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The Occurrence of *N*-nitrosodimethylamine (NDMA) in Swimming Pools: An Overview

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ABSTRACT: The occurrence of several disinfectant byproducts has been investigated in swimming pools. Until now, there are only a few studies on nitrosamine, particularly *N*-nitrosodimethylamine in swimming pool water. This could be due to the lack of a suitable method that is sensitive enough for the measurement of *N*-nitrosodimethylamine in pool waters. Other disinfectant byproducts formed in pool water widely documented are trihalomethanes, haloacetic acids, halonitromethanes, and chloramines but inadequate information on *N*-nitrosodimethylamine. This paper provides a review of the nitrogenous disinfectant byproduct in swimming pools and its health implications. Anthropogenic substances introduced by swimmers such as sweat, lotions, and urine contribute to the formation of *N*-nitrosodimethylamine. The reaction of secondary amines such as dimethylamine with mono/dichloroamines produced dimethyl hydrazine and further undergo oxidation to form *N*-nitrosodimethylamine. The reaction of chlorine and other disinfectants with these anthropogenic sources in swimming pools cause cancer and asthma in human tissues. Thus, the assessment of *N*-nitrosodimethylamine in the swimming pool is less well documented. Therefore, the health consequences, mutagenic, and genotoxic potentials of *N*-nitrosodimethylamine should be the focus of more research studies.

KEYWORDS: Swimming pool, *N*-nitrosodimethylamine, disinfectant byproducts, anthropogenic sources

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Introduction

Numerous emerging micro-pollutants have been detected at trace concentrations in waters, especially in drinking water globally. Some of them have been connected with ecological influences, even at these very low concentrations. Researchers have placed so much emphasis on micro-pollutants in public health assessments and environmental risk assessment in drinking water, focusing less on swimming pool water. Therefore, providing clean water without harmful disinfection byproducts is needed for supplying safe swimming pool water. Chlorine, chlorine dioxide, ozone, and chloramines are the most common disinfectants in use today. Although these disinfectants can effectively kill microbial pathogens, they oxidize anthropogenic contaminants and other organic materials naturally present in source waters due to their strong oxidizing properties, leading to the formation of disinfection by-products (DBPs), such as carbonaceous and nitrogenous disinfectant compounds.¹

The consumption of chlorinated water creates an increased risk of deleterious health outcomes which poses serious challenges. Therefore, researchers have focused on most of these

emerging contaminants in water, such as disinfection by-products which include nitrosamines and their precursors.² One of these nitrosamines is *N*-nitrosodimethylamine (NDMA) which has been identified as a carcinogenic, mutagenic, and teratogenic compound. NDMA was shown to be a major contributor to increased lifetime cancer risk in humans.³ Report by the U.S. Environmental Protection Agency (EPA) has identified nitrosamines to be among the potential carcinogenic contaminants emphasized for monitoring action.⁴ The first documented report on the presence of NDMA in the waters was in the 1970s.⁵ Several nitrosamines subjected to carcinogenicity tests were also found in animals while other sources include cigarette smoke, effluents from pesticides, cosmetics, metals, rubber, and tannery industries.⁶

Other nitrosamines include nitrosomethylethylamine (NMEA), nitrosodiethylamine (NDEA), nitrosodi-*n*-butylamine (NDBA), nitrosopyrrolidine (NPyr), nitrosopiperidine (NPip), and nitrosomorpholine (NMor).⁷ In most cases, disinfected water treatment companies are the principal sources of nitrosamine⁸ while other sources include alcoholic beverages and food,⁹ meats,¹⁰ cigarette smoke,¹¹ and cosmetics.¹²



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The level of NDMA becomes high in chlorinated pools as a result of an increase in anthropogenic activities. Sensitive analytical methods have detected nitrosamines in the water at very low concentrations as low as nanograms per liter (ng/L). Detecting nitrosamines at these low levels are good for proper monitoring and control. These determinations are performed based on extraction and detection. Examples are solid-phase extraction (SPE) and solid-phase microextraction followed by either gas chromatography/mass spectrometry (GC/MS) or liquid chromatography/mass spectrometry (LC/MS) analysis.¹³⁻¹⁷

Different methods have been adopted for the control of NDMA in the water, namely; degradation of NDMA after its formation and removal of its precursors to prevent the formation of NDMA. Among the treatment techniques used are adsorption, ultraviolet (UV) photolysis, bioremediation, zeolite entrapment, reverse osmosis, and advanced oxidation processes. Beita-Sandí et al¹⁵ examined the removal of NDMA precursors by powdered activated carbon (PAC) adsorption during water treatment and found that the combination of biodegradation, photolysis, and adsorption reduces the precursors. Seid et al¹⁸ investigated NDMA removal in water using UV/sulphite chemistry and discovered that bromide ions reduce NDMA formation during chloramination.

This paper reviews the formation and detection of NDMA in swimming pools because of preliminary findings which showed adverse health implications for swimmers exposed to it during swimming.

Nitrosamines

Nitrosamines (NAs), particularly NDMA, are popularly known as B2 carcinogens by U.S. Environmental Protection Agency¹⁹ and they are categorized as nitrogenous disinfection byproducts. NAs are reported to be more carcinogenic than carbonaceous DBPs, such as trihalomethanes (THMs) and haloacetic acids (HAAs).²⁰ N-nitrosamines occur in water as disinfection by-products (DBPs) during chlorination, chloramination, and ozonation and they have been known for centuries. Barnes and Magee²¹ discovered their carcinogenic properties of these compounds and this is confirmed by Nawrocki and Andrzejewski.⁵ These compounds have been reported to be present in food products, soil, wastewater, drinking water, and swimming pools.

Ayanaba and Alexander²² detected NDMA in treated sewage and environmental waters. In the early 1990s, NDMA was detected in drinking water in Canada, while in the last few decades, researchers have revealed that disinfected drinking water is not the only route of exposure to nitrosamines but bathing and anthropogenic activities lead to high levels to these chemical compounds. Due to the growing concern regarding the health effects of nitrosamines as a result of their potential carcinogenicity, their characteristics have been summarized in Table 1.

The Formation Mechanism of N-nitrosodimethylamine

The formation of NDMA involves the reaction of secondary amines such as dimethylamine with mono or dichloroamines. It was noticed that dichloramine reacts with dimethylamine to produce an unsymmetrical dimethylhydrazine (UDMH) intermediate. This intermediate undergoes oxidation by monochloramine, to give the targeted carcinogenic compound, NDMA, as shown in Figure 1.

This consists of (i) the formation of monochloramine (a result of the reaction between hypochlorite and ammonia), (ii) the reaction of monochloramine with dimethylamine (DMA) for the formation of the dimethyl chloroamine (DMCA) through chlorine transfer, (iii) the formation of dimethylhydrazine via Raschig synthesis followed by (iv) the oxidation of UDMH by monochloramine and hydrolysis to give NDMA. However, the overall mechanistic reaction indicated that chlorination of nitrite in the presence of nitrosamine precursors leads to the formation of nitrosamine as explained by Soltermann et al.²³ Apart from chlorine and ammonia addition during the formation of NDMA, the reaction of water treatment polymers such as poly(diallyldimethylammonium chloride) (polyDADMAC) and poly(epichlorohydrin dimethylamine) (polyamine) have been found to lead to the formation of NDMA. As suggested by Padhye et al,²⁴ the reaction of polyDADMAC and chlorine to produce NDMA involves Hofmann elimination occurring at the β -H to the quaternary amine, leading to the formation of tertiary amine via cleavage from the α -carbon to nitrogen. The tertiary amine produced DMA upon reacting with monochloramine/dichloramine. In another study by Park et al,²⁵ the polyDADMAC and polyamine upon reaction with chlorine formed tertiary amines which degraded to secondary amines through electrophilic substitution reaction. In the same vein, the formation of NDMA was as a result of nucleophilic substitution between secondary amine and chloramine.

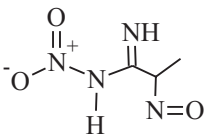
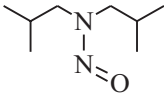
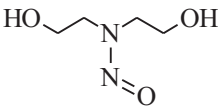
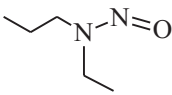
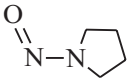
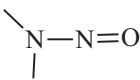
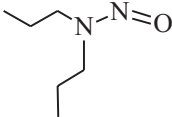
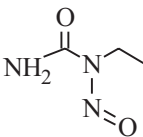
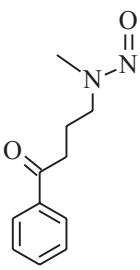
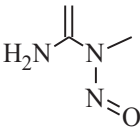
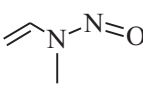
Some N-N-dimethylhydrazine compounds have been found to form a considerable amount of NDMA during ozonation resulting in the release of DMA, leading to the formation of NDMA. The mechanism of the NDMA formation using this treatment method produced N-N-dimethylhydrazine compounds (UDMH and DMZ) as proposed in Figure 2 by Lim et al.²⁶ During this process, the reaction pathways involved hemolytic cleavage forming N-oxide and singlet oxygen and a heterolytic cleavage forming N-oxide radical, oxygen radical, amine radical, and ozonide radical. The N-oxide reacted with ozone to form N-N-hydroxyl oxide and subsequently degraded into (NDMA and water) and (NDMA and SCA) for UDMH and DMZ, respectively.

Occurrence of NDMA

Swimming pool

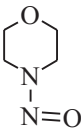

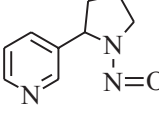
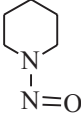
Chlorine gas and sodium or calcium hypochlorite are important chemicals used for the disinfection of swimming pool

Table 1. Properties of nitrosamines.

COMPOUND	FORMULA	STRUCTURE	MOLAR MASS (G/MOL)	COLOR	MELTING POINT (°C)
Methylnitronitrosoguanide (MNNG or MNG)	$C_2H_5N_5O_3$		147.09	Yellow	118
N-Nitrosodiisobutylamine (NDBA)	$C_8H_{18}N_2O$		158.245	Yellow	1.86-18.4
N-Nitrosodiethanolamine (NDELA)	$C_4H_{10}N_2O_3$		134.135	Light yellow	
Nitrosodiethylamine (NDEA)	$C_4H_{10}N_2O$		102.137	Slightly yellow	<25
N-Nitrosopyrrolidine (NPYr)	$C_4H_8N_2O$		100.120	Light yellow	
Nitrodimethylamine (NDMA)	$C_2H_6N_2O$		74.083	Yellow	50
N-Nitrosodi-n-propylamine (NDnPA)	$C_6H_{14}N_2O$		130.191	Pale yellow	
N-Nitroso-N-ethylurea	$C_3H_7N_2O_2$		117.130		
4-(N-Nitrosomethylamino)-1-(3-pyridyl)-1-butanone (NNK)	$C_{10}H_{13}N_3O_2$		207.233	Light yellow	62-64
N-Nitroso-N-methylurea	$C_2H_5N_3O_2$		103.081	Pale yellow	124
N-Nitrosomethylvinylamine	$C_3H_6N_2O$		86.094	Yellow	

(Continued)

Table 1. (Continued)

COMPOUND	FORMULA	STRUCTURE	MOLAR MASS (G/MOL)	COLOR	MELTING POINT (°C)
N-Nitrosomorpholine	$C_4H_8N_2O_2$		116.120	Yellow	29
N-Nitrososarcosine	$C_3H_6N_2O_3$		118.092	Pale yellow	66-67
N-Nitrosornicotine (NNN)	$C_9H_{11}N_3O$		177.200	Light yellow	42-45
Nitrosopipendine	$C_5H_{10}N_2O$		114.150	Light yellow	170

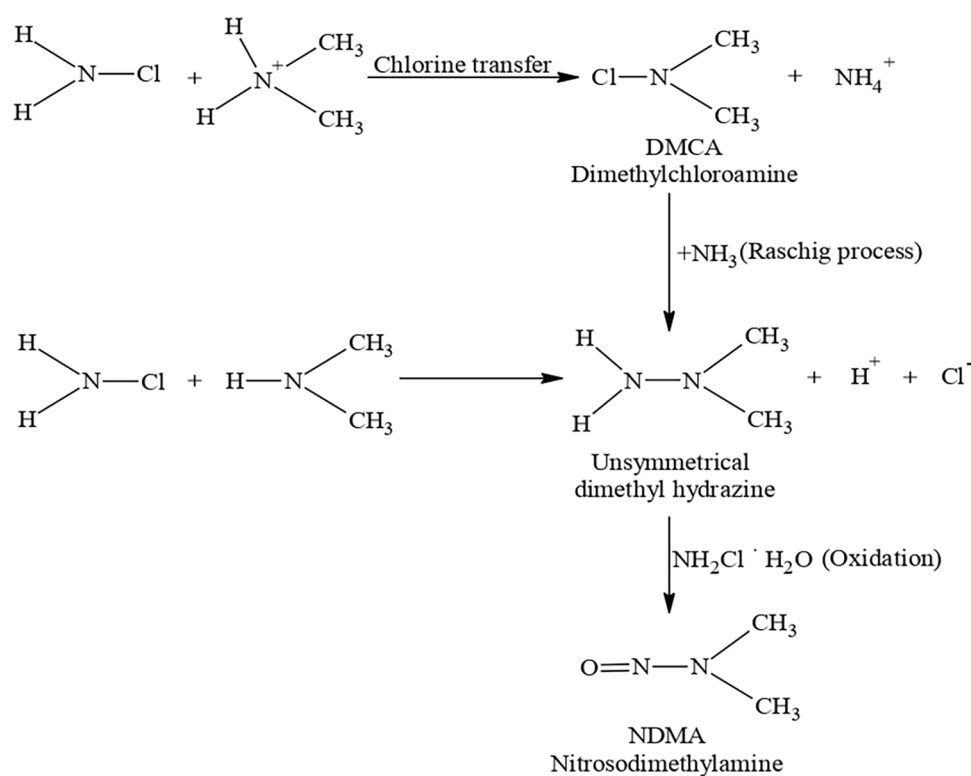


Figure 1. Mechanism modification of N-nitrosodimethylamine (NDMA) formation.

water. Besides their disinfecting properties, chlorine reacts with organic matter introduced into water by the bathers to produce hazardous disinfection by-products (DBPs), such as inorganic chloramines and organohalogenated byproducts. Exposure to these disinfection by-products has resulted in a lot of health problems, according to the work of several researchers.²⁷ In water, NDMA is formed by the addition of chlorine to the

water, which undergoes oxidation and reduction reaction forming hydrochloric acid (HCl) and hypochlorous acid (HOCl). The presence of organic substances such as ammonia (NH₃) in the chlorinated water results in the formation of monochloramine, dichloroamine, or trichloroamine depending on the pH of the swimming pool water. The rapid reaction of monochloramine with ammonia would account for the production of

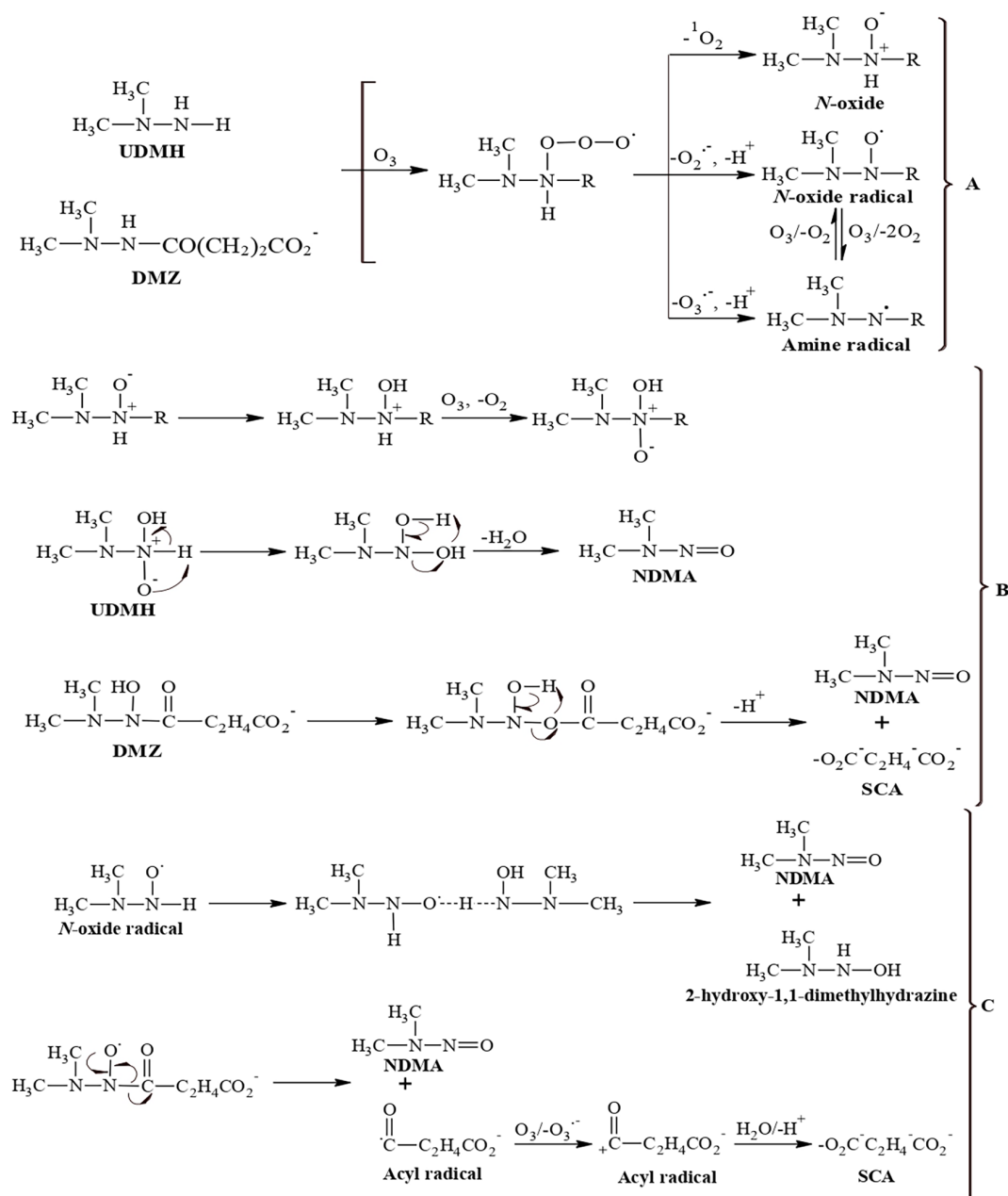
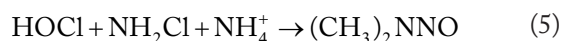
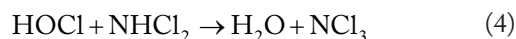
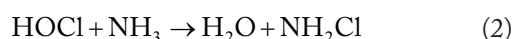
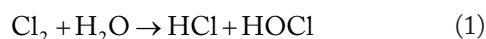


Figure 2. Initial reactions (A), reactions of *N*-oxide intermediates (B) and reactions of *N*-oxide radical intermediate of UDMH and UMZ (C).

NDMA. The following equations describe the various forms of chloramines formed in this process.



A study conducted by Kim and Han²⁸ on 3 public indoor pools in Chuncheon, Korea detected nitrosamines at measurable concentrations in chlorinated indoor pool water. The nitrosamines, NMOR, NDMA, and NDEA were found at higher concentrations in swimming pool waters than in the chlorinated drinking water samples. The high levels of these substances were said to be probably as a result of swimming activities in these pools. The authors suggested that the subsequent release of these carcinogenic substances in swimming pools could be declined via a better understanding of several swimming pools. A similar experiment was done by Jurado-Sánchez et al,²⁹ but adequate documentation was not provided on the effect of nitrosamines in pool waters.

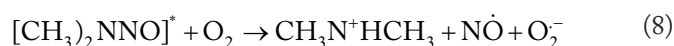
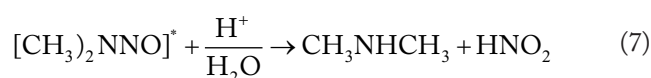
The formation of N-Nitrosamine (1%-2%) was postulated to be due to the reactions of oxides of nitrogen such as nitric oxide (NO) and peroxyxynitrite (ONOO⁻) with the secondary amines in the presence of ultraviolet irradiation by Soltermann et al.²³ Thus, the formation of nitrosamines plays a major role in chloraminated pool water containing secondary amines. In another study carried out by Soltermann et al.,³⁰ it was reported that trichloramine was the principal precursor that is formed through the reaction of urea with chlorine and hypochlorous acid in pool waters. The authors stated that the formation of trichloramine was due to the swimmers' activities based on the reaction of chlorine and nitrogen-containing precursors. The reduction of the precursors in water has been a necessary preventive strategy suggested by these authors since the degradation of NDMA is very difficult. The formation of NDMA was not analyzed and quantified during their investigation. This could be a result of the complexity in the mechanism of the formation of nitrosamines in pool waters or the limitation of their study plan.

In the study of Lee et al.,³¹ NDMA was successfully detected in the 4 pools that were studied and the occurrence of other nitrosamines was monitored using UV photolysis and Griess reagent. This method's detection limits for the 8 N-nitrosamines ranged from 4 to 27.6 ng/L. The examined total level of nitrosamines followed the order: UV/chlorinated pool water (149 mM) > chlorinated pool water (16-38 nM) > chlorinated, ozonated, and activated carbon treated pool water (6 nM). About 78% of UV-resistant compounds were detected in the pool water and 3 nitrosamines, namely; NDMA, NDPA, and NDPA were detected. Nitrosamine is a disinfection by-product in chlorinated swimming pools that was quantified by Walse and Mitch.³² They pointed out that the use of chlorine with the increase of water temperature, the presence of amines, and nitrogen oxide as precursors contributed to the significant occurrence of the compound in swimming pools.

Kulshrestha et al.³³ reported the NDMA range of 3% to 46% in 6 disinfected swimming pool water. Nitrite and S-nitrosothiols were the major precursors but they can be removed from the system through biological pretreatment methods. Fu et al.³⁴ found that NDMA had the highest concentration (100 ng/L) among the nitrosamines determined in experimental samples of swimming pool water. It was established that the amount of this carcinogenic substance depends on the disinfectant applied and the precursors of oxidative nitrosamines formed which could also be harmful to swimmers.

Interest has waned in the last few years about the presence of NDMA in swimming pool water. This could be as a result of limited or lack of no information on a specified regulatory limit for NDMA in swimming pools in most countries. Although before the disinfection process in swimming pool maintenance, appropriate attention has been paid to the disinfection by-products (DBPs). On the other hand, these chemicals may be undesirable to the swimmer when exposed to during swimming.

Swimming pool users introduce anthropogenic substances such as cosmetic products, saliva, urine, and sweat to pool waters.³⁵ Sharifan et al.³⁶ and Teo et al.³⁷ concluded that these products from humans increase the DBPs in chlorinated swimming pools. The presence of these chemical contaminants is influenced by the types of pools, kind of disinfectants, disinfectant dosages, bather loads, temperature, and pH of the water. They also reported that the reaction of parabens and ultraviolet (UV) filters with these disinfectants could be toxic and may lead to serious health implications. The concentration of water quality parameters such as total nitrogen, dissolved organic carbon, chloride, nitrate, and sulfate strengthen NDMA and other forms of nitrosamines in swimming pools via the organic and inorganic substances for bathers.²⁸ In another study by Knon et al.³⁸ and Guo et al.,³⁹ they discussed the UV-photolytic mechanisms of NDMA degradation. Following the excitation of NDMA by UV light, it undergoes photolysis, oxidation, bond cleavage, and hydrolysis. The reaction steps are as follows:



A study found other types of DBPs in swimming pools besides NDMA. This raised important questions about previous researchers' findings on what could be responsible for the lack of detection of NDMA in swimming pool water. Some of these questions include (i) was there a lack of sufficient analytical methods for identifying NDMA? and (ii) what is the level of NDMA that will not be deleterious to human health? For example, Manasfi et al.⁴⁰ examined trichloroacetic acid, chloral hydrate, dichloroacetone, 1,1,1-trichloropropanone, dibromoacetic acid, bromoform, dibromoacetone, and chloroform in fresh and seawater swimming pools. They elucidated that the safety of swimming pool water could be achieved by reducing or eliminating the production of DBPs. Trihalomethanes (THMs) were the most common DBPs found in outdoor swimming pool water, according to Peng et al.,⁴¹ due to the presence of organic and inorganic micropollutants in the water. Their findings contradicted the outcomes of Berg et al.,⁴² who discovered haloacetic acids (HAAs) in greater concentrations than THMs in swimming pool water.

The level of a carbonaceous DBP in chlorinated outdoor swimming pool water was investigated by Tang and Xie.⁴³ It was reported that at low contact time, residual chlorine was

present in the swimming pool water. It is expected that if a further analysis was conducted, there could be a possible formation of nitrosamines either as intermediates or final products. Hang et al⁴⁴ studied the level of DBPs in 13 public indoor swimming pools in Nanjing, China. Among the dominant carbonaceous DBPs found in the studies were trihalomethanes, haloacetonitriles, haloketones, and trichloronitromethane. The DBPs concentrations were affected by chlorination, thus making it possible to correlate DBPs and water quality parameters in swimming pools. The DBPs that were identified in swimming pools are highlighted in Table 2.

The noticeable prevalent compound was chlorine. Therefore, there could be possible sources of DBPs such as nitrosamines when there are subsequent reactions of the aforementioned by-products with disinfectants and natural organic substances.

Analytical Techniques for Detecting NDMA

Several established methods for the detection and control of NDMA in swimming pools have helped in providing disinfectant residues in the distribution network during water treatment. The monitoring of this contaminant in parts per trillion levels has been a serious challenge for most water establishments across the globe. The measurement of N-nitrosamine concentration levels is generally achieved using analytical methods such as either gas chromatography or high-pressure liquid chromatography coupled with tandem mass spectrometry detector.^{58,59} Nitrosamines found in swimming pools could be quite different in composition due to various operating conditions such as pH, precursor identity, and residual disinfectant concentrations.

Soltermann et al²³ analyzed and quantified NDMA in swimming pools using high-performance chromatography (HPLC) and solid-phase extraction (SPE). From their findings, potential precursors for NDMA were degraded via photolysis, and approximately 1% to 2% NDMA was formed as a result of the reaction of nitric oxide or peroxyxynitrate with secondary aminyl radicals. It was observed that NDMA in treated pool water can be significantly degraded by using the UV treatment method in experiments that compared treated pool water to untreated pool water. The result of this study signifies that the occurrence of nitrosamines as emerging contaminants in swimming pools is a result of frequent chlorination and swimmers are unprotected from these compounds in urban regions.

Automated SPE and gas chromatography coupled with mass spectrometer were developed for the detection of NDMA in swimming pools.²⁹ Among the analyzed pool water samples, NDMA was found to be of the highest concentration in the range of 5.0 to 5.9 ng/L. The chlorination of swimming pool water for disinfection purposes and the presence of amine precursors of urine and sweat from swimmers were the key factors pointed out to be responsible for the rise in NAs in the pool water samples. Thus, simple measures such as public awareness and periodic change of water were advocated

to be necessary for the improvement of the qualities of swimming pool water.

The SPE and HPLC-Post Column UV photolysis/Griess reaction (PCUV) methods were used to determine the concentrations of nitrosamine compounds in 4 swimming pool waters with and without disinfection by Lee et al.³¹ The nitrosamine compounds analyzed and identified NDMA, NDPA, and NDMA. It was established that pools that were treated by chlorination and UV irradiation had the highest concentration of nitrosamines, followed by those that were only chlorinated and then those that were treated by a combination of chlorination, ozonation, and treatment with activated carbon. However, employing UV irradiation is advantageous because it is cheap and easy to implement. According to Tardif et al,⁶⁰ UV causes an increase in DBPs such as halonitromethanes, haloketones, and trihalomethanes in water but it causes a reduction in the concentrations of NDMA in pool water. To minimize false-positive responses from impurities (nitrite producing compounds upon UV irradiation) present in the extraction solvent, the introduction of UV pre-treatment N-nitro(so) compounds and nitrite-producing compounds to confirm specific N-nitrosamines such as NDMA based on their photostability among peaks that were found in water samples. Walse and Mitch³² established that concentrations of NDMA detected in the indoor pools were far greater than the outdoor pools. They concluded that the level of this water contaminant was reduced upon the treatment of pool water by combining UV and a low dose of chlorine treatment. Therefore, the need for preventing swimmers from getting infections can be achieved by the replacement of the pool waters frequently and using UV treatment.

Solid-phase extraction (SPE) and gas chromatography/mass spectrometry (GC/MS) coupled with chemical ionization (CI) were used for the determination of N-nitrosamines in water samples from 5 swimming pools from Bologna, Italy by Pozzi et al.² In their study, N-nitrosopyrrolidine (NPYR) was detected at concentrations ranging from 53 to 127 ng/L. In another study Italian pools by Kanan,⁶¹ NDMA was found to be less than 1 ng/L in the indoor pools, but higher levels were found in indoor pools from South and North Carolina, United States of America in the range of 2 to 83 ng/L. The researchers concluded that DBPs were formed from nitrogen precursors introduced by swimmers.

In the study of Lashgari et al,⁶² N-nitrosamines in swimming pool water were determined and quantified by micro-solid-phase extraction (μ -SPE) and gas chromatography-tandem mass spectrometry with electron impact ionization (EI) and triple quadrupole analyzer (GC-EI-MS/MS). The concentrations of these compounds greater than 2 ng/cm³ were determined in the swimming pool water. The study suggested that there is a need for proper monitoring of NAs in pool water by regulatory bodies and organizations. This will help to determine the contamination of nitrosamines and prove if its precursor occurs as a result of swimming activities.

Table 2. DBPs in swimming pools.

DISINFECTANT BY-PRODUCTS	ANALYSIS	TREATMENT METHOD	OPERATIONAL CONDITION	FINDINGS	REFERENCE
THMs, HANs, miscellaneous DBPs (TCNM, DCP)	Purge and trap, GC-MS	UV/ozonation	Dosage	<ul style="list-style-type: none"> DBPs decreased under the integral treatment (UV/ozonation) 	Cheema et al ⁴⁵
THMs, HAAs, HANs, CA, urine	L-C			<ul style="list-style-type: none"> Exposure of DBPs in swimmers are higher and associated with molecular changes 	van Veldhoven et al ⁴⁶
THMs, HAAs	GC-ECD		pH, chlorine, dosage, temperature, bromine concentration, TOC and TN	<ul style="list-style-type: none"> The amount of HAAs was higher than THMs. The increase in bromine in water caused an increase in brominated HAAs. 	Avsar et al ⁴⁷
THMs	Purge and trap, GC-MS	UV/chlorination	Chlorine dose	<ul style="list-style-type: none"> The post UV/chlorination treatment accelerates the formation of THM and brominated THM. 	Spiliotopoulou et al ⁴⁸
THMs, HAAs and HANs	GC-ECD			<ul style="list-style-type: none"> The concentrations of HAAs were found to be higher than THMs and HANs. The DBPs concentrations were not affected by swimmers, pH, temperature and free chlorine. 	Bahmani and Ghahramani ⁴⁹
THMs, HANs, TCNM	GC-ECD			<ul style="list-style-type: none"> THMs were found to be the highest followed by HANs and TCNMs. Chloroform was the most important DBP detected and dichloroacetonitrile was the major nitrogenous DBP. 	Yang et al ⁵⁰
THMs, HAAs	GC-MS	UV-radiation	Reaction time, dosage, temperature, body fluid analog and free chlorine concentration	<ul style="list-style-type: none"> Higher temperature enhanced free consumption of chlorine and formation of DBPs. Natural organic matter and body fluid analog contributed to different types of DBPs. 	Yang et al ⁵¹
THMs, HAAs, HAN, CH, DCP, TCP, TCNM	GC-MS	UV-radiation	UV dose	<ul style="list-style-type: none"> UV dechloramination of swimming pool changed the formation potentials of DBPs. The UV dose gave rise to an increase in chlorine and formation of DBPs of pool water 	Cimetiére and De Laat ⁵²

(Continued)

Table 2. (Continued)

DISINFECTANT BY-PRODUCTS	ANALYSIS	TREATMENT METHOD	OPERATIONAL CONDITION	FINDINGS	REFERENCE
THMs, HAAs, HANs, HKs, TCNMs	GC	Ozonation/chlorination		<ul style="list-style-type: none"> The concentrations of DBPs in pools disinfected with ozonation/chlorination were less than the disinfection by chlorination. 	Hang et al ⁴⁴
THMs, HAAs	GC-MS			<ul style="list-style-type: none"> The interaction of DOC and N₂ affects the formation of THMs. The interaction of swimmer with N₂ had a significant effect in HAA formation 	Chowdhury et al ⁵³
HAAs, HKs, HALs, N-nitrosamines	GC-MS	UV/chlorination	pH, free chlorine	<ul style="list-style-type: none"> DBPs correlated with non-purgeable organic carbon, indicating that organic carbon determine the formation of DBPs in swimming pools 	Carter et al ⁵⁴
HBQs	LC-MS	UV		<ul style="list-style-type: none"> The chloride in pools promoted the formation of HBQs. Chloramines inhibited HBDs formation. 	Wu et al ⁵⁵
THMs	GC-MS	Volatilization air, exchange with fresh filling water		<ul style="list-style-type: none"> The formation of DBPs through induction of anthropogenic pollutant into swimming pool water should be determined using analytical techniques. DOC is an important parameter for the precursor to predict the production of THM 	Peng et al ⁴¹
THMs, HAAs, HKs, TCNM	GC-ECD			<ul style="list-style-type: none"> The chloride ion showed positive correlations with HAAs and NAs while nitrate in load correlates with NAs. NAs, THMs and HAAs were the main contributors to cancer risk via dermal absorption and ingestion 	Peng et al ⁵⁶
THMs, HAAs	GC-MS	Ozonation, UV/chlorination, UV/H ₂ O ₂	Contact time, dosage and temperature	<ul style="list-style-type: none"> UV/H₂O₂ significantly degraded the DBPs precursors eventually decrease the concentration of DBPs. Organic matter body fluid contributed to the increase in DBPs in the swimming pools. 	Liu et al ⁵⁷

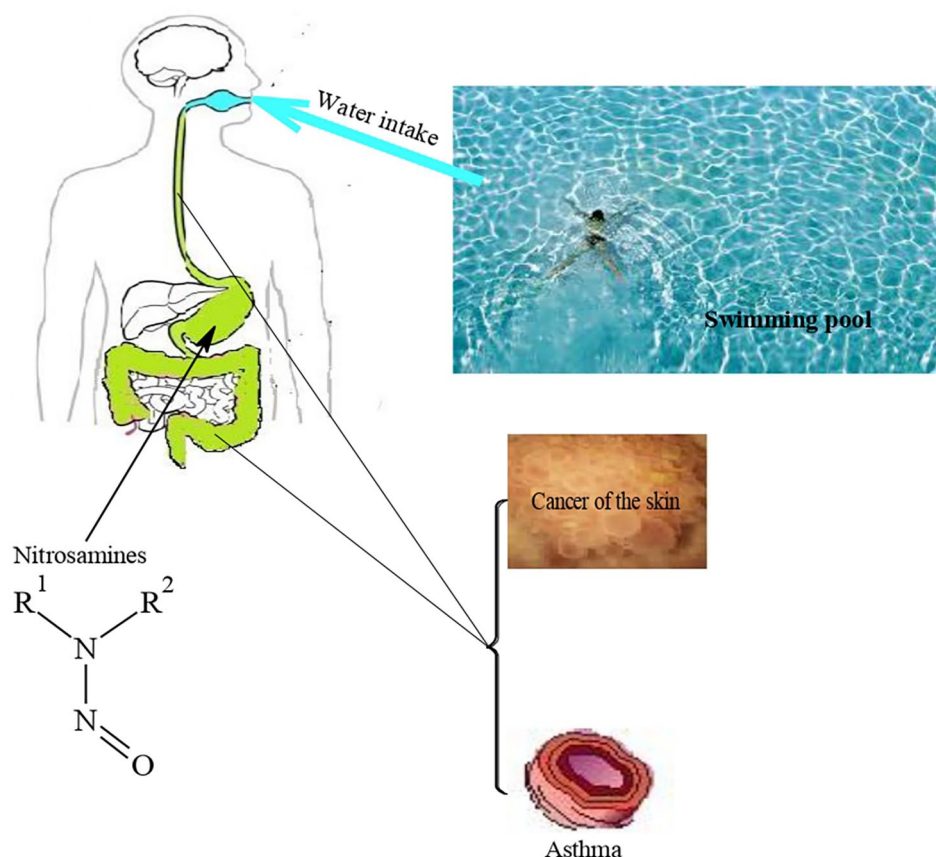


Figure 3. Effect of pool water on the human body.

Health Implication of NDMA

Numerous investigations have demonstrated the occurrence of adverse health effects of NDMA in swimming pools and a schematic diagram of its health implications on human is shown in Figure 3. According to United States National Institutes of Health,⁶³ epidemiological studies have revealed an increased risk of bladder cancer as a result of the use of chlorinated water in swimming pools. Other diseases for epidemiological studies include upper digestive tract cancers,⁶⁴ brain cancer,^{65,66} bladder cancer,⁶⁷ gastric cancer,^{68,69} and liver damage.^{70,71} Studies on the relationship between swimming and the occurrence of asthma in swimmers have been conducted because there is already a link between swimmers' professions and respiratory syndromes.⁷² Trichloramine, an NDMA precursor, is a respiratory irritant produced by chlorine in the water, the swimmers, water temperature, and ventilation of the swimming pool, as well as the presence of some undesired products used for maintenance purposes.⁷³ It has been found to have negative health consequences according to the California Department of Public Health.⁷⁴ There are potential risks from chlorinated swimming pools including cancer and asthma among swimmers. Thus, there is a need to find approaches for controlling hazardous substances in swimming pools. Manasfi et al,⁷⁵ evaluated some NDMA precursors and their adverse health effects upon human exposure. From their study, epidemiologic studies showed that exposure to these DBPs has adverse effects on respiration and they may

cause bladder cancer. There are also indications that trichloramine from swimming pools facilitates the occurrence of asthma in swimmers.⁷⁶ This respiratory health problem, they asserted, is as a result of accidental exposure to chlorine by swimmers.

Although these disinfectants reduce the microbial pathogen growth in swimming pools, they interact with natural organic matter and organic micro-pollutants excreted in the pools by swimmers forming hazardous compounds as disinfection by-products (DBPs).⁷⁷ These hazardous compounds or teratogenic and embryopathy organic substances in swimming pools are known to be highly carcinogenic to the bladder tissues and are biomarkers of bladder cancer in humans. They can be generated from the reaction of nitrosating agents and secondary amines. Sanagi et al⁷⁸ reported that nitrosamines are metabolically triggered via interactions with cytochrome-P450 enzymes and they exert their carcinogenic properties in the human body as shown in the schematic diagram. Weisel et al 2009⁷⁹ and Walse and Mitch³² found NDMA in swimming pools to be most abundant and the epidemiological results suggested a link between nitrosamine in swimming pools and bladder cancer. In the reports by Moore et al⁸⁰ and Davis et al,⁸¹ nitrosamines were indicator biomarkers of bladder cancer in human and carcinogenic bladder tissue. Furthermore, the study of Tardif et al⁶⁰ revealed the presence of NDMA contaminants in swimming pool water, indicating the high potential of health risk to workers and bathers.

Conclusions and Suggestion

A review of the occurrence and existence of NDMA in swimming pool water has been presented in this review and some negative impacts of the nitrogenous disinfectant byproducts are highlighted. NDMA is a human carcinogen and its formation is triggered by the activities of swimmers such as the introduction of their sweats or other body fluids, lotions, and urine. However, information on the existence and degradation of NDMA in swimming pool water is still relatively scanty. Therefore, there is a need for the development of techniques for monitoring, assessing, and removing this potentially toxic nitrogenous compound from swimming pools.

The quantification of NDMA in swimming pools is challenging and this has become a serious issue noticed globally. Numerous studies have focused on the detection and control of NDMA in drinking water and industrial effluents. The gap analysis in the review of NDMA, exposure to it, and the human health effect needs to be critically evaluated. These are some suggestions about future work that should be done to evaluate and control NDMA in swimming pools.

- The identification and quantification of NDMA in swimming pools should be conducted on swimming pools that have undergone full-scale advanced treatments at the pilot and bench scale.
- Better understanding and assessment of the integration of analytical tools in water samples from indoor and outdoor pools should be checked to facilitate good management practices. This approach will help to remove NDMA and its precursors from disinfected swimming pools.
- The release of nitrogenous DBPs via used cosmetics, urine, skin, and hair lotions by swimmers should be addressed. There should be rules and regulations requiring showering by swimmers and pool attendants before they enter the pool. This policy will reduce organic and inorganic water toxicity, DBPs formation, and exposure of swimmers to NDMA.

Author Contributions

SM drafted the article critically for important intellectual content. All authors substantially contributed to the conception and design of the article and interpreting the relevant literature.

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