tricker *et al.*, 1994). While these data may suggest that diethylamine concentrations are lower than dimethylamine concentrations in wastewater, these amines may be removed to different extents by treatment. Table 4 presents the concentrations of NDMA, NDEA, NPYR and *N*-nitrosopiperidine (NPIP) in the effluent from three wastewater treatment plants. In addition, results from secondary treatment effluent subjected to chloramination for extended periods of time are presented. The extended chlorination periods resulted in the formation of sufficient nitrosamine to enable detection, and permitted the evaluation of the relative concentrations of these nitrosamines. The results indicate that NDMA is present in far higher concentrations than the other nitrosamines. NDEA was detected in the effluent of the West Basin Municipal Water District's Water Recycling Facility and NPYR was detected in the effluent of the Truckee Meadows Water Reclamation Facility. The extended chloramination experiments indicated that NDEA and NPYR are generally formed at one order of magnitude lower concentrations than NDMA, while NPIP is formed at two orders of magnitude lower concentrations.

Conclusions

The reaction scheme previously proposed by the authors (Mitch and Sedlak, submitted) to explain the formation of *N*-nitrosamines during chlorination is consistent with data from the chlorination of wastewater. This reaction scheme can be used to understand *N*-nitrosamine formation and to assess treatment processes likely to reduce their formation.

Studies of potential precursors indicate that secondary amines form their corresponding nitrosamines to the greatest extent. In particular, dimethylamine may be responsible for the relatively high concentrations of NDMA observed after chlorination of secondary effluent. Compounds containing these secondary amines as functional groups can also serve as nitrosamine precursors to a lesser extent.

NDMA may be the predominant nitrosamine formed during wastewater chlorination. As such, its removal or the prevention of its formation may be the controlling factor in the design of treatment processes for potable water reuse. Other nitrosamines with similar toxicities are formed to a lesser degree. The formation of these other nitrosamines may be significant when the total risk is assessed from the exposure to the individual nitrosamines during indirect potable reuse of wastewater.

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