

N-NITROSO COMPOUNDS : ENVIRONMENTAL CARCINOGENS

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Abstract

N-nitroso compounds are present in environmental media including in food. Although the concentrations found are in notably low range, the carcinogenic action of these compounds in experimental animals have been shown to occur in many different organs. Most of them are positively mutagenic in test systems. There is still inadequate quantitative and clinical data at present, but it is highly probable that *N*-nitroso compounds are carcinogenic in man. Human exposure to these carcinogens and their precursors should be kept as low as practically achievable. The information on their chemistry, formation, occurrence, toxic activity and possible evaluation of health risks to man is reviewed.

Introduction

It is now more than thirty years since one of *N*-nitroso compounds was firstly described to cause acute hepatic intoxication¹. The subsequent historic experiments of Magee and Barnes²⁻⁵ showed many cases of tumour induced by *N*-nitroso compounds in a variety of animal species. The carcinogens are widespread in various environmental media and frequently occur in industrial areas. The works on *N*-nitroso compounds have been mainly done on experimental animals or with bacterial test systems. Even though there is not much epidemiological evidence at present, it is markedly feasible that these compounds may also be carcinogenic in man. Human exposure to these potent carcinogens, and its prevention are related to health problems in all parts of the world. This article reviews the chemistry, synthesis, common sources, toxicity, mutagenic activity of these compounds, and briefly examines the effects and evaluation of health hazards to man.

Chemistry and Formation

The chemistry of *N*-nitroso compounds have been widely studied^{6,7}. They have a general structure as shown below (1).



The *N*-nitroso compounds are divided into two classes with different chemical properties: firstly, *nitrosamines*, derived from dialkyl, alkaryl, diaryl, or cyclic secondary amines,

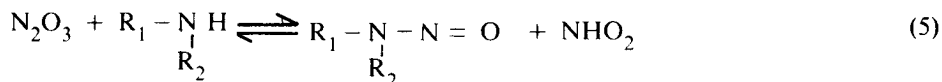
where R_1 and R_2 are alkyl or aryl groups ; and secondly, *nitrosamides*, derived from *N*-alkylureas, *N*-alkylcarbamates, and simple *N*-alkylamides, where R_1 is an alkyl or aryl group and R_2 is an acyl group⁶.

Nitrosamines are generally stable compounds which are slowly decomposed in light or in aqueous acid solutions. In contrast, nitrosamides are much less stable in aqueous acid and unstable in basic solutions. The physical properties of *N*-nitroso compounds widely vary depending upon the substituent groups in their molecular structures^{8,9}. For instance, dimethylnitrosamine or *N*-nitrosodimethylamine (NDMA) is oily liquid miscible with polar solvents. Some are solids, e.g. diphenylnitrosamine, or *N*-nitroso-*N*-phenylbenzenamine, is slightly soluble in ethanol and insoluble in water. Nitrosamines show ultraviolet absorption peaks in aqueous solution at 230-240 nm and 330-350 nm, nitrosamides absorb in the long wave-length region at 390-420 nm⁶.

N-nitroso compounds are formed by chemical reactions between nitrosating agents and nitrosatable amines. In most cases, the nitrosating agent which participates in *N*-nitroso compound formation is nitrous anhydride (N_2O_3). Nitrous anhydride readily forms from nitrite (NO_2^-) in aqueous acidic solutions as described in equation (2) to (4) as follows :



Nitrous anhydride reacts with the unshared pair of electrons on unprotonated nitrosatable amines, especially secondary amines to form *N*-nitroso compounds as indicated in equation (5), the reaction is called *N*-nitrosation.



The reaction rate is governed by the total amounts of amine and nitrite as shown in equation (6) and it is also pH dependent. The optimal pH for nitrosation of most basic secondary amines is between 2.5 and 3.5. This is due to the counteracting effects of acidity on the concentration of unprotonated amine and of nitrous anhydride^{6,10}

$$\text{Rate} = k_1 [\text{Amine}] [\text{Nitrite}]^2 \quad (6)$$

Nitrosation can be influenced by a number of accelerators and inhibitors¹¹⁻¹⁴. Several nucleophilic or anionic salts, for instances, nitrosyl iodide (I-NO) and nitrosyl thiocyanate (SCN-NO) can form effective nitrosating agents when they are present with nitrite in aqueous and acidic solutions. Enhanced nitrosation of lipophilic secondary amines has been demonstrated in aqueous systems containing micelles and some carbonyl

compounds^{15,16}. Ascorbic acid, sulfur dioxide, α -tocopherol, and gallic acid inhibited the *N*-nitroso compound formation in certain conditions¹⁷⁻¹⁹. It should be noted that ascorbic acid is required in the manufacture of bacon in many countries. The role of ascorbic acid is to reduce nitrous anhydride to nitric oxide (NO) in the absence of catalysts as described in equation (7). Since nitric oxide, a nonnitrosating agent can be reoxidized to nitrogen dioxide, ascorbic acid has to be added into the system in excess²⁰.



Investigation of nitrosatable precursors or model compounds has shown that nitrosation reaction with nitrosating agents does not occur only *in vitro*. *In vivo* formation of *N*-nitroso compounds has been also found under similar conditions in both short-term and long-term experiments^{6,20,21-23}. Scheunig and Ziebarth²² reported that the quantity of amine drugs in the nitrosation in human stomach was equal to the maximally tolerated single dose and a nitrite level corresponding to the amount most likely to be ingested in a single day. It was observed that under conditions of very limited levels of amino drugs, yields of *N*-nitroso compounds and their derivatives are nondetectable. Essential information has been gained regarding the occurrence and identification of reactants, reaction kinetics, and influencing factors to *N*-nitrosation phenomena. In 1978, the WHO Study Group on carcinogenicity of nitrosatable drugs including other nitrosatable amino compounds established the standard conditions criteria as followings : concentrations of drugs and nitrite, reaction time, reaction temperature, and acid-base condition. These criteria were applied as a means of obtaining comparable nitrosation data, and of ranking of potentially nitrosatable compounds. With regard to the significance of nitrosatable amino compounds including drugs and nitrite-induced carcinogenesis in man, none of the drugs that are markedly nitrosated *in vivo* is known. Recently, studies related to the endogenous nitrosation reactions were made in animal and human experiments²⁴⁻²⁶. In a dose-response study on the *in vivo* formation in rats, estimations were carried out with a kinetic model using published data on nitrosation and carcinogenic activity of some selected *N*-nitroso compounds. In addition, the endogenous formation of carcinogenic *N*-nitroso compounds was readily monitored by measuring the amount of particular compounds, especially *N*-nitroproline (NPRO) excreted in urine and feces, since NPRO is almost completely excreted^{24,27}.

Environmental Occurrence

The occurrence of *N*-nitroso compounds in urban air was reported eight years ago at a wide range of concentration 0.02-0.96 ppb^{28,29}. These compounds are present in air presumably due to industrial omissions either or due to their formation from secondary amines and nitrogenous oxides. There are very few reports on the occurrence of *N*-nitroso compounds in water. In 1976, Fine and his coworkers²⁹ analyzed water samples from the

Mississippi River and from water treatment plants by using the new techniques. The estimated concentrations were about 0.1 µg/kg on average, and these levels should belong to *N*-nitroso derivatives of some pesticides. Since precursors for production of *N*-nitroso compounds occur in tobacco, it was thought that tobacco and tobacco smoke might contain trace amounts of these compounds^{30,31}.

Numerous determinations of *N*-nitroso compounds have been made in a variety of foods from various countries^{20,32-42}. The great majority of the investigations list volatile nitrosamine levels in cured meats, dairy products, fish, whiskey, and beer. The methods employed for analysis mainly involved gas chromatography. Some results were confirmed by mass-spectroscopic techniques, which are now increasingly employed. A summary of reported occurrences of *N*-nitroso compounds in foods, adapted from Sen³⁴ and Scanlan²⁰ is presented in Table 1. The nitrosation reaction is readily affected under the conditions in which various amines, amino acids, proteins and other food constituents can react with nitrite in food systems^{20,43}. The accelerators and inhibitors which may be present in certain foods possibly play an important role in this particular reaction^{11,12,20}. Obviously, the formation of *N*-nitroso compounds in foods is influenced by a variety of parameters such as pH, temperature, time during the processing, cooking, or storing of foods, thus making it difficult to predict the extent to which these compounds might be produced^{20,44-46}.

Moreover, since a number of drugs and some pesticides are tertiary amines, volatile nitrosamines have been produced by nitrosation reaction under defined conditions^{6,23,47,48}. *N*-nitroso compounds, especially nitrosamines, have been also determined in industrial environments, oesophagus, dish washer, cutting fluids including rubber baby bottle, rubber nipples and pacifiers⁴⁹⁻⁵³. It was reported that a portion of those volatile nitrosamines could migrate from the rubber nipples into the baby's milk in the bottle upon overnight storage.

TABLE 1. LEVELS OF *N*-NITROSO COMPOUNDS IN VARIOUS FOODS.

Foods	Country	N-nitroso compounds found	Level (µg/kg)
Dry sausage	Canada	NDMA	10-20
Salami sausage (uncooked)	Canada	NDMA	20-80
Bacon	Canada	NPYR	4-25
Bacon	Canada	NPYR	25-40
Bacon	Netherlands	NDMA	0.8
Bacon	Netherlands	NPYR	0.4
Bacon	Netherlands	NPIP	0.6
Smoked meat	Netherlands	NDMA	3.0
Smoked meat	Netherlands	NDEA	7.91
Cooked ham	Netherlands	NDMA	6.0
Bologna sausage	Canada	NDEA	25.0
Bologna sausage	Canada	NPYR	20-105
Fish meal	Canada	NDMA	0.35-0.50
Smoked or salted fish (uncooked)	UK	NDMA	1-9
Salted white herring	Hong Kong	NDMA	40-100
Salted yellow croakers	Hong Kong	NDMA	10-60
Beer	USA	NDMA	1.5
Beer	Canada	NDMA	1.5
Nonfat dry milk	USA	NDMA	0.3-0.7

NDMA : *N*-nitrosodimethylamineNPYR : *N*-nitrosopyrrolidineNPIP : *N*-nitrosopiperidineNDEA : *N*-nitrosodiethylamine**Experimental Studies on Toxicity, Carcinogenicity and Mutagenicity***Acute toxicity study*

The toxicity of this class of compounds is not of great significance⁴⁵, and there is no good correlation between acute toxicity and carcinogenic potential of *N*-nitroso compounds. It was firstly reported that *N*-nitrosodimethylamine at 20-40 mg/kg body

weight given to rats, dogs, rabbits, and guinea pigs produced severe hepatic damage¹. A single dose of this compound orally administered to rats, or by intravenous, intraperitoneal or subcutaneous injection, produced centrilobular necrosis accompanied by haemorrhages in the liver. The centrilobular and mid-zonal regions of liver cells became pale, and the cytoplasm then became amorphous and vacuolated; the nuclei were pale and irregular in outline. The cells were necrotic and confluent areas became haemorrhagic by 24 hours, it was generally enhanced after 48 hours but after 72 hours the

TABLE 2 LOCALIZATION OF CANCERS INDUCED BY *N*-NITROSO COMPOUNDS-
IN RATS^a

Target organ	Number of <i>N</i> -nitroso compounds affecting target organ	
	Nitrosamines	Nitrosamides
Liver	35	2
Oesophagus-pharynx	32	3
Nasal cavities	18	—
Respiratory tract	10	1
Kidney	8	9
Tongue	8	—
Forestomach	7	11
Bladder	4	1
Central and peripheral nervous system	2	9
Ear duct	2	1
Testis	1	1
Ovary	1	2
Mammary glands	1	1
Intestine	—	7
Glandular stomach	—	6
Skin	—	3
Jaw	—	1
Uterus	—	2
Vagina	—	1
Haemopoietic system	—	2

^a Adapted from ref. 56.

recovery process had started and was almost complete in 3 weeks^{1,3}. Pathological and biochemical changes in the liver of a number of animal species have been observed ; the main effect is to inhibit protein synthesis which might be a result of an accelerated degradation of messenger ribonucleic acid (mRNA)^{4,54}. However, the acute toxicity of *N*-nitroso compounds is widely varied; some were mildly toxic while others pronounced highly destructive lesions of target organs^{4,23,55}.

Carcinogenicity

The carcinogenic activity of *N*-nitroso compounds has been studied by Magee and his colleagues^{4,54}. Several animal species including mammals, amphibians, avians, and fishes have been demonstrated to be susceptible to the carcinogenic action of nitrosamines. These compounds have been introduced in rats: not less than 80 percent of them have proved to be carcinogenic⁵⁶. *N*-nitroso compounds show an obvious organ specificity as shown in Table 2. Nitrosamines produce a carcinogenic effect in the liver, oesophagus, kidney, and respiratory system, whereas nitrosamides mainly affect the gastro-intestinal tract organs, and central and peripheral nervous systems. In addition, nitrosamines exert their adverse biological activities after being metabolically activated by microsomal mixed function oxidases to form reactive intermediates. The importance of hydroxylation of the α -position of nitrosamines is demonstrated by study with diphenylnitrosamines⁵⁴.

The biochemical mechanisms of carcinogenesis produced by *N*-nitroso compounds have been extensively studied by a number of investigators^{4,54,57-59}. In early studies, it was suggested that the mechanism of carcinogenic action involved the alkylation of the 7 position of guanine base in nucleic acid. An important further finding of O'Conner and his coworkers⁵⁹ was that O⁶-alkylation of deoxyguanosine was the significant site reaction. The amount of methylation at the O⁶-position of guanine DNA isolated from animals treated with *N*-nitrosodimethylamine (NDMA) was estimated at approximately 4-6 percent of methylation. The O⁶-methylguanine was lost from DNA with a half life of about 13 hours. It was demonstrated that the excision of the abnormal components of DNA, and the unstable acid-labile products might be important in hepatic carcinogenesis. Events leading to the cancer development were presumably related to the efficiency of the cellular excision system for such certain alkylation products rather than to the level of alkylation at a particular site.

Mutagenicity.

The early investigation of mutagenic activity of *N*-nitroso compounds was made by using *Neurospora crassa* as a genetic indicator⁶⁰. More recently, the mutagenic effect of this class of compounds was assayed by mutation in *Salmonella typhimurium*. It was found that the metabolic activation would be essentially required for the test system^{4,53,61}. The development of this screening test system was established with many bacterial tester

strains since last decade by Ames's group⁶²⁻⁶⁷. Ames's method has been widely introduced in a great number of laboratories for detection the carcinogens as mutagens⁶⁸⁻⁷⁰. The mutagenicity of nitrosamines could not be tested with bacteria and liver preparation in an over-layer agar, even though those substances could be detected in a liquid system^{68,71-74}. Yahagi and his associates⁷⁵ therefore developed a new technique by combining the Ames's standard test with the liquid method. In this modification, the specific strains of *Salmonella typhimurium* and test chemical were preincubated with liver microsomes at 25°C for 20 minutes, and then the mixture poured onto a plate containing a limited amount of L-histidine. Yahagi's technique is simple, economical, reliable and more sensitive for detecting nitrosamines, and has been applied by a large group of investigators^{68,69,76-85}.

In general, *N*-nitroso compounds have proved relatively active in liquid pre-incubation assay system⁷⁵, and high concentration is required for some certain nitrosamines. Their mutagenic activity is dependent on metabolic activation, and acid-base condition, being enhanced in weakly acidic mixture solution^{81,86}. Even though many *N*-nitrosamines show a good qualitative correlation between mutagenicity and carcinogenicity, there are several important exceptions. Potency correlations between mutagenesis and carcinogenesis of these particular carcinogens are also dependent upon their chemical structure⁸³⁻⁸⁵. Thus, the activity correlations may only be used as the semi-quantitative indication for *N*-nitroso compounds.

Exposure of Humans and Evaluation of Health Risks

The levels of *N*-nitroso compounds in the environment including in diet, and determination of the risk of human exposure to these carcinogenic substances have been investigated in several countries^{69, 87-92}. Even though the epidemiology of cancer in various target organs has been reported that the availability of clinical data is not adequate to illustrate the relationship with exposure to *N*-nitroso compounds or their possible precursors such as nitrites, nitrates and nitrosatable amines occurring as environmental and food components^{20,69,87,93,94}. In addition, the US National Academy of Science⁹⁵ has demonstrated recently the assessment of human health effects of *N*-nitroso compounds and their precursors.

Undoubtedly, more than 80 percent of over one hundred *N*-nitroso compounds have been proved to be mutagenic in test systems, and carcinogenic in a wide range of animal species, producing cancers in many organs. A dose-response relationship has been established in different experimental animals for these carcinogenic substances. As the dose is reduced, the cancer incidence decreases, the induction time for cancer increases and the life span of the animals is prolonged. From available results, it is obviously feasible that *N*-nitroso compounds are carcinogenic to man. The related precursors which can be found in the environment may also be classified as potential cancer-inducing factors.-

Additional research on *N*-nitroso compound-induced human carcinogenesis will be further required in order to clarify the role of these carcinogens in the etiology of human cancers. However, present knowledge of *N*-nitroso compounds and an understanding of their mechanism of action suffice to warrant precaution toward their potential effects.

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บทคัดย่อ

เอ็น-ไนโตรโซ เป็นกลุ่มของสารประกอบที่พบได้ในสิ่งแวดล้อมทั่วไป รวมทั้งในอาหาร ถึงแม้ว่าเราจะพบสารประกอบกลุ่มนี้ในปริมาณที่ค่อนข้างน้อยก็ตาม สามารถกล่าวได้ว่ามันออกฤทธิ์ทำให้เกิดมะเร็งในอวัยวะต่าง ๆ ของสัตว์ทดลองหลายชนิด และเมื่อนำไปตรวจวัดผลการกลายพันธุ์โดยอาศัยแบคทีรี พบว่าส่วนใหญ่ได้ผลดีเช่นกัน ในปัจจุบันเราค้นพบข้อมูลเชิงปริมาณ และเชิงการแพทย์ยังไม่มากเพียงพอ แต่เราก็มั่นใจว่าสารประกอบกลุ่มนี้สามารถมีผลต่อการก่อมะเร็งในคนเราได้ด้วย ดังนั้นคนเราควรตระหนักถึงอันตรายของสารก่อมะเร็งประเภทนี้ และพึงระมัดระวังมิให้รับสารพิษกลุ่มนี้เข้าสู่ร่างกายมากที่สุดเท่าที่จะกระทำได้ ด้วยเหตุนี้ผู้เขียนจึงใคร่ขอเสนอความรู้เกี่ยวกับกลุ่มสารเอ็น-ไนโตรโซมาเรียบเรียงไว้ในแง่ต่าง ๆ ตามลำดับดังต่อไปนี้ เคมี, การสังเคราะห์, แหล่งที่พบ, ความเป็นพิษ, ปริมาณที่คาดว่าร่างกายคนเราอาจจะได้รับ และผลกระทบต่อสุขภาพพลานามัย