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Free Radical Chemistry of Advanced Oxidation Process Removal of Nitrosamines in Water

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Abstract

Absolute rate constants and degradation efficiencies for hydroxyl radical reactions with seven low-molecular-weight nitrosamines in water have been evaluated using a combination of electron-pulse radiolysis/absorption spectroscopy and steady-state radiolysis/GCMS measurements. The hydroxyl radical oxidation rate constants were found to depend upon nitrosamine size and to have a very good linear correlation with the number of methylene groups in these compounds. This correlation, given by $\ln(k_{\bullet\text{OH}}) = (19.72 \pm 0.14) + (0.424 \pm 0.033)(\#\text{CH}_2)$, suggests that hydroxyl radical oxidation predominantly occurs by hydrogen atom abstraction from constituent methylene groups in each of these nitrosamines. In contrast, the hydrated electron reduction rate constants measured for these compounds were remarkably consistent, with an average value of $(1.67 \pm 0.22) \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$. These reduction kinetic data are consistent with this predominantly diffusion-controlled reaction occurring at the N–NO moiety in these carcinogens. From steady-state radiolysis measurements under aerated conditions, specific hydroxyl radical degradation efficiencies for each nitrosamine were evaluated. For larger nitrosamines, the efficiency was constant at 100%; however, for the smaller alkyl substituted species, the efficiency was significantly lower, with a minimum value of only 80% determined for *N*-nitrosodimethylamine. The reduced efficiency is attributed to radical repair reactions competing with the slow peroxy radical formation.

Introduction

Nitrosamines ($\text{R}_1\text{R}_2\text{N–NO}$) are a class of mutagenic, teratogenic, and carcinogenic chemicals (1–5) that exist in the environment as the byproducts of various manufacturing, agricultural, and natural processes (6–9). These potent carcinogens often target specific organs based on their structure, but generally affect the GI tract, associated organs, and the brain (10). Nitrosoamines, particularly *N*-nitrosodimethylamine (NDMA, $(\text{CH}_3)_2\text{N–NO}$) are also present in foods and beverages that contain nitrite or have been exposed to nitrous

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oxides (11, 12). Moreover, studies have recently shown that NDMA can be formed in situ under water disinfection conditions from the reactions of chloramines with either dissolved dimethylamine (13, 14), unsymmetrical dimethylhydrazines (14), or natural organic matter (15).

While there has been recent focus on NDMA, there are at least 300 known carcinogenic nitrosamines that have been shown to induce tumors in over 30 animal species (16). At this time, no federal or state maximum contaminant levels for any nitrosamines in water have been set. However, the California Department of Health Services has presently set notification levels of 10 ng L⁻¹ for NDMA and *N*-nitrosodiethylamine (NDEA) in drinking water.

Various water treatment technologies are presently being attempted for the quantitative removal of these carcinogens. In general, nitrosamines are not readily removed by conventional treatments such as carbon absorption or air stripping. Mineral absorption using zeolites is not generally useful for removing trace amounts of nitrosamines from aqueous media (17). Biodegradation is possible using bacterial strains that produce monooxygenase enzymes, with a reported degradation rate of 5 ng/mg-protein/min for *Pseudomonas mendocina* (18).

Another approach to treated nitrosamine-contaminated waters currently being investigated is the use of advanced oxidation processes (AOPs). These technologies include ozone, UV/ozone, and UV/H₂O₂, which utilize oxidation via the hydroxyl radical ([•]OH), and heterogeneous catalysis by TiO₂, sonolysis, or the electron-beam process, which produce a mixture of oxidizing [•]OH radicals with reducing hydrated electrons (e⁻(aq)) and hydrogen atoms ([•]H). AOPs have been shown to be efficient at nitrosamine removal from water, especially as further reactions of hydroxyl radicals with NDMA degradation byproducts, such as dimethylamine, may help prevent the reformation of nitrosamines. The most widely used remediation method for NDMA is UV photolysis, either steady-state or pulsed, but there are concerns of nitrosamine reformation occurring after irradiation under these conditions (19). Ozone alone has not been shown to readily react with nitrosamines, but may be combined with hydrogen peroxide to quantitatively produce hydroxyl radicals, which have been proposed as a measure to prevent reformation upon chlorination, and further oxidize the byproducts of UV photolysis (20). Some recent work utilizing TiO₂ has demonstrated that aqueous NDMA destruction occurs mostly by hydroxyl radical reaction, rather than by valence-band holes (21). However, the efficiency of all these methods is dictated by the hydroxyl radical scavengers present in waters (22). To ensure that any AOP treatment process occurs efficiently and quantitatively, a full understanding of the chemistry involved under the conditions of use is necessary. This information can be used to develop kinetic computer models that provide the best test of the actual engineering data, as all defined or proposed chemistry in the system is considered (23). A critical component for the kinetic modeling of any free-radical-based technology is a description of the kinetics and mechanisms of the reactions of all the organic compounds involved.

Recently, the kinetics and initial reaction mechanisms for the oxidizing hydroxyl radical and the reducing hydrated electron and hydrogen atom with NDMA were reported (24).

Additional studies for the hydroxyl radical and hydrated electron reaction with NDEA and *N*-nitrosomethylethylamine (NMEA) were subsequently performed (25). For these three compounds, it was found that the hydrated electron rate constant was independent of alkyl substitution and that the reaction only formed an electron-adduct species. However, the hydroxyl radical reaction occurred by hydrogen atom abstraction from one of the alkyl moieties, and the rate constant was seen to increase with increasing complexity of the nitrosamine.

The measurement of the kinetic parameters for all known nitrosamines in water is a daunting task, and therefore, the establishment of structure–reactivity relationships that allows extrapolation to the more complex nitrosamines is necessary. The purpose of this work was to quantitatively establish rate constants and initial reaction mechanisms for seven additional low-molecular-weight nitrosamines in water to provide sufficient data to begin to establish structure–reactivity relationships.

In addition, we have performed steady-state irradiations and gas chromatography/mass spectrometry (GC/MS) product analyses that have allowed the calculation of absolute hydroxyl radical degradation efficiencies for all compounds. These efficiency data are the first determined for these chemicals. On the basis of these results, kinetic models for nitrosamine removal from waters by AOPs can then be constructed.

Experimental Section

Nitrosamines were purchased commercially (Sigma-Aldrich) at the highest purity available (>99%) and used as received. All sample solutions were prepared in water filtered through a Millipore Milli-Q system, constantly illuminated by a UV lamp to maintain total organic carbon (TOC) concentrations below 13 $\mu\text{g/L}$, as measured by an on-line TOC analyzer.

The hydroxyl radical and hydrated electron rate constants were obtained using the linear accelerator (LINAC) electron-pulse radiolysis system at the Radiation Laboratory, University of Notre Dame. This irradiation and transient absorption detection system has been described in detail previously (26). During the irradiation process, the solution vessels were bubbled with only the minimum amount of gas necessary to prevent air ingress, to prevent loss of chemical. The solution flow rates in these experiments were adjusted so that each irradiation was performed on a fresh sample.

The radiolysis of water generates free radicals in solution according to (27, 28)

The coefficients in this equation are the micromolar concentrations of each species produced for every joule of energy deposited into this solution (*G* values). The LINAC electron pulses used were of 2–3 ns duration, giving total radical concentrations in the range of 2–4 μM .

Dosimetry (29) was performed using N₂O-saturated, 1.00×10^{-2} M SCN⁻ solutions at λ 475 nm, ($G\epsilon = 5.2 \times 10^{-4}$ m² J⁻¹) with average doses of 3–5 Gy per 2–3 ns pulse. Throughout this paper, G is defined in $\mu\text{mol J}^{-1}$, and ϵ is in units of M⁻¹ cm⁻¹.

For hydroxyl radical rate constant experiments, solutions were presaturated with nitrous oxide (N₂O) at natural pH (unbuffered at ~pH 7.0), which removes dissolved oxygen and reacts quickly with hydrated electrons and hydrogen atoms to quantitatively convert them to hydroxyl radicals (27). For all the nitrosamines in this study, no significant transient absorption was found upon hydroxyl radical oxidation, and therefore, these rate constants were determined using SCN⁻ competition kinetics, as previously described (24, 25).

To perform hydrated electron kinetic measurements, solutions were presaturated with nitrogen gas to remove dissolved oxygen and had 0.10 M methanol added to quantitatively scavenge hydroxyl radicals and hydrogen atoms (27), which isolated the hydrated electrons and formed relatively inert methanol radicals. The reaction of the hydrated electron and nitrosamine was monitored directly by measuring the rate of change of the hydrated electron absorbance at 700 nm.

All kinetics experiments were performed at ambient room temperature (19 ± 1 °C) in natural pH (~7.0) solution, ensuring that no protonation of these nitrosamines occurred.

Degradation efficiency measurements were conducted using 20.0 mL of 1.0 mM nitrosamine solutions subjected to a continuous, low intensity (~100 Gy/min), ⁶⁰Co-irradiation source at the Radiation Laboratory, University of Notre Dame. This irradiation again produces both oxidizing and reducing radicals in these aerated solutions according to eq 1. Under our steady-state irradiation conditions, the radical production rate was typically about 20 $\mu\text{M}/\text{min}$ for each species. At the relatively high nitrosamine concentrations (100–1000 μM) of these studies, this would give steady-state concentrations of radicals of the order of 10^{-12} to 10^{-14} M, similar to typical AOP conditions.

Vials of each separate nitrosamine were irradiated for different doses up to 6.0 kGy, based upon the literature finding that 99% degradation of nitrosamines occurs at a radiation dose of 5 kGy (30). The capped irradiated solutions were then sealed with Parafilm and shipped back to facilities at California State University, Long Beach. All irradiated solutions were kept at 4 °C to prevent significant hydrolysis or further reaction of parents or products until analysis.

All samples were extracted and analyzed within several weeks. The extraction procedure used 5.00 mL of the irradiated nitrosamine sample, to which 100 μg of NDEA or *N*-nitrosodibutylamine (NDBA) was added as a surrogate standard to measure extraction efficiency. Samples were then extracted using three separate 3–4 mL aliquots of methylene chloride. The extract was dried using anhydrous sodium sulfate (Fisher Scientific) and then quantitatively transferred and made up to volume using either a 10.00 or 25.00 mL volumetric flask. For GC/MS analyses, a 1.00 mL aliquot of this latter sample was transferred to an auto-sample vial and had 20 μg of *m*-nitroxyline (Sigma-Aldrich) added as an internal standard. Standard calibration curves were also built on an internal basis for the

surrogate standards and for selected nitrosamine analytes. Extractions performed on the same solutions several weeks later gave the same results within experimental error.

The above samples and calibration standards were then analyzed by an Agilent 6890N GC system in tandem with an Agilent 5973 mass selective detector (MSD). An Agilent 7683B auto-sampler was used to deliver sample injections to a JW Scientific DB-5ms column. GC parameters were as follows: Injection temp, 225 °C, with pulsed splitless injection; pulse pressure, 30 psi, with He as the carrier gas at a constant flow rate of 1.5 mL/min. Initial oven temperature was 45 °C for 5 min, ramped at 15 °C/min to 125 °C, 5 °C/min to 150 °C, then 15 °C/min to 250 °C, and finally held for 5 min. The MSD transfer line temperature was 225 °C, with a MSD quad temperature of 150 °C and a MSD source temperature of 230 °C. Electron ionization detection was used, with an ionizing energy of 70 eV. MSD *Chemstation* software version D.01.02.16 was used for data analysis. Nitrosamines and reaction products were identified by reference standards or the online NIST mass spectral library.

Results and Discussion

Hydroxyl Radical Reactions

The reaction of hydroxyl radicals with nitrosamines in water did not generate any significant intermediate species absorption in the wavelength range 250–800 nm. Therefore, the reactions of the hydroxyl radical with all of the nitrosamines of this study were determined as established previously (24, 25), using SCN[−] competition kinetics and monitoring the change of absorption intensity of the produced (SCN)₂^{•−} transient at 475 nm in an N₂O-saturated solution with added nitrosamine. Typical SCN[−] concentrations used were ~100–150 μM.

On the basis of the hydroxyl radical reaction with both SCN[−] and the nitrosamine (R₁R₂N–NO) in these solutions

one can derive the following analytical expression for the change in yield of the product (SCN)₂^{•−} (27)

$$\frac{[(\text{SCN})_2^{\bullet-}]_0}{[(\text{SCN})_2^{\bullet-}]} = 1 + \frac{k_2[\text{R}_1\text{R}_2\text{N} - \text{NO}]}{k_3[\text{SCN}^-]} \quad (4)$$

Therefore, by plotting the ratio of the (SCN)₂^{•−} transient absorption intensity in the absence ([(SCN)₂^{•−}]₀) and presence ([(SCN)₂^{•−}]) of nitrosamine against the concentration ratio [R₁R₂N–NO]/[SCN[−]], one should get a straight line of slope k_2/k_3 . Typical transformed plots obtained in this study are shown in Figure 1a. From the established rate constant for the hydroxyl radical reaction with thiocyanate ($k_3 = 1.05 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$ at our temperature, (27)), the value of k_2 can be determined. The hydroxyl radical reaction rate constants for all

of the nitrosamines of this study are summarized in Table 1, in comparison to the values previously determined by this method for NDMA (24), NDEA, and NMEA (25). It is important to note that for all of these data, the quoted errors are for 1 standard deviation but include the precision of the linear fits as well as the purity of the compound and the reproducibility of the measurements.

In these hydroxyl radical data, a consistent trend was observed where the oxidation reaction rate constant became faster as the nitrosamine complexity increased (see Scheme 1 for general structures). This is to be expected, as previous electron-paramagnetic-resonance/spin-trap measurements for NDMA (24) have shown that the hydroxyl radical reaction consists of hydrogen atom abstraction from the methyl groups in this molecule. In these more complex nitrosamines, thermodynamic considerations suggest that hydrogen atom abstraction would mainly occur from one of the constituent methylene ($-\text{CH}_2-$) groups, which would be better able to stabilize the resultant carbon-centered radical due to the electron-donating nature of adjacent carbon atoms. This behavior is shown in Figure 1b, where we plot the natural logarithm of the measured rate constant, $\ln(k/\text{M}^{-1} \text{s}^{-1})$, against the number of methylene groups in the molecule. A very good linear trend is observed, supporting the NDMA result that hydrogen atom abstraction is the major pathway for hydroxyl radical oxidation. No specific correlation with the alkyl substituents being symmetric, asymmetric, or in a ring was observed for this oxidative reaction, although it is recognized that this correlation may only hold for low-molecular-weight aliphatic nitrosamines and that different reaction pathways may dominate for nitrosamines with alkene or heterocyclic aromatic substituents. Unfortunately, no comparison rate constants for the hydroxyl radical reaction with these more complex nitrosamines could be found in the literature.

Hydrated Electron Reactions

The presence of dissolved oxygen in AOP-treated waters containing low levels of contaminants would initially consume any formed reducing hydrated electrons to form the superoxide radical. However, for the electron-beam AOP, the high rate of total delivered dose quickly removes this dissolved oxygen, allowing the subsequent reaction of this reducing species with nitrosamines.

The reduction of nitrosamines by hydrated electron reaction also did not give any significant transient absorptions over the UV-vis wavelength range; therefore, the rate constants for this reaction were determined by direct measurement of the rate of change of the hydrated electron absorption decay at 700 nm. These solutions also contained 0.10 M methanol to quantitatively scavenge hydroxyl radicals and hydrogen atoms (27). For the pseudo-first-order decay kinetics obtained in the reaction

the bimolecular reaction rate constants were obtained by plotting these values against the nitrosamine concentration, as shown in Figure 2a. All these rate constants are summarized in Table 1.

Previous spin-trap measurements on the hydrated electron reduction of NDMA (24) showed that this reaction was only an addition to give a radical anion. The rate constants for the hydrated electron reaction with all the nitrosamines of this study are remarkably similar to NDMA (see Figure 2b), indicating that a common reaction mechanism occurs. The electron adduct may be formed through the interaction of the hydrated electron with the NO group or form a type of conjugated structure with the π orbitals of the molecule. In either case, the identity of the alkyl ligands on the amine nitrogen had little effect on the rate constant. However, these rate constants are significant in that although the reduction of all these nitrosamines only appears to form adduct species, they may be capable of transferring their extra electron to another acceptor, such as dissolved organic matter or oxygen, to regenerate the parent nitrosoamine.

Degradation Efficiency Measurements

Overall hydroxyl radical oxidative removal efficiencies for each nitrosamine in aerated solution were also determined in this study, using a steady-state/low intensity ^{60}Co -irradiation source at the Radiation Laboratory, University of Notre Dame.

The loss of nitrosamine in irradiated aerated solution showed first-order behavior, as evidenced by the plot of $\ln(C/C_0)$ against dose for NDEA shown in Figure 3a (inset). The linearity of this transformed plot is very good, indicating that the products of chemical oxidation do not significantly compete for the produced radicals. Traditionally, the slope of this plot gives a “dose constant”; however, as has been recently demonstrated (31), slopes calculated in this manner are not independent of initial solute concentration and so do not readily translate from laboratory conditions to the lower concentrations observed in other waters. Therefore, to provide quantitative removal data that can be used under all conditions, we instead plot the absolute change of nitrosamine concentration with dose, as seen in Figure 3a. The initial slopes of these plots are also linear (values summarized in Table 1), and correspond to the total G values for the destruction of these nitrosamines in aerated water. At higher doses, there is significant deviation from linearity, indicating that competition from formed products becomes a factor.

The efficiency of the free-radical-induced removal of these nitrosamines from water can be readily converted to a percentage basis, using eq 1. As the reduction of all these nitrosamines by the hydrated electron only results in an electron-adduct species, we can ignore the contributions of this radical in overall nitrosamine degradation. The hydrogen atom has also been shown to react with NDMA (24), with a rate constant of $k = (2.01 \pm 0.03) \times 10^8 \text{ M}^{-1} \text{ s}^{-1}$; however, this reaction mechanism was again postulated to be by addition to the nitroso group in these molecules. Moreover, in aerated solutions, the reaction of both hydrated electrons ($k = 1.9 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$ (27)) and hydrogen atoms ($k = 1.2 \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$ (27)) with dissolved oxygen, ($[\text{O}_2] = 2.5 \times 10^{-4} \text{ M}$) will be the dominant reaction for these species. Therefore, only the reactions of the hydroxyl radical will result in nitrosamine degradation under our experimental conditions. Therefore, by dividing our initial slopes by $G_{\bullet\text{OH}} = 0.28$, we can calculate the percentage efficiencies for nitrosamine removal. These values are also given in Table 1 and shown in Figure 3b.

It is immediately clear that for the higher-molecular-weight nitrosamines, defined as those which contain more than three methylene groups, the hydroxyl radical reaction is 100% efficient, which means that *every* hydroxyl radical reaction results in the *complete* destruction of the nitrosamine. However, for the three smaller aliphatic species of this study (NDMA, NMEA, and NDEA), the degradation efficiency is significantly less than unity, with a lower-limit value for NDMA of 80% found. This finding has important implications for AOP applications and computer models, as it appears that excess hydroxyl radicals will be required to achieve quantitative removal of low-molecular-weight nitrosamines from waters.

At this time we have not established the reason for the lower degradation efficiencies measured for these three nitrosamines. In these oxidations (eq 2), it would be expected that the initially formed methylene carbon-centered radical would react with dissolved oxygen to form a peroxy radical

These peroxy radicals are relatively unreactive and usually dimerize to form intermediate tetroxides (32–34), which then decompose to give a variety of smaller, oxygen-containing, products. This peroxy radical formation reaction for NDMA has been determined previously (24), with a rate constant of $k = (5.3 \pm 0.6) \times 10^6 \text{ M}^{-1} \text{ s}^{-1}$ measured. This rate constant is several orders of magnitude slower than that usually observed for a carbon-centered radical reaction with dissolved oxygen (35), which was attributed (24) to considerable spin-density delocalization from the original $\bullet CH_2(CH_3)NNO$ species formed into the N–NO bond(s), thereby giving a much less reactive radical species. For these more complex nitrosamines, the formation of carbon-centered radicals not adjacent to the N–NO group may prevent this electron delocalization, and therefore, it is possible that under our experimental conditions, some nitrosamine repair reactions of the form

might compete with peroxy radical formation, especially as the concentration of dissolved oxygen is depleted. These repair reactions may be slower in the larger nitrosamines, due to steric and resonance stabilization factors, thus increasing the degradation efficiency.

It is also important to note that these efficiency measurements were made in very high quality water, which limits the subsequent chemistry of the formed carbon-centered radicals. However, these kinetic data also provide a quantitative foundation for the evaluation of the AOP efficiency in removing nitrosamines from waters. These oxidation rate constants are relatively slow, which suggests that in waters containing high levels of dissolved natural organic matter (NOM), the hydroxyl radicals produced by AOPs might not have any significant impact on nitrosamine removal. For example, in typical wastewaters containing 7 ppm NOM (580 μM NOM assuming 12 g C per mole C) and 10 ppb NDMA (135 nM) at pH

8.0 and a typical alkalinity of 100 mg/L (as CaCO₃, corresponding to ~1.0 mM HCO₃⁻), the hydroxyl radical reaction will be partitioned according to

On the basis of the relative rates of these three reactions, the fraction following eq 10 would only be 0.033%. This fraction would remain constant under these conditions, independent of the rate of hydroxyl radical production or the AOP used.

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Literature Cited

1. EPA US. CASRN 62-75-9, *N*-Nitrosodimethylamine, IRIS Substance File. 1997
2. O'Neill, IK, Borstel, RCV, Miller, CT, Long, J, Bartsch, H. *N*-Nitroso Compounds: Occurrence, Biological Effects and Relevance to Human Cancer, IARC Scientific Publication No. 57. Oxford University Press; Lyon: 1984.
3. Magee PN, Barnes JM. Carcinogenic nitroso compounds. *Adv. Cancer Res.* 1967; 10:163–246. [PubMed: 4862936]
4. Magee PN. Toxicity of nitrosamines: Their possible human health hazards. *Food Cosmet. Toxicol.* 1971; 9:207–18. [PubMed: 4997817]
5. Loeppky, RN, editor. *Nitrosamines and Related N-nitroso Compounds: Chemistry and Biochemistry.* American Chemical Society Division of Agricultural and Food Chemistry; Washington, DC: 1994.
6. Tricker AR, Spiegelhalder B, Preussmann R. Environmental exposure to preformed nitroso compounds. *Cancer Surv.* 1989; 8:251–72. [PubMed: 2696580]
7. Fine DH, Rounbehler DP, Pellizzari ED, Bunch JE, Berkley RW, McCrae J, Bursey JT, Sawicki E, Krost K, DeMarrais GA. *N*-Nitrosodimethylamine in air. *Bull. Environ. Contam. Toxicol.* 1976; 15:739–46. [PubMed: 938767]
8. Fine DH, Rounbehler DP, Belcher NM, Epstein SS. *N*-Nitroso compounds: Detection in ambient air. *Science.* 1976; 192:1328. [PubMed: 17739836]
9. Fine DH, Rounbehler DP, Rounbehler A, Silvergleid A, Sawicki E, Krost K, DeMarrais GA. Determination of dimethylnitrosamine in air, water, and soil by thermal energy analysis: Measurements in Baltimore, MD. *Environ. Sci. Technol.* 1977; 11:581–4.
10. Mirvish SS. Role of *N*-nitroso compounds (NOC) and *N*-nitrosation in etiology of gastric, esophageal, nasopharyngeal and bladder cancer and contribution to cancer of known exposures to NOC. *Cancer Lett.* 1995; 93:17–48. [PubMed: 7600541]

11. Lijinsky W. *N*-Nitroso compounds in the diet. *Mutat. Res.* 1999; 443:129–38. [PubMed: 10415436]
12. Sen NP, Seaman SW, Bergeron C, Brousseau R. Trends in the levels of *N*-nitrosodimethylamine in Canadian and imported beers. *J. Agric. Food Chem.* 1996; 44:1498–501.
13. Mitch WA, Sedlak DL. Formation of *N*-nitrosodimethylamine (NDMA) from dimethylamine during chlorination. *Environ. Sci. Technol.* 2002; 36:588–95. [PubMed: 11878371]
14. Choi J, Valentine RL. *N*-Nitrosodimethylamine formation by free-chlorine-enhanced nitrosation of dimethylamine. *Water Res.* 2002; 36:817–24. [PubMed: 11848351]
15. Gerecke AC, Sedlak DL. Precursors of *N*-nitrosodimethylamine in natural waters. *Environ. Sci. Technol.* 2003; 37:1331–6.
16. Hecht SS. Approaches to cancer prevention based on an understanding of *N*-nitrosamine carcinogenesis. *Proc. Soc. Exp. Biol. Med.* 1997; 216:181–91. [PubMed: 9349687]
17. Zhu JH, Yan D, Xai JR, Ma LL, Shen B. Attempt to adsorb *N*-nitrosamines in solution by use of zeolites. *Chemo-sphere.* 2001; 44:949–56.
18. Sharp JO, Wood TK, Alvarez-Cohen L. Aerobic biodegradation of *N*-nitrosodimethylamine (NDMA) by axenic bacterial strains. *Biotechnol. Bioeng.* 2005; 89:608–18. [PubMed: 15672376]
19. Stefan MI, Bolton JR. UV direct photolysis of *N*-nitrosodimethylamine (NDMA): Kinetic and product study. *Helv. Chim. Acta.* 2002; 85:1416–26.
20. Liang S, Min JH, Davis MK, Green JF, Remer DS. Use of pulsed-UV processes to destroy NDMA. *J. Am. Water Works Assoc.* 2003; 95:121–31.
21. Lee J, Choi W, Yoon J. Photocatalytic degradation of *N*-nitrosodimethylamine: Mechanism, product distribution, and TiO₂ surface modification. *Environ. Sci. Technol.* 2005; 39:6800–7. [PubMed: 16190242]
22. Mitch WA, Sharp JO, Trussell RR, Valentine RL, Alvarez-Cohen L, Sedlak DL. *N*-Nitrosodimethylamine (NDMA) as a drinking water contaminant: A review. *Environ. Eng. Sci.* 2003; 20:389–404.
23. Crittenden JC, Hu S, Hand DW, Green SA. A kinetic model for H₂O₂/UV process in a completely mixed batch reactor. *Water Res.* 1999; 33:2315–28.
24. Mezyk SP, Cooper WJ, Madden KP, Bartels DM. Free radical destruction of *N*-nitrosodimethylamine in water. *Environ. Sci. Technol.* 2004; 38:3161–7. [PubMed: 15224750]
25. Mezyk SP, Ewing D, Kiddle JJ, Madden KP. Kinetics and mechanisms of the reactions of hydroxyl radicals and hydrated electrons with nitrosamines and nitramines in water. *J. Phys. Chem. A.* 2006; 110:4732–7. [PubMed: 16599441]
26. Whitman, K; Lyons, S; Miller, R; Nett, D; Treas, P; Zante, A; Fessenden, RW; Thomas, MD; Wang, Y. Linear accelerator for radiation chemistry research at Notre Dame 1995.. *Proceedings of the '95 Particle Accelerator Conference and International Conference on High Energy Accelerators*; Dallas, TX. 1996;
27. Buxton GV, Greenstock CL, Helman WP, Ross AB. Critical review of rate constants for reactions of hydrated electrons, hydrogen atoms and hydroxyl radicals (OH/O⁻) in aqueous solution. *J. Phys. Chem. Ref. Data.* 1988; 17:513–887.
28. Spinks, JWT, Woods, RJ. *An Introduction to Radiation Chemistry.* John Wiley & Sons; New York: 1990.
29. Buxton GV, Stuart CR. Re-evaluation of the thiocyanate dosimeter for pulse radiolysis. *J. Chem. Soc., Faraday Trans.* 1995; 91:279–82.
30. Ahn HJ, Yook HS, Rhee MS, Lee CH, Cho YJ, Byun MW. Application of gamma irradiation on breakdown of hazardous volatile *N*-nitrosamines. *J. Food Sci.* 2002; 67:596–9.
31. Mezyk SP, Neubauer T, Cooper WJ, Peller J. Free-radical-induced oxidative and reductive degradation of sulfa drugs in water: Absolute kinetics and efficiencies of hydroxyl radical and hydrated electron reaction. *J. Phys. Chem. A.*
32. Russel GA. Deuterium-isotope effects in the autoxidation of aralkyl hydrocarbons. Mechanism of the interaction of peroxy radicals. *J. Am. Chem. Soc.* 1957; 79:3871–77.
33. von Sonntag C, Schuchmann H-P. Elucidation of peroxy radical reactions in aqueous solution with radiation chemistry technology. *Agnew. Chem., Int. Ed. Engl.* 1991; 30:1229–53.

34. von Sonntag, C, Schuchmann, H-P. Peroxyl Radicals in Aqueous Solution.. In: Alfassi, ZB, editor. Peroxyl Radicals. Wiley; Chichester, U.K.: 1997. 173–234.
35. Neta P, Huie RE, Ross AB. Rate constants for reactions of peroxy radicals in fluid solutions. J. Phys. Chem. Ref. Data. 1990; 19:413–513.
36. Westerhoff P, Mezyk SP, Cooper WJ, Minakata D. Electron pulse radiolysis determination of hydroxyl radical rate constants with Suwannee River fulvic acid and other dissolved organic matter isolates. Environ. Sci. Technol. 2007; 41:4640–46. [PubMed: 17695909]

FIGURE 1.

(a) Competition kinetics plots for N -nitrosohexamethyleneimine ($\square$), N -nitrosopiperidine ($\circ$), and N -nitrosodipropylamine ($\triangle$) at room temperature and natural pH. Linear plots correspond to weighted linear fits, with slopes of 0.412 ± 0.045 ; $R^2 = 0.9996$, 0.282 ± 0.015 ; $R^2 = 0.9999$, and 0.218 ± 0.034 ; $R^2 = 0.9993$, respectively. (b) Transformed plot of $\ln(k_{OH^-})$ vs number of methylene groups in nitrosamine for symmetric aliphatic ($\square$), asymmetric aliphatic ($\circ$), and ring ($\triangle$) structures. Error bars correspond to 1 standard deviation, as determined from the data in a. The straight line is the weighted linear plot, with a slope of 0.424 ± 0.033 and an intercept of 19.72 ± 0.14 .

SCHEME 1.

(from left) Structures of Symmetric Aliphatic ($n = 0-3$), Asymmetric Aliphatic ($n, m = 0-3$), and Ring ($X = \text{C}, 0; n, m = 0-3$) Nitrosamines

FIGURE 2.

(a) Second-order rate constant determinations for hydrated electron reaction with N -nitrosomorpholine (Δ), N -nitrosopyrrolidine ($\circ$), and N -nitrosopiperidine ($\square$) in water at room temperature and natural pH. Linear plots correspond to weighted linear fits, with slopes of $(2.17 \pm 0.02) \times 10^{10}$, $(1.91 \pm 0.02) \times 10^{10}$, and $(1.54 \pm 0.02) \times 10^{10} \text{ M}^{-1} \text{ s}^{-1}$, respectively. Data for N -nitrosomorpholine and N -nitrosopyrrolidine have been offset by $+2.0 \times 10^6 \text{ s}^{-1}$ and $+1.0 \times 10^6 \text{ s}^{-1}$, respectively, to aid comparison. (b) Transformed plot of $\ln(k_e^-)$ vs number of methylene groups in nitrosamine for symmetric aliphatic ($\square$), asymmetric aliphatic ($\circ$), and ring (Δ) structures. Error bars correspond to 1 standard deviation, as determined from the data in a. The straight line is the linear plot, with a slope fixed at zero.

FIGURE 3.

(a) Steady-state ^{60}Co irradiation removal of nitrosamines in water at natural pH. Data plotted as absolute change in nitrosamine concentration for *N*-nitrosodimethylamine (□), *N*-nitrosodiethylamine (○), and *N*-nitrosohexamethyleneimine (◇). Solid lines correspond to linear fits of initial data, with slopes determined as $(2.241 \pm 0.047) \times 10^{-4}$, and $(2.908 \pm 0.018) \times 10^{-4}$, and $(2.908 \pm 0.018) \times 10^{-4} \text{ kGy}^{-1}$, respectively. Inset: Plot of the natural logarithm of the ratio of remaining concentration of *N*-nitrosodiethylamine divided by the original concentration, $\ln(C/C_0)$, against dose. The solid line is the linear fit, with a slope corresponding to the dose constant of removal in aerated waters of $0.409 \pm 0.016 \text{ kGy}^{-1}$. (b) Percentage efficiency for hydroxyl-radical-induced reaction with nitrosamines in water, plotted against number of methylene groups in each nitrosamine for symmetric aliphatic (□), unsymmetric aliphatic (○), and ring (△) structures. Error bars correspond to 1 standard deviation.

TABLE 1

Summary of Hydroxyl Radical and Hydrated Electron Reaction Rate Constants and Hydroxyl Radical Degradation Efficiencies for Nitrosamines of This Study

species	S/A/ R ^c	$k\cdot\text{OH}$ (M ⁻¹ s ⁻¹)	$k_e\text{-(aq)}$ (M ⁻¹ s ⁻¹)	no. CH ₂ groups	initial slope (kGy ⁻¹)	degradation efficiency (%)
<i>N</i> -nitrosodimethylamine ^a	S	$(4.30 \pm 0.11) \times 10^8$	$(1.41 \pm 0.01) \times 10^{10}$	0	$(2.24 \pm 0.05) \times 10^{-4}$	80.0 ± 1.7
<i>N</i> -nitrosomethylethylamine ^b	A	$(4.95 \pm 0.21) \times 10^8$	$(1.67 \pm 0.13) \times 10^{10}$	1	$(2.33 \pm 0.14) \times 10^{-4}$	83.2 ± 4.8
<i>N</i> -nitrosodiethylamine ^b	S	$(6.99 \pm 0.28) \times 10^8$	$(1.61 \pm 0.12) \times 10^{10}$	2	$(2.41 \pm 0.09) \times 10^{-4}$	86.0 ± 3.3
<i>N</i> -nitrosodipropylamine	S	$(2.30 \pm 0.06) \times 10^9$	$(1.53 \pm 0.08) \times 10^{10}$	4	$(2.82 \pm 0.06) \times 10^{-4}$	100.9 ± 2.3
<i>N</i> -nitrosoethylbutylamine	A	$(3.10 \pm 0.13) \times 10^9$	$(1.56 \pm 0.07) \times 10^{10}$	4	$(2.94 \pm 0.13) \times 10^{-4}$	105.1 ± 4.7
<i>N</i> -nitrosodibutylamine	S	$(4.71 \pm 0.19) \times 10^9$	$(1.55 \pm 0.11) \times 10^{10}$	6	$(2.82 \pm 0.05) \times 10^{-4}$	100.8 ± 1.7
<i>N</i> -nitrosomorpholine	R	$(1.75 \pm 0.27) \times 10^9$	$(2.18 \pm 0.11) \times 10^{10}$	4	$(2.60 \pm 0.18) \times 10^{-4}$	92.9 ± 6.4
<i>N</i> -nitrosopyrrolidine	R	$(1.75 \pm 0.07) \times 10^9$	$(1.90 \pm 0.10) \times 10^{10}$	4	$(2.77 \pm 0.17) \times 10^{-4}$	98.9 ± 6.0
<i>N</i> -nitrosopiperidine	R	$(2.98 \pm 0.09) \times 10^9$	$(1.74 \pm 0.12) \times 10^{10}$	5	$(2.74 \pm 0.08) \times 10^{-4}$	98.0 ± 2.9
<i>N</i> -nitrosohexamethyleneimine	R	$(4.35 \pm 0.14) \times 10^9$	$(1.54 \pm 0.09) \times 10^{10}$	6	$(2.91 \pm 0.05) \times 10^{-4}$	103.9 ± 1.7

^aKinetic data taken from ref 24.

^bKinetic data taken from ref 25.

^cS = symmetric aliphatic, A = asymmetric aliphatic, and R = ring nitrosamine.