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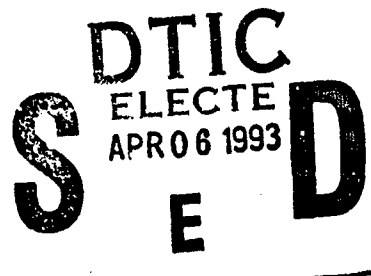
STRUCTURE-ACTIVITY COMPARISON OF HYDRAZINE TO OTHER NASOTOXIC CHEMICALS

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TECHNICAL REVIEW AND APPROVAL

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The experiments reported herein were conducted according to the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER



JAMES N. McDOUGAL, Lt Col, USAF, BSC
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PREFACE

This document serves as a technical report describing the results of a literature search for information regarding the biotransformation of chemicals that were found to produce either nasal tumors or changes in nasal epithelial tissue when tested in 2-year bioassays by the National Toxicology Program (NTP). The research described herein began in August 1991 and was completed in October 1991. It was performed under Department of the Air Force Contract No. F33615-90-C-0532 (Study No. F16). Lt Col James N. McDougal served as the Contract Technical Monitor for the Toxicology Division, Occupational and Environmental Health Directorate, Armstrong Laboratory, located at Wright-Patterson Air Force Base, OH.

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INTRODUCTION

Most of the classic organic carcinogens are classified as DNA-reactive, or genotoxic. This category includes chemicals that chemically react with DNA to form adducts. Biotransformation may not be required for the chemical to bind to DNA (activation-independent), but the vast majority of chemical carcinogens in the environment must first be activated by enzymes to reactive intermediates that can bind to DNA (activation-dependent). Activation-independent carcinogens usually produce tumors at the site of administration but activation-dependent carcinogens produce their effects in tissues where metabolic activation occurs.

A second category of carcinogens are those classified as epigenetic. These carcinogens include those that lack evidence of interaction with genetic material. The mechanisms involved in the production of tumors by these agents may involve chronic tissue injury and cell proliferation, generation of reactive species, immunosuppressive effects, hormonal imbalances, blocks in differentiation, breakage of gap junctions, or promotion of preexisting genetically altered cells. Although a single exposure to a low dose of a genotoxic carcinogen may be sufficient to produce tumors, epigenetic carcinogens require sustained exposure to high doses before any carcinogenic effects can be observed.

The active species involved in the interaction with DNA was identified by Miller and Miller (1981) as either an electrophile or radical cation. An electrophile is deficient in electrons and can form covalent bonds with tissue nucleophiles that have electrons to share. Electrophilic species include carbonium ions, nitrenium ions, free radicals, diazonium ions, epoxides, aziridinium ions, episulfonium ions, strained lactones, sulfonates, halo ethers, and enals (Williams and Weisburger, 1991). The effectiveness of such chemicals depends on the differences in the interaction between the chemical and DNA, reactions with other cellular nucleophiles, and competing enzymatic biotransformation reactions. In the case of most activation-dependent carcinogens, bioactivation is mediated by mixed function oxidases that are part of the cytochrome P₄₅₀ enzyme system of the endoplasmic reticulum. Such reactions result in the formation of intermediates that contain these reactive functional groups; however, in some cases subsequent conjugation reactions are required for activation.

The purpose of this report is to compare the biotransformation of several chemicals that have caused nasal epithelial toxicity in long-term carcinogenesis experiments in laboratory rodents, with the biotransformation of hydrazine (HZ), in order to determine if these chemicals share common metabolic pathways with HZ. The list of chemicals to be examined includes the following: 1,3-butadiene (BTD), 1,2-epoxybutane (EB), 1,2-propylene oxide (PO), naphthalene (NPT), vinyl

1,2-dibromoethane (DBE), 1,2-dibromo-3-chloropropane (DBCP), monochloroacetic acid (MCA), 2-chlorobenzalmalononitrile (CS), *p*-cresol and mixed cresol isomers, methyl methacrylate (MMA), 1,4-dioxane (DX), titanocene dichloride (TD), tetranitromethane (TNM), 2,6-xylydine (XL), and *p*-cresidine. These chemicals were obtained from the carcinogenicity data base of the National Toxicology Program (NTP). The biotransformation of HZ as it relates to its toxic effects will be presented first.

LITERATURE REVIEW

Hydrazine

Hydrazine is widely used in industry and is used by the military as a rocket fuel. It has been shown to be the metabolite of isoniazid and hydralazine (Blair et al., 1984). Hydrazine is acutely toxic to the liver, kidney, and central nervous system (CNS), and is necrogenic at high doses (Shank, 1981). These effects are likely caused by the metabolism of HZ to reactive intermediates that can subsequently bind to tissue nucleophiles (Mitchell et al., 1976; Nelson et al., 1976), although HZ itself is a potent reducing agent and may cause toxicity directly. In a chronic inhalation study, squamous cell carcinomas, adenocarcinomas, and squamous cell papillomas of the nasal turbinates were detected in rats exposed to the highest concentration (5.0 ppm) (MacEwen et al., 1981; Vernot, 1985). Oral administration in rats has produced both hepatocellular carcinomas and pulmonary adenocarcinomas (Severi and Biancifiori, 1968; Biancifiori, 1970). The biochemical and molecular mechanism of HZ toxicity is still not clear, but is believed to result from bioactivation by cytochrome P450.

The biotransformation of HZ is presented in Figure 1. Hydrazine is rapidly oxidized to nitrogen gas (a) and diimide (b) and is also acetylated to mono- (c) and diacetylhydrazine (d) (Dost et al., 1979; Nelson and Gordon, 1980; Springer et al., 1981). Recently Timbrell (1990) investigated the *in vitro* and *in vivo* metabolism of HZ. In this study, HZ was metabolized by rat liver microsomes, and this metabolism was inhibited by piperonyl butoxide and increased by phenobarbital. Interestingly, a second pathway believed to be responsible for the bioactivation of HZ was acetone-inducible, although further studies are required for confirmation. Shank et al. (1984) suggested that HZ and endogenous formaldehyde could form a hydrazone derivative (e) which could be oxidized to diazomethane, a known DNA alkylating agent. Although DNA alkylation could not be shown *in vivo*, *in vitro* studies clearly demonstrated that DNA alkylation by HZ required microsomal activation. Based on these studies, Shank (1987) proposed that the *in vivo* reaction of HZ and formaldehyde may be complex and that activation of this reaction product seems to require active aldehyde dehydrogenase. This activated reaction product, tetraformyltrisazine (f), has been shown to produce 4 to 5 times more 7-methylguanine and 10 times more O6-methylguanine than HZ (Shank, 1987). Although alkylation of guanine is a possible mechanism to explain the toxic effects of HZ, other studies have shown that acetylated metabolites of HZ and HZ derivatives can undergo deacetylation (Sinha, 1987). This reaction results in the formation of carbon-centered radicals that have been implicated in liver necrosis (Mitchell et al., 1976; Nelson et al., 1976) and in the binding of hydralazine and procarbazine to microsomal proteins (Streeter and Timbrell, 1983, 1985).

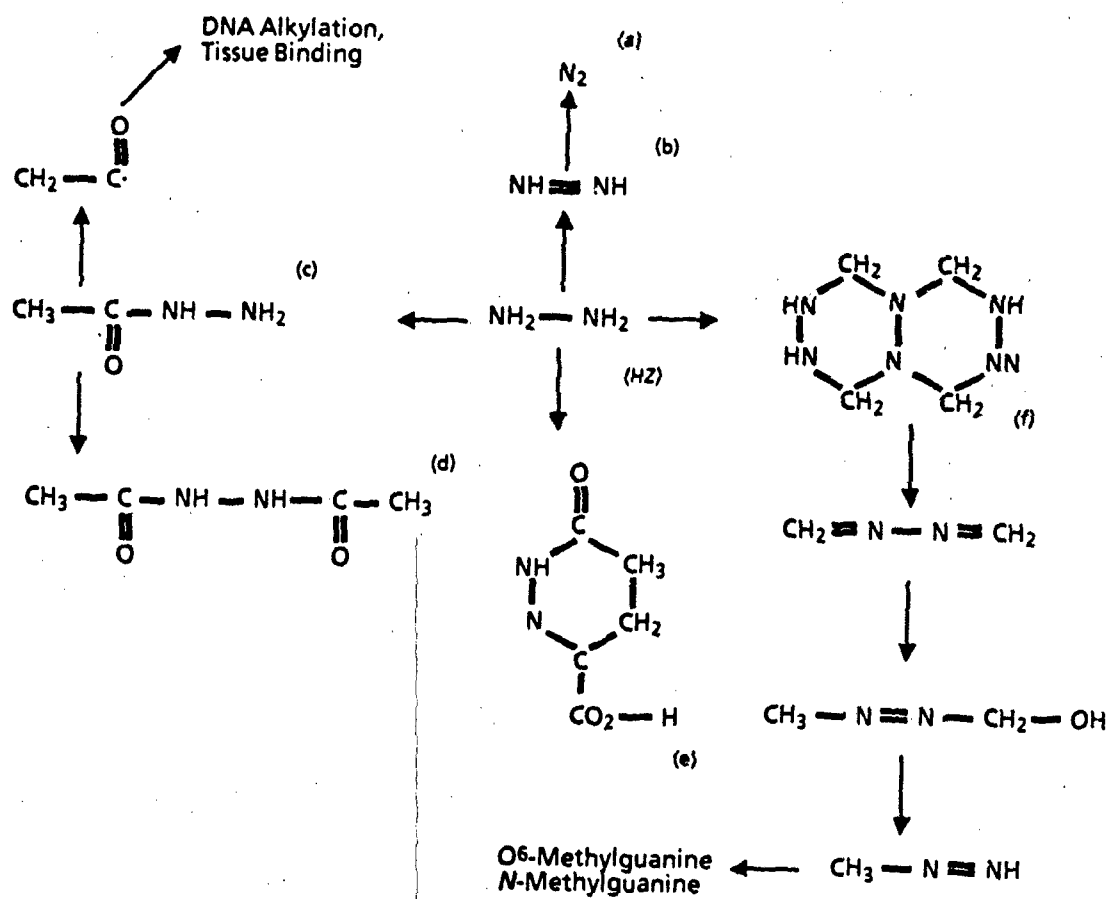


Figure 1.

EPOXIDES AND CHEMICALS THAT CAN FORM EPOXIDES DURING BIOTRANSFORMATION

1,3-Butadiene

1,3-Butadiene is an industrial chemical that is used as an intermediate in chemical synthesis, or as a monomer in the synthesis of polymers. The pathway for the biotransformation of BTB is presented in Figure 2. Incubation of BTB with microsomal enzymes has resulted in the formation of butadiene oxide (a), (Malvoisin et al., 1979). In a subsequent report, Malvoisin and Roberfroid (1982) incubated butadiene oxide with rat liver microsomes and showed that it was further metabolized to diepoxybutane (b) and 3-butene-1,2-diol (c). The latter product is further biotransformed to 3,4-epoxy-1,2-butanediol (d). Butadiene oxide has also been shown to form glutathione conjugates (Malvoisin and Roberfroid, 1982). Butadiene oxide is the major *in vivo* metabolite, and has been demonstrated in the expired breath of animals exposed to BTB at concentrations between 6000 and 7000 ppm (Boit et al., 1983).

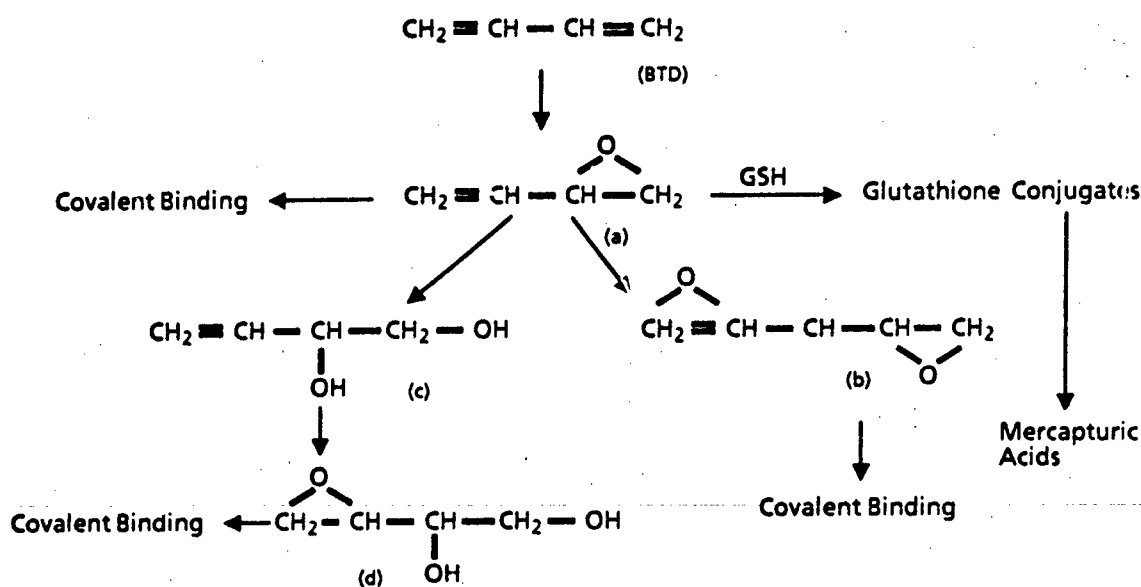


Figure 2.

Both butadiene oxide and diepoxybutane are mutagenic in the Ames test (deMeester et al., 1978) and carcinogenic in experimental animals (IARC, 1976). Intraperitoneal injection of diepoxybutane in mice resulted in a significant increase in lung tumors, whereas subcutaneous or intramuscular injection resulted in fibrosarcomas in rats and mice (IARC, 1976). Neither 3-butene-1,2-diol nor 3,4-epoxy-1,2-butanediol are mutagenic in the Ames test (Malvoisin and Roberfroid, 1982), which suggests that the epoxides are the reactive species involved in induction of carcinogenesis.

Recent long-term inhalation studies in rats (Loeser, 1982) and mice (NTP, 1984) have demonstrated that rats can survive higher BTB exposure levels than mice. The rats also demonstrated minimal toxicity and lung tumor formation when compared to mice, which suggested that rats may have less cytochrome P₄₅₀ or higher levels of epoxide hydrolase and glutathione S-transferase than mice. Further species differences have been reported by Kreiling et al. (1986) that indicated that radiolabeled BTB was covalently bound to liver DNA and that the amount was the same in both species. However, the covalent binding to mouse liver nucleoproteins was twice as high as in rats. Schmidt and Loeser (1985) have further shown that butadiene oxide formation in mouse lung homogenates was 5 to 6 times higher than in rat lung preparations. In the case of both monkey and human lung homogenates, no butadiene oxide could be detected, which is consistent with the low cytochrome P₄₅₀ levels in the lungs of both species (Lorenz et al., 1979).

1,2-Epoxybutane and 1,2-Propylene Oxide

1,2-Epoxybutane is a short-chain epoxide closely related in structure to BTB. It is used as a stabilizer in chlorinated hydrocarbon solvents, as a gasoline additive, and for the preparation of butanediols, glycol ethers and esters, and in the preparation of surfactants. 1,2-Propylene oxide is shorter than EB by one carbon. It has been used as an intermediate in the synthesis of insecticides, repellants, and synthetic resins, and has also been used as a fumigant, principally for sterilizing packaged food products. Both compounds are highly reactive, electrophilic chemicals. The biotransformation of either EB or PO has not been described in the literature. Nevertheless, metabolic pathways have been proposed for both chemicals and are presented in Figure 3.

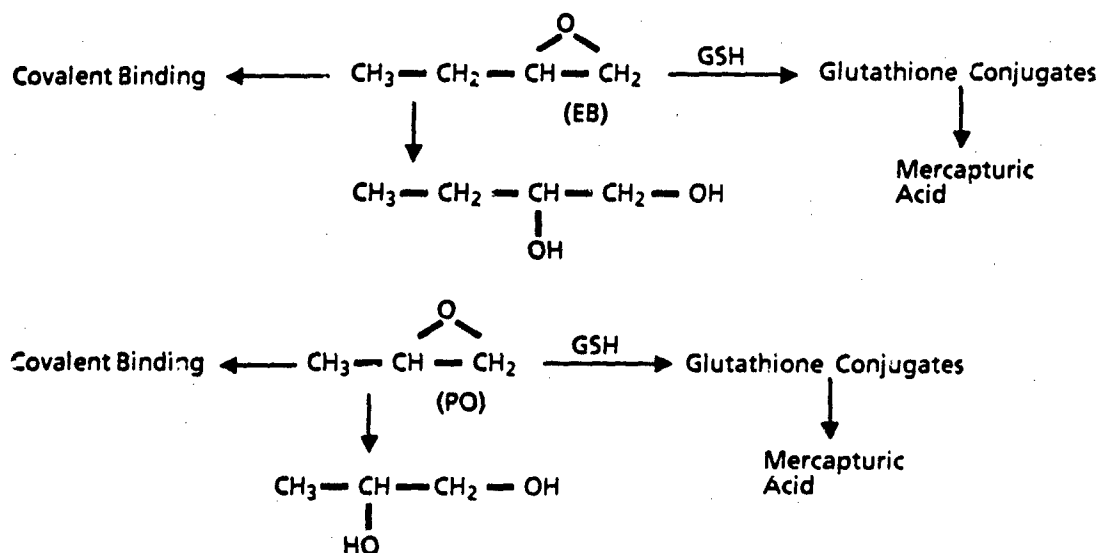


Figure 3.

Studies conducted by the NTP have shown that EB was mutagenic in the Ames test, induced mutations in mouse lymphoma cells, and induced both sister chromatid exchange and chromosomal aberrations in Chinese hamster ovary cells (NTP, 1988). Subchronic inhalation studies with EB in both rats and mice resulted in inflammatory and degenerative lesions of the nasal cavity, neoplastic lesions of the nasal cavity and the lung in male rats, and neoplastic lesions of the nasal cavity of female mice (Dunnick et al., 1988).

1,2-Propylene oxide was mutagenic to bacteria, fungi, and insects; produced DNA damage and chromosomal aberrations in cultured mammalian cells; and produced micronuclei in bone marrow cells of mice (IARC, 1985). Chromosomal aberrations and micronuclei in lymphocytes have been observed in workers exposed to PO (Hogstedt et al., 1990) and DNA adducts of PO have been produced *in vitro* (Solomon and Segal, 1989). Nasal cavity tumors, but not lung tumors, have been observed in rats and mice following inhalation exposures to PO (NTP, 1985a). 1,3-Butadiene, a compound known to be biotransformed to reactive epoxide intermediates, apparently does not cause nasal tumors, but induces tumor formations at other sites such as the lung (NTP, 1984; Huff et al., 1985). It is possible that the difference in location of the tumors may be simply due to carbon chain length differences (Dunnick et al., 1988).

Napthalene

Napthalene is a widespread environmental contaminant. Most of the NPT in industry has been used as a starting material in the synthesis of dyes and of carbaryl (an insecticide). Acute, high-dose exposures have resulted in necrosis of the nonciliated bronchiolar epithelial cells in mouse lung as well as proximal tubular cells of the mouse kidney (O'Brien et al., 1985). Napthalene was administered by inhalation in a 2-year bioassay and was shown to produce chronic inflammation of the nasal cavity, metaplasia of the olfactory epithelium, hyperplasia of the respiratory epithelium, and chronic inflammation of the lung (NTP, 1991a). This study also reported a 21% incidence of alveolar and bronchiolar adenomas at the highest exposure concentration (30 ppm). Stillwell et al. (1982) have indicated that NPT is metabolized to reactive, potentially toxic metabolites. The proposed pathway for NPT biotransformation is presented in Figure 4.

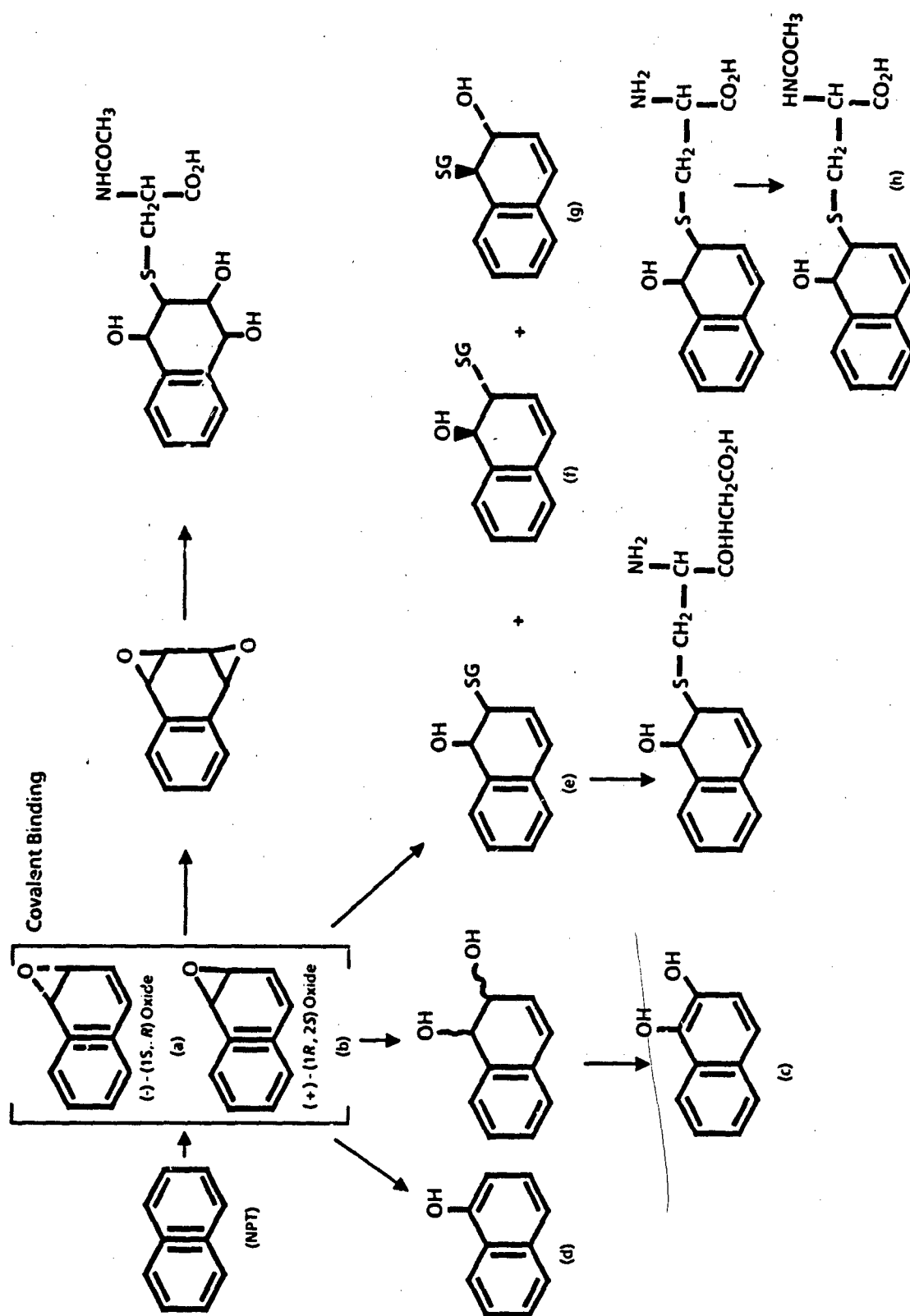


Figure 4.

In vitro studies by Buckpitt et al. (1987) have shown that a major portion of NPT oxides (a,b) generated in incubations with microsomal enzymes were either trapped as glutathione conjugates or were hydrated by the enzyme epoxide hydrolase to NPT dihydrodiol (c). Covalently bound metabolites and 1-naphthol (d) accounted for 2 and 12% of the metabolism of NPT, respectively. Incubation of NPT, glutathione, and glutathione S-transferase with pulmonary, hepatic, or renal microsomes from mouse, rat, or hamster tissues resulted in the formation of three enantiomeric glutathione conjugates (e,f,g) in all species, but substantial differences in the rates of formation of these conjugates were observed. In mouse lung preparations, the major target organ for acute toxicity in this species, the predominant NPT oxide formed was shown to be the enantiomer labeled "b" because of the glutathione conjugate that was isolated and identified (f). By contrast, no such stereoselectivity was observed in mouse liver or kidney preparations, although the rate of metabolism in kidney preparations was low.

Total rates of metabolism in the rat were lower than those in the mouse. In lung preparations, in contrast to the mouse, the other NPT oxide enantiomer (a) was formed in slight excess. This isomer was also apparently favored, in an approximate 4:1 ratio, in rat and hamster liver preparations. The data from the hamster study could not be relied upon because the dihydrodiol (c) was the major metabolite produced. The idea that the stereochemistry of epoxidation is related to tissue-selective injury resulting from NPT administration was supported by the data with mouse lung preparations. It is also possible that the toxicity of NPT is related to the inability of the mouse lung to biotransform the oxide to less reactive metabolites. Finally, the kidney toxicity observed after acute high-dose exposures may be due to the formation of mercapturic acids (h) from the glutathione conjugates. Mercapturic acids have been implicated in kidney toxicity and carcinogenesis (Monks and Lau, 1988).

Vinyl Toluene

Vinyl toluene is structurally similar to styrene and is important in the production of paints and plastics, and is also used as a solvent.

The first study that profiled the metabolism of this compound was conducted by Bergemalm-Rynell and Steen (1982), who analyzed the urine from rats that had been administered intraperitoneal (ip) injections of VT (See Figure 5). These authors concluded that the metabolism of VT was similar to that of styrene. One of the initial metabolic conversions was the formation of vinyl toluene-7,8-oxide (a); the similar pathway occurs in the case of styrene (el-Masri et al., 1958). Vinyl toluene-7,8-oxide has been shown to alkylate guanosine residues *in vitro* (Hemminki et al., 1981) and is mutagenic in bacteria and Chinese hamster V79 cells (Sugiura et al., 1978). Both VT and its epoxide metabolite induce sister chromatid exchanges in human lymphocytes (Norppa and Vainio, 1983). In spite of these findings, an *in vivo* exposure of rats to concentrations of VT ranging from 0 to 300 ppm did not produce any evidence of tumors. However, nonneoplastic lesions in the nasal cavity and metaplasia of the olfactory epithelium were observed (NTP, 1990a).

In a subsequent article, Heinonen (1984) also characterized the metabolism of VT after injecting different doses of the material ip. This study indicated that the major detoxification pathway also results in the formation of vinyltoluene-7,8-oxide, followed by glutathione conjugation. The subsequent formation of mercapturic acids from glutathione conjugates was confirmed by Kuhler (1984). This study also indicated that the other main detoxification pathway occurs via hydration of the epoxide to diols (b,c), although these metabolites only accounted for 2.5% of the injected dose. The third metabolic route that was detected in this study was the oxidation of the methyl group of VT (d), which was also considered to be a minor route in the biotransformation of VT.

Iodinated Glycerol

Iodinated glycerol is used therapeutically as a mucolytic expectorant to clear bronchiolar secretions in humans and is a source of organically bound iodine. The manufactured product is described by the patent and chemical literature as a mixture of two isomeric iodopropylideneglycerols, but a study by Cannon et al. (1989) indicated that the two principal components of the product were 3-iodo-1,2-propanediol and glycerol. The two iodopropylideneglycerols were not observed.

Two-year toxicology and carcinogenesis studies were conducted by administering IDG orally to groups of rats and mice 5 days per week for 103 weeks at doses ranging from 0 to 250 mg/kg. Under these conditions, there was some evidence for carcinogenicity in male Fisher 344 (F-344) rats because adenomas of the nasal cavity were observed in two high dose male rats (NTP, 1990b). In NTP *Salmonella* studies, IDG induced a strong dose-related increase in the number of revertant colonies, but only in those *Salmonella* mutants containing base-substitutions. No increase in revertants was observed in the frame-shift mutant strains (Zeiger et al., 1987). Epstein et al. (1972) reported that 3-iodo-1,2-propanediol did not induce dominant lethal mutations, as measured by early fetal deaths and preimplantation losses in female mice mated to males dosed with 80 mg/kg.

Hoffnagle and Osol (1958) administered 2 mg radiolabeled IDG orally and intravenously to male Wistar rats. Within 2 h, 77% of the radiolabel was absorbed intact, with little or no decomposition of IDG in the gastrointestinal tract. Within 24 h after oral administration, approximately 30 to 60% of the labeled iodine was found in the thyroid gland, the remainder was excreted in the urine and feces. Barrigon et al., (1986) administered radiolabeled IDG (284 mg) orally to human volunteers and the principal urinary product was IDG (94.8% of the dose within 48 h). 3-iodo-1,2-propanediol, the principal ingredient in IDG, was metabolized after ip administration of 100 mg/kg to male rats or 200 mg/kg to male mice (See Figure 6). In this study, two metabolites were found in the urine: S-(2,3-dihydroxypropyl)cysteine (a) and N-acetyl-S-(2,3-dihydroxypropyl)cysteine (b) (Jones, 1975). It has been proposed that the metabolism of 3-iodo-1,2-propanediol occurs through the release of iodide and the subsequent formation of the epoxide intermediate glycidol (2,3-epoxypropanol) (c), and subsequent conjugation with glutathione. The release of radiolabeled

carbon dioxide (CO₂) through glycerol formation, presumably from formation of glycidol, and subsequent metabolism supports this hypothesis (Jones, 1975). Interestingly, mutagenicity studies conducted by the NTP on glycidol show it to be positive for induction of gene mutations in *Salmonella* (Canter et al., 1986), positive for induction of trifluorothymidine resistance in mouse L5178Y/TK cells (NTP, 1990c), and positive for induction of sister chromatid exchanges and chromosomal aberrations in cultured Chinese hamster ovary cells (NTP, 1990c).

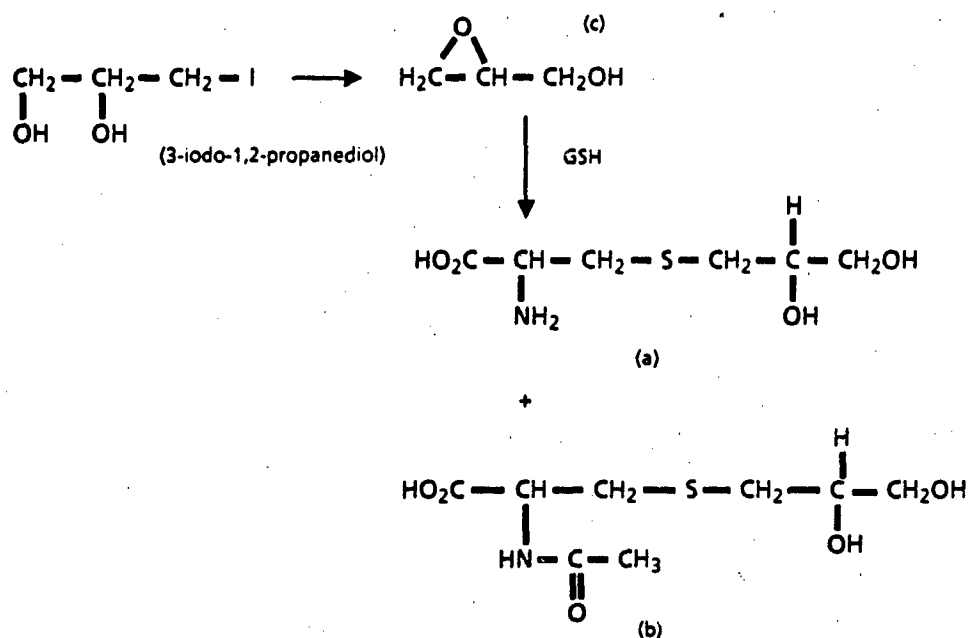


Figure 6.

Allyl Glycidyl Ether

Allyl glycidyl ether is used as a stabilizer of chlorinated compounds, vinyl resins, and rubber. It is also used as an intermediate in the synthesis of rubber. Of all the glycidyl ethers, AGE is one of the most toxic. The LD₅₀ in the rat and mouse are 1.6 and 0.39 g/kg, respectively, whereas the LC₅₀ in the rat has been reported to be 3120 mg/m³ (Hine et al., 1956). Hine et al. (1956) reported that AGE produced labored breathing and CNS depression during acute oral exposures and it has been reported to produce moderate-to-severe skin and eye irritation. During repeated exposure, these authors also reported severe toxic effects at concentrations of 600 and 900 ppm. These effects included bronchopneumonic consolidation, severe emphysema, bronchiectasis, and inflammation. In more recent studies, rats and mice were exposed to AGE at concentrations ranging up to 10 ppm for 2 years (NTP, 1990d). Under these conditions, there was equivocal evidence of carcinogenic activity based on the presence of one papillary adenoma of respiratory epithelial origin, one squamous cell carcinoma of respiratory epithelial origin, and one poorly differentiated adenocarcinoma of olfactory epithelial origin, all occurring in the nasal passages of males exposed to 10 ppm. There was no

evidence of carcinogenicity in female rats. Some evidence of carcinogenic activity was reported in male mice based on the presence of three adenomas of the respiratory epithelium, dysplasia in four males, and focal basal cell hyperplasia in the respiratory epithelium in seven males exposed to 10 ppm. There was no evidence of carcinogenicity in female mice. Allyl glycidyl ether was mutagenic in *Salmonella* both with and without activation (NTP, 1990d). Sister chromatid exchange, chromosomal aberrations, and sex-linked recessive mutations in *Drosophila* were also observed in this study.

Little is known about specific pathways for biotransformation of AGE but it seems reasonable to assume that it is metabolized in a way similar to other epoxides. The proposed metabolic pathway is presented in Figure 7. Allyl glycidyl ether can undergo hydrolysis of the epoxide group to form the corresponding diol (a) and also can form glutathione conjugates. Both the diol and the parent can undergo a subsequent epoxidation reaction to yield the epoxydiol (b) and the diepoxide (c), respectively. The epoxide rings are highly reactive and can undergo SN1-type reactions with proteins and DNA.

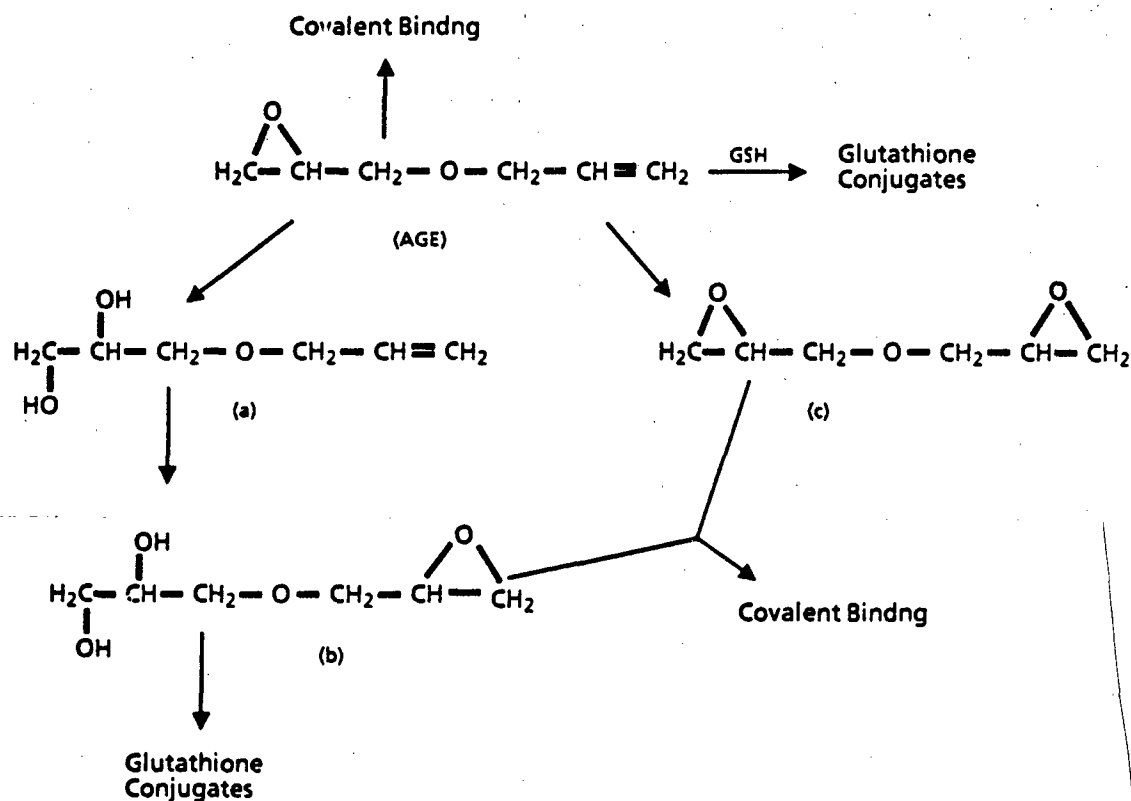


Figure 7.

HALOGENATED COMPOUNDS

Dimethyl Vinylchloride

Dimethyl vinylchloride is a structural analog of vinyl chloride, a documented human carcinogen (Maltoni and Selikoff, 1988). In a 2-year bioassay, DMVC was found to increase the incidence of neoplasms of the nasal cavity, oral cavity, esophagus, and forestomach of F-344 rats (NTP, 1985b). The metabolism (Figure 8) and disposition of DMVC revealed that mice and rats exhaled 25% of a dose of radiolabeled DMVC as CO₂ in the 24 h following administration, whereas 30% and 5% of the dose were exhaled unchanged by rats and mice, respectively. The 24-h urine of rats and mice contained 35 and 47% of the administered dose, respectively. The major urinary metabolites were cysteine and *N*-acetylcysteine conjugates (Ghanayem and Burka, 1987). The cysteine conjugate (a) was the major urinary metabolite and accounted for 23% (rat) or 35% (mouse) of the total urinary metabolites. The mercapturic acid (b) accounted for 9% (rats) and 12% (mice) of the total urinary metabolites. The nature of these metabolites indicated that DMVC was metabolized differently from vinyl chloride and other polyhalogenated ethylenes that undergo epoxidation (Henschler, 1985). Because of the presence of the methyl groups in DMVC, oxidation results in the production of E- and Z-alcohols (c,d) in a ratio of 2:1, showing that the reaction is stereoselective. This is followed by formation of an aldehyde (e,f), followed by conjugation with sulfur-containing nucleophiles and subsequent oxidation of the aldehyde functional group to a carboxylic acid (a,b).

As indicated above, approximately 30% of the administered dose of DMVC was exhaled unchanged by rats, as compared to 5% by mice. This observation may explain the presence of tumors in the nasal and oral cavity of rats but not in those of mice (NTP, 1985b). Although the mechanism is unclear, if metabolic activation is required for the initiation of these lesions, then it probably occurs in the nasal cavity. If the reactive species were generated elsewhere and eliminated via the lungs, one would not expect to see lung lesions. In the 2-year bioassay (NTP, 1985b), only 2 to 4% of nonneoplastic lesions, and no neoplastic lesions, were observed in the lungs of either mice or rats. In a subsequent study, Srinivas and Burka (1988) concluded that the reactivity of the haloenoic aldehydes makes them likely candidates for the reactive species responsible for the toxicity and carcinogenicity of DMVC.

mice, the incidence of these lesions was greatly reduced (NTP, 1982a), but the incidence of alveolar and bronchiolar adenomas and carcinomas was greater than in the rat

1,2-Dibromoethane appears to require metabolic activation to elicit its mutagenic and carcinogenic properties. Two paths can be considered for bioactivation (Figure 9). Cytochrome P₄₅₀ can produce a gem-halohydrin, which can debrominate to form 2-bromoacetaldehyde (a) (Hill et al., 1978). 2-Bromoacetaldehyde has been shown to bind to protein irreversibly (Shih and Hill, 1981) and can react with glutathione, protein thiols, or DNA (Guengerich et al., 1981). In the second possible pathway, DBE can directly react with glutathione, undergoing an internal dehydrobromination to form ethyl GSH episulfonium ion (b), which can easily react with DNA (Ozawa and Guengerich, 1983), although this has not been proven *in vivo*. Conjugation with glutathione most likely results in the mutagenic activity (Van Bladeren et al., 1981) and the DNA binding (Sundheimer et al., 1982). MacFarland et al. (1984) concluded that glutathione-dependent metabolism may occur with those tissues associated with the *in vivo* toxicity of DBE.

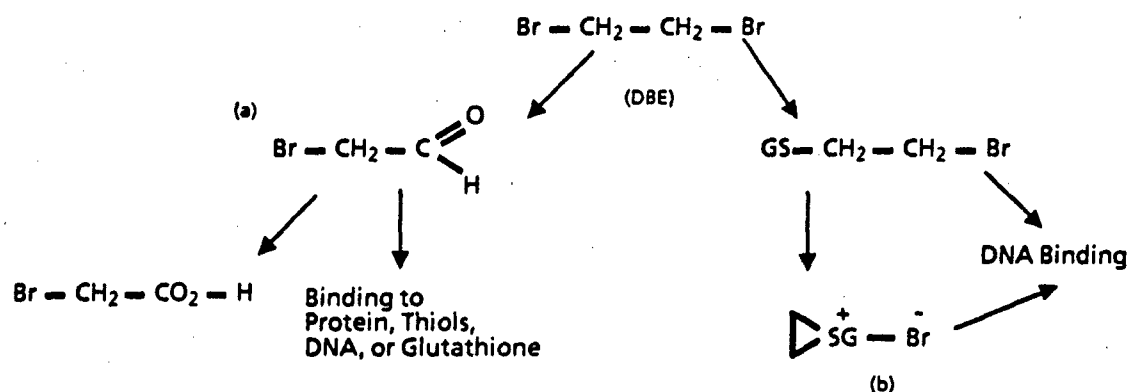


Figure 9.

1,2-Dibromo-3-chloropropane

1,2-Dibromo-3-chloropropane is used as a fumigant because of its nematocidal activity. It is both mutagenic and carcinogenic, as well as toxic to kidneys and gonads (Blum and Ames, 1977; NCI, 1980; NTP, 1982b; Kluwe et al., 1983). It has been proposed that the toxicity of DBCP is mediated by electrophilic products of metabolic activation that bind to tissue macromolecules (Kato et al., 1980; Jones et al., 1979).

The metabolism of DBCP is presented in Figure 10. A known metabolite of DBCP is 2-bromoacrylic acid (a), which can arise during oxidation of DBCP to 2-bromoacrolein (b) (Marsden and Casida, 1980). The aldehyde can then be further oxidized to the acid. 2-Bromoacrolein is a known mutagen (Segall et al., 1985). 1,2-Dibromo-3-chloropropane is metabolized to 2-bromoacrolein *in vitro* and mechanistic studies have indicated that the initial oxidative dehalogenation at C-1

followed by β -elimination of bromide was the preferred pathway of formation (Omichinski et al., 1988). Inhibitors of cytochrome P₄₅₀, addition of glutathione, or incubation of DBCP with microsomes under anaerobic conditions blocked its mutagenicity. Therefore, the formation of an episulfonium ion does not appear to be involved in the toxic mechanism of DBCP, in contrast to the metabolic pathway described for DBE (Omichinski et al., 1988). Although glutathione is not involved in the bioactivation of DBCP, MacFarland et al. (1984) have shown that glutathione-dependent debromination of DBCP occurs in cytosolic fractions prepared from a number of tissues obtained from Sprague-Dawley rats and Swiss-Webster mice.

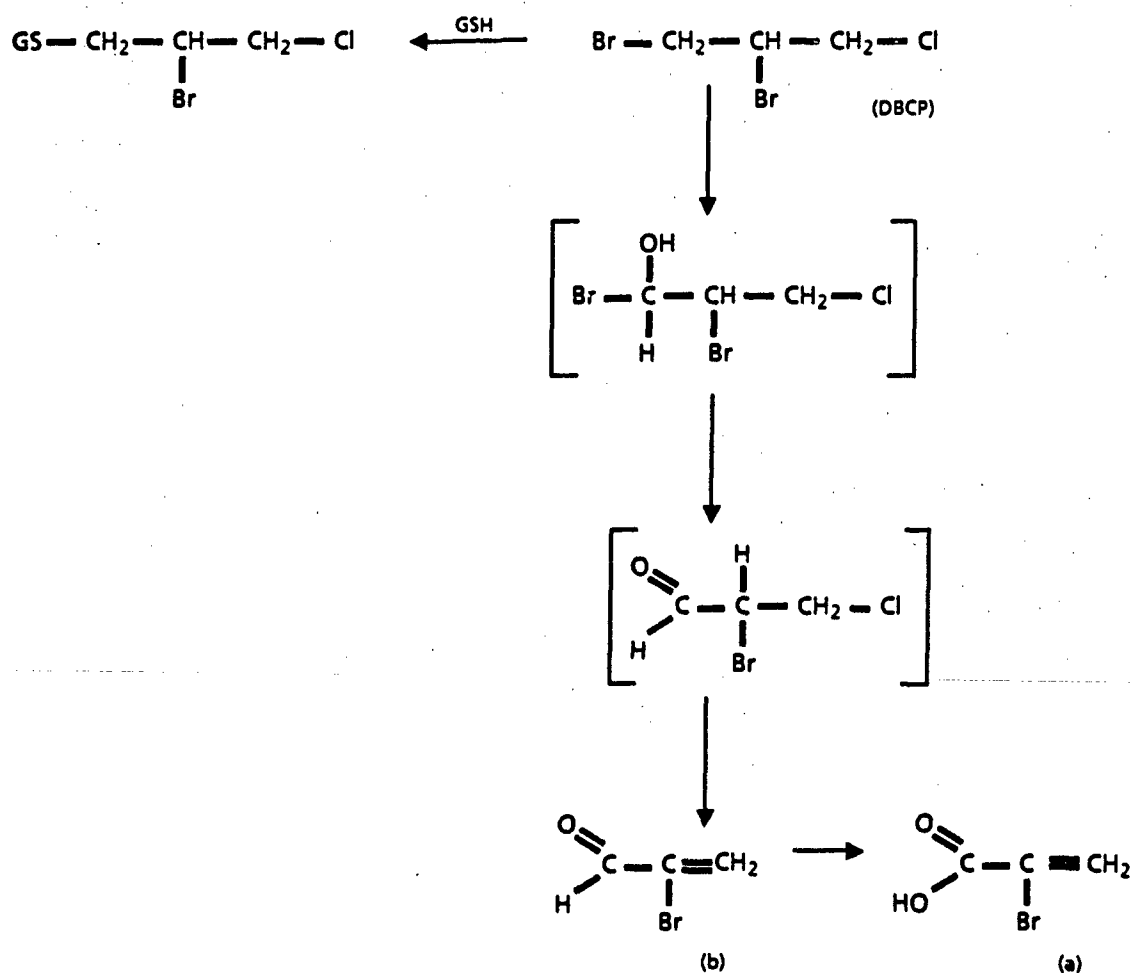


Figure 10.

Monochloroacetic Acid

Monochloroacetic acid is the monochlorinated analog of acetic acid used as a post-emergence contact herbicide, and as an intermediate in the synthesis of other organic compounds. Monochloroacetic acid is a strong irritant to the skin, eyes, and mucuous membranes of humans (Sax, 1984), and is more acutely toxic to rats and mice than are acetic acid, dichloroacetic acid, or trichloroacetic acid. Signs of toxicity in male Sprague-Dawley rats have included convulsions and respiratory depression. No exposure-related gross or microscopic lesions were observed in male rats fed diets that contained up to 0.1% MCA for 30 weeks, and there was no evidence of carcinogenic activity in either male or female rats in a 2-year bioassay (NTP, 1992a). In the same 2-year bioassay, male and female mice showed evidence of inflammation of nasal mucosa. Metaplasia of olfactory epithelium was also found in female mice.

It has been suggested that the mechanism of MCA toxicity involves the inhibition of sulfhydryl groups (Dickens, 1933; Chaiken and Smith, 1969; Hayes et al., 1973) and inhibition of acetate oxidation by uncompetitive inhibition (Hayes et al., 1972, 1973). A reduction of sulfhydryl concentration has been shown in rat liver and kidney *in vivo*, but MCA does not alkylate *in vitro* cysteine sulfhydryl groups, suggesting that MCA requires bioactivation for production of sulfhydryl-alkylating metabolites (Hayes et al., 1973).

The biotransformation pathway for MCA is presented in Figure 11. Yllner (1971) reported that 3 days following ip injection of 2 mg of radiolabeled MCA in mice, 82 to 88% of the dose was eliminated in the urine, 8% was eliminated in the expired air as CO₂, and less than 3% was eliminated in the feces; 2 to 3% of the administered dose remained in the animal. Of the radiolabel recovered in the urine, 6 to 22% was present as the parent compound. Metabolites of MCA identified in the urine included S-carboxymethylcysteine (a) (33 to 43% free and 1 to 6% conjugated), thiodiglycolic acid (b) (33 to 42%), glycolic acid (c) (3 to 5%), and oxalic acid (d) (0.1 to 0.2%). In separate experiments conducted in mice, thiodiglycolic acid was found to be the major urinary metabolite of S-carboxymethylcysteine, and glycolic acid was largely oxidized to CO₂. In Wistar rats given 50 mg/kg MCA by gavage, thiodiglycolic acid was identified as the major urinary metabolite, accounting for 60% of the administered dose (Green and Hathway, 1975). A greater percentage of administered MCA was excreted as thiodiglycolic acid in rats than in mice, most of the remainder of the dose was excreted as S-carboxymethylcysteine (Jones and Hathway, 1978).

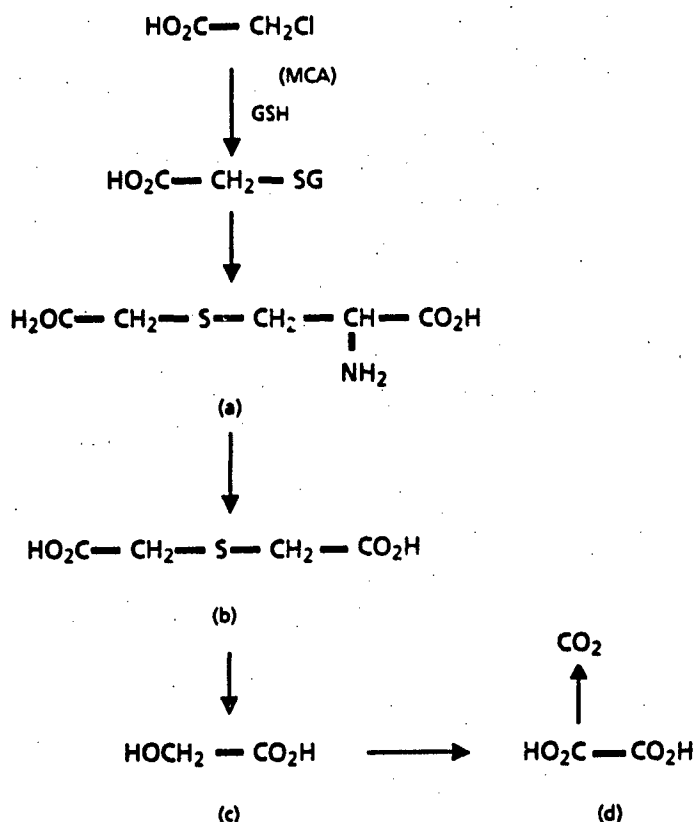


Figure 11.

2-Chlorobenzalmalononitrile

2-Chlorobenzalmalononitrile is a short-acting sensory irritant. Typical symptoms of exposure to aerosols of CS include eye irritation, excess lachrimation, burning sensation of the nose and throat, sneezing and coughing, and burning sensation of exposed skin (Ballantyne, 1977). Because of these effects, CS has been used for military purposes and for the control of civil disturbances.

2-Chlorobenzalmalononitrile is not teratogenic in either rats or rabbits (Upshall, 1973). The carcinogenic potential of CS has been assessed (McNamara et al., 1973; Marrs et al., 1983), but these studies did not use concentrations that were high enough and the exposure period was not long enough. Rats exposed to CS at concentrations of 21,000 mg/m³ showed marked congestion of alveolar capillaries, intrapulmonary hemorrhage, and excessive broncheolar and bronchial secretions. In a more recent study, rats and mice were exposed to concentrations of CS ranging from 0.075 to 1.5 mg/m³ for two years. The results of that study indicated that CS was not carcinogenic (NTP, 1991g). The only findings were inflammation of the nasal mucosa and squamous metaplasia of the olfactory epithelium. 2-Chlorobenzalmalononitrile does not bind to DNA (von Daeniken et al., 1981) and bacterial mutagenicity studies have generally been negative (Rietveld et al., 1983; Wild et

al., 1983), although positive results have been reported in mouse lymphoma tests and sister chromatid exchange assays (MacGregor et al., 1988; NTP, 1990g).

The metabolic pathway is outlined in Figure 12. 2-Chlorobenzalmalononitrile was administered to rats by both intravenous (iv) and oral routes and the greatest proportion of the dose was eliminated in the urine (Brewster et al., 1987). 2-Chlorohippuric acid (b) was produced in the greatest abundance and together with its precursor, 2-chlorobenzoic acid (c), accounted for 72% of the urinary metabolites. A minor pathway was found to occur via reduction of the olefinic side chain of CS to yield 2-chlorobenzylmalononitrile (a) followed by hydrolysis via the amide to yield 2-chloro-2-cyanopropionate (d). The finding of squamous metaplasia in the nasal cavities of rats and mice may be due to irritation effects, but the exact mechanism responsible for this effect is not understood.

MISCELLANEOUS CHEMICALS

p-Cresol and Mixed Isomers of Cresol

Cresols are monomethyl derivatives of phenol, and are natural constituents of coal, petroleum, and wood. Coal tar products containing mixed isomers of cresol are used as pharmaceutical vehicles, and industrial and agricultural uses of cresols include the production of solvents, cleaners, and phenolic resins. *p*-Cresol is an intermediate in the production of disinfectants, explosives, perfumes, metal cleaners, and synthetic flavors. *p*-Cresol, a normal constituent of human urine with levels of excretion ranging from 16 to 74 mg/24 h, is reportedly the result of tyrosine metabolism in the gut.

Information regarding acute cresol toxicity has been obtained from suicide case studies involving Lysol®, that formerly contained mixed isomers of cresol. Symptoms following ingestion of from 1 to 60 mL have included involuntary muscle movements followed by paresis, gastrointestinal disturbances, renal toxicity, initial CNS stimulation followed by depression, tachycardia, peripheral vasoconstriction, dyspnea, acute pancreatitis, and hematological changes (Chan et al., 1971; NIOSH, 1978; Harvey, 1980; Deichmann and Keplinger, 1981; Craft, 1983; Cote et al., 1984; Gosselin et al., 1984; Arena and Drew, 1986; Plunkett, 1987). Effects of local exposure can include severe skin and eye irritation, corrosive effects upon the skin and mucuous membranes, and skin depigmentation (NIOSH, 1978; Deichmann and Keplinger, 1981; Sax and Lewis, 1989). The available data have indicated that cresol isomers are not mutagenic in bacteria (Dean, 1985). Only the ortho isomer produced a significant increase in sister chromatid exchange, but the response was weak even at the highest nontoxic concentration tested (8 mM) (Cheng and Kligerman, 1984).

In a 28-day feed study of *p*-cresol and mixed cresol isomers, a dose-related hyperplasia of the nasal respiratory epithelium occurred in F-344 rats and B6C3F₁ mice of both sexes (NTP, 1992b), presumably a direct result of the irritant effects of the chemical or its vapors.

The proposed metabolic pathway for biotransformation of cresols is presented in Figure 13. Absorption of cresols from the gastrointestinal tract results in the formation of glucuronides or sulfates (Bray et al., 1950; Mandel, 1971; DeBruin, 1976a,b). These metabolites are highly ionized at physiological pH and are rapidly excreted from the kidney. In addition to urinary excretion, cresols undergo enterohepatic circulation (Deichmann and Keplinger, 1981), which is maintained by conjugate hydrolysis in the gut (Scheline, 1973). Rabbits exposed orally to cresols excreted 60 to 72% of all three isomers as glucuronides and 10 to 15% as sulfates in the urine (Bray et al., 1950; DeBruin, 1976b). Following oral administration of cresols to rabbits selective hydroxylation of *o*-cresol and *m*-cresol (3% of the dose) to 2,5-dihydroxytoluene (a) and *p*-cresol (<1% of the dose) to 3,4-dihydroxytoluene (b) was found; side chain oxidation of *p*-cresol (10% of the dose) to *p*-hydroxybenzoic acid (c) was also found (Bray et al., 1950; el-Masri et al., 1956; Hook and Smith,

1967; Kaubisch et al., 1972; Goldstein et al., 1974; DeBruin, 1976b). Hydroxybenzoic acid can then undergo conjugation with sulfates and glucuronides.

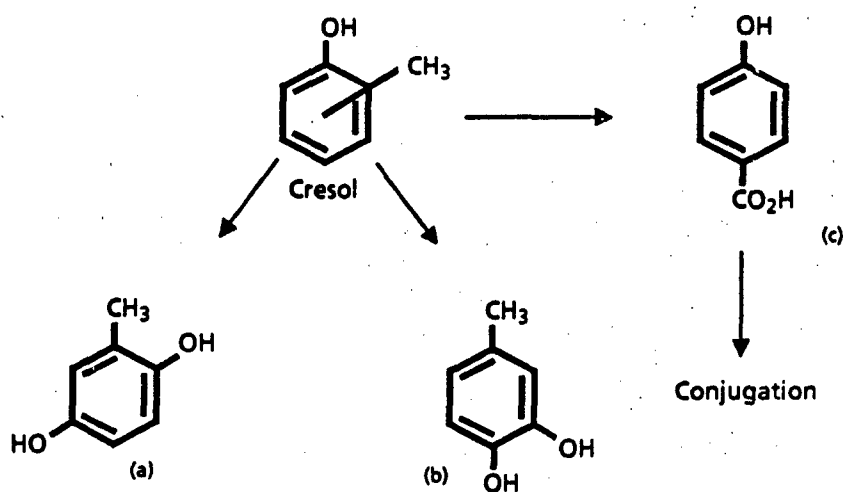


Figure 13.

Methyl Methacrylate

Methyl methacrylate is one of a number of acrylic acid esters that are the main ingredients in acrylic resins. Dermatitis, hypersensitivity, and blistering occur in humans after contact with acrylic esters (Delbressine et al., 1981). Animal experiments have shown that continuous absorption of small doses of these esters damages lungs, liver, and kidneys (Deichmann, 1941; Spealman et al., 1945; Treon et al., 1949; Autian, 1975). However, the LD₅₀ has been reported to be 5 g/kg in rats, and MMA is therefore not considered toxic in that species. Teratogenicity has been reported following ip administration (Singh et al., 1972) and an increased occurrence of sarcomas has been observed in rats following subcutaneous administration (Laskin et al., 1954; Oppenheimer et al., 1955). Methyl methacrylate was negative in the *Salmonella* reverse-mutation assay (Lijinsky and Andrews, 1980). Forward mutations to 8-azaguanine resistance was observed when cells were exposed to concentrations ranging from 50 to 100 mM but the effect was associated with high cytotoxicity (Poss et al., 1979). In cultured Chinese hamster ovary cells, MMA produced a reproducible, dose-related increase in the frequency of sister chromatid exchanges (NPT, 1986). In a 2-year inhalation study, rats and mice were exposed to MMA at concentrations ranging from 0 to 500 ppm for female rats and mice, and from 0 to 1000 ppm for male rats and mice (NTP, 1986). Rats showed inflammation of the nasal mucosa and degeneration of the olfactory sensory epithelium at the highest doses. Mice of both sexes showed an increase in inflammation, epithelial hyperplasia, and degeneration of the olfactory epithelium at 500 ppm.

Although the use of this material is widespread, few studies of the metabolism of MMA have been reported. The proposed biotransformation pathway is presented in Figure 14. A major

pathway involves carboxylesterase hydrolysis of MMA to methacrylic acid (a) (Corkill et al., 1976; Crout et al., 1979) because potentiation of MMA toxicity has been observed when the activity of carboxylesterase is inhibited (Silver and Murphy, 1978). Methyl methacrylate does not appear to involve glutathione in the process of detoxification (Hashimoto and Aldrige 1970), but Boyland and Chasseaud (1967) showed that rat liver thiol levels were reduced after ip administration, suggesting the possible formation of mercapturic acids. The isolation of mercapturic acids (b) from urine after administration of MMA to rats confirmed these findings and explains the kidney toxicity (NTP, 1986). During the biotransformation, glutathione is added to the ethylene group via a Michael addition. Methacrylic acid does not undergo this reaction (Delbressine et al., 1981), but it is detoxified by a second pathway described below. The present evidence suggests that it is unlikely that metabolism of MMA affords a DNA-reactive metabolite because the microsomal and cytoplasmic enzymes, normally involved in the bioactivation of xenobiotics, are not involved in MMA biotransformation.

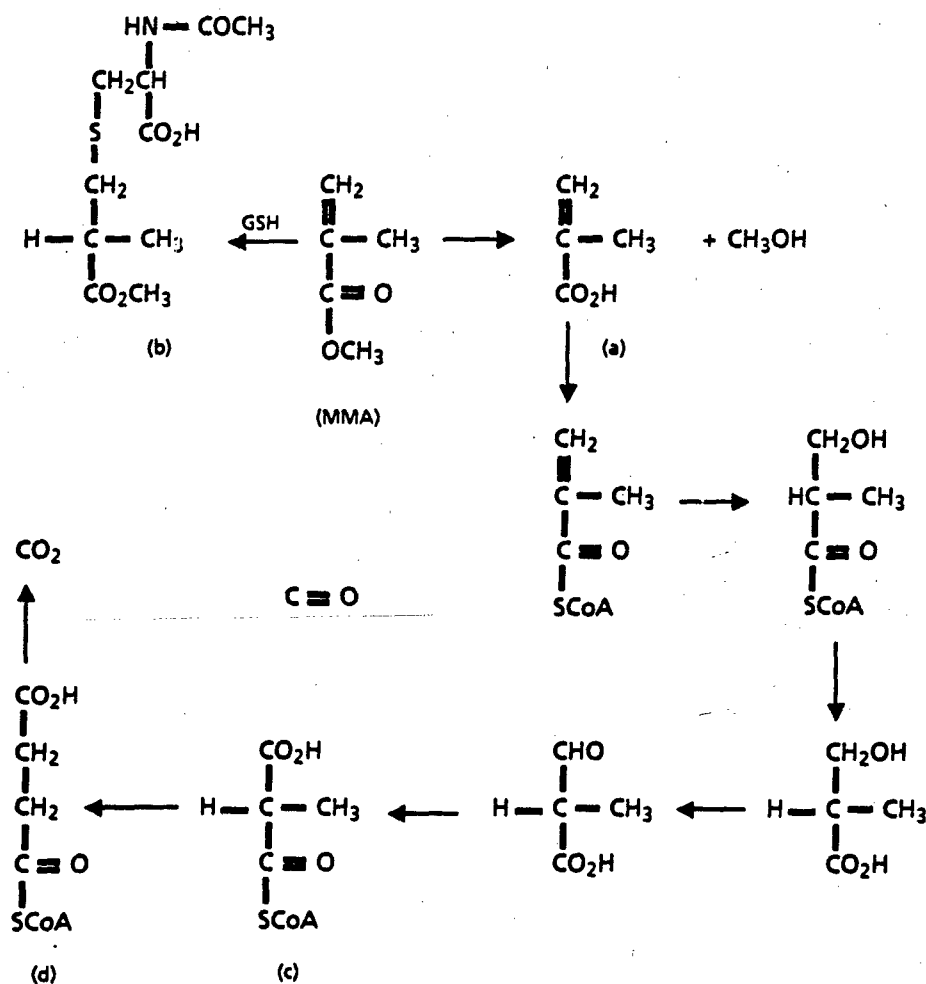


Figure 14.

When methyl(Me-¹⁴C)methacrylate was given ip to female Wistar rats, 80% of the radioactivity was eliminated as CO₂ within 10 h (Crout et al., 1982). These authors concluded that MMA was metabolized by the normal pathway for valine catabolism. In this pathway, methyl malonylCoA (c), a known intermediate in valine catabolism, was converted by methylmalonyl mutase into succinyl CoA (d), a normal substrate for the Krebs's cycle.

1,4-Dioxane

1,4-Dioxane is a cyclic diether commonly used as an industrial and laboratory solvent. Symptoms of overexposure in humans have included irritation of the upper respiratory passages, eye irritation, drowsiness, vertigo, headache, anorexia, stomach pains, nausea and vomiting, uremia, coma, and death (Andrews and Snyder, 1991). The oral LD₅₀ is high, ranging from 2 to 6 g/kg in the case of rabbits and mice, respectively. 1,4-Dioxane reportedly causes hepatomas and nasal carcinomas in rats maintained on drinking water containing 0.75 to 1.8% DX for over 13 months (Argus et al., 1965; Hoch-Ligeti et al., 1970; Argus et al., 1973). These findings were confirmed by Kociba et al. (1974) who showed that DX produced variable degrees of renal and hepatic degenerative changes when rats were given 0.1% DX; no discernible effects were noted at a concentration of 0.01% DX. Rats exposed to 111 ppm of DX for 7 h/day, 5 days/week for 2 years showed neither treatment-related toxic effects nor incidence of tumors (Torkelson et al., 1974).

The metabolism of DX is presented in Figure 15. Woo et al. (1977b) showed that metabolism of DX was significantly increased by the pretreatment of rats with inducers of cytochrome P₄₅₀, and was decreased by inhibitors of cytochrome P₄₅₀. This has suggested that the biotransformation of DX is a cytochrome P₄₅₀-mediated process. Several possible metabolic pathways can be written. Braun and Young (1977) identified α -hydroxyethoxyacetic acid (HEAA) (a) as the major metabolic product in the urine of rats. Young et al. (1976) reported that both DX and HEAA were recovered from the urine of humans exposed to 1.6 ppm for 7.5 h. Woo et al. (1977a) reported that 1,4-dioxane-2-one (b) was the major urinary metabolite of DX. 1,4-Dioxane-2-one was excreted by rats given ethylene glycol, which supports Pathway I, but the absence of ethylene glycol in the urine suggests that it is either rapidly biotransformed or that an alternative mechanism for the formation of the lactone exists. One possibility (Pathway II) is the formation of a keto-peroxy radical as an intermediate. This mechanism, similar to the mechanism of conversion of benzo[a]pyrene to benzo[a]pyrene dione (Terao et al., 1987), involves a direct attack by the radical followed by autoxidation. Compounds that are related to benzo[a]pyrene but less carcinogenic show little reactivity to lipid peroxy radicals. Another alternative route (Pathway III) has not been demonstrated but involves the hydroxylation of DX followed by the oxidation of the aldehyde intermediate.

Data on the acute toxicity of 1,4-dioxane-2-one indicates that it is considerably more toxic than the parent and may be the proximate carcinogen. This is certainly possible because lactones with similar structures, such as β -propiolactone, are known to be carcinogenic (Dickens, 1964; Van Duuren, 1969).

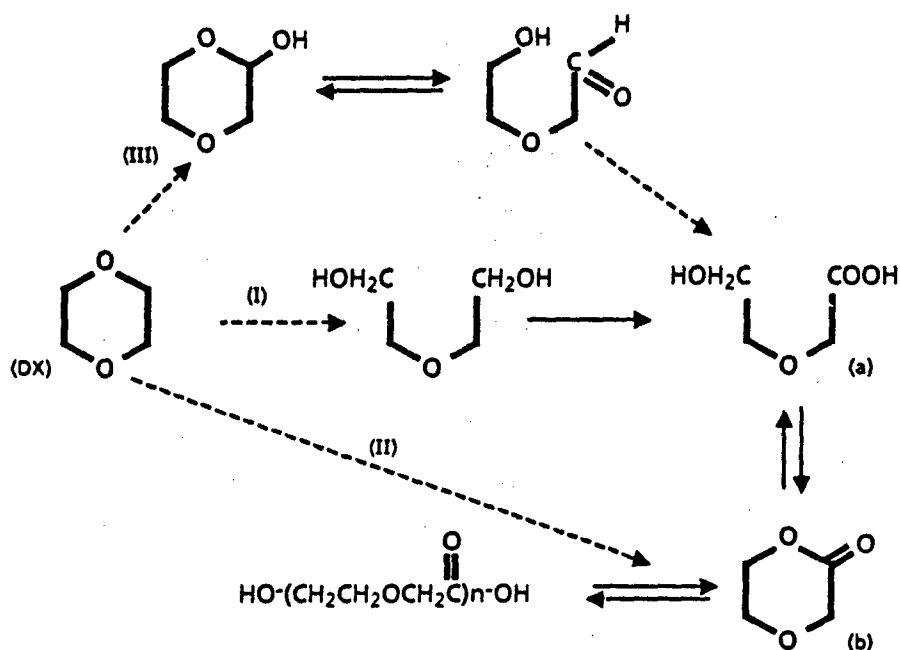


Figure 15.

Titanocene Dichloride

Titanocene dichloride is an organometallic compound composed of two cyclopentadienyl rings, titanium, and chloride. It has limited use as a cocatalyst for polymerization reactions. Transition metal complexes such as TD are representatives of a recently developed group of antitumor agents that include cisplatin.

Treatment of pregnant mice with TD at doses of 30 or 60 mg/kg was associated with an increase in the incidence of cleft palate and costal malformations, and a reduction in the number of live fetuses per litter (Kopf-Maier and Erkenwick, 1984). Injections of TD in the right thigh muscle of F-344 rats (25 injections of 8 mg) caused fibrosarcomas at the injection site, and some of the animals developed hepatomas and malignant lymphomas of the spleen (Furst and Schlauder, 1971). The chemical has induced DNA damage in mammalian cells and gene mutations in *Salmonella* (NTP, 1991b). In this report, inflammation of the nasal mucosa and the lung were observed. These findings were attributed to aspiration of lavage solution caused by the irritating effects of TD on the stomach mucosa.

The mechanism of DNA damage by TD probably involves interference with cellular nucleic acid metabolism (Kopf-Maier, 1982, 1988). Model complexes have confirmed an interaction of similar compounds with nucleic acid constituents by formation of covalent linkage or hydrogen bonding to the bases and/or phosphate groups (Toney et al., 1986; Pneumatikakis et al., 1988). Organ distribution studies have revealed that the main accumulation sites of titanium are the liver and intestine (Kopf-Maier et al., 1988). A recent study confirmed that titanium-containing metabolites of TD are able to enter cells and cell nuclei in the liver, where they first appear in the nucleolus and are then extruded into the cytoplasm for incorporation into inclusion bodies (Kopf-Maier and Martin, 1989). The information regarding metabolism is scarce, but it is likely that TD is metabolized in much the same way as cisplatin, a known chemotherapeutic agent. Cisplatin enters cells by diffusion, and once inside the cell, the chloride atoms are hydrolyzed, forming the activated drug, which can form DNA ligands. The geometry of the *cis* compound results in the chelation of the C-6 and N positions of guanine (Williams and Weisburger, 1991). The structure and biotransformation of TD is presented in Figure 16.

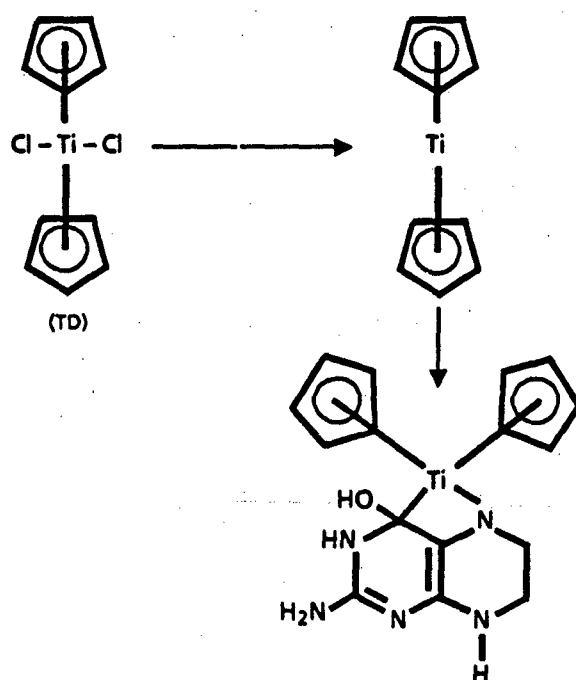


Figure 16.

Tetranitromethane

Tetranitromethane has been used as an oxidizer in rocket propellants, in explosives, and as an additive to increase the octane number of diesel fuel. It has also been used as a chemical reagent for detection of double bonds and as a mild nitrating agent because it reacts with tyrosine residues in

proteins (Riordan and Vallee, 1972). Tetranitromethane is also the principal volatile contaminant of TNT (trinitrotoluene). The signs and symptoms of TNT intoxication (caused by inhalation of fumes of crude TNM) have included nasal irritation, burning of the eyes, dyspnea, cough, tightness of the chest, and dizziness. Drowsiness, headache, cyanosis, respiratory distress, and bradycardia have been reported after prolonged exposure. Deaths have resulted from severe exposure and were attributed to respiratory failure and methemoglobinemia.

The metabolism of TNM has not been described in the literature. However, from effects seen after oral administration of the chemical, certain information can be inferred. Blood samples obtained 90 min after administration of single oral doses of TNM to Sprague-Dawley rats indicated a dose-related production of methemoglobin. That finding suggested that metabolism could include formation of nitrite ions (Kinkead et al., 1977). After iv administration or inhalation exposure, methemoglobin formation was not seen, nor was it reduced when compared with that seen after an oral exposure. This suggested that nitrate oxidase activity in the gut may be involved (Kinkead et al., 1977; Vernot et al., 1977). Little is known about the mutagenic potential of TNM except that it is positive in the Ames test and induces sister chromatid exchanges and chromosomal aberrations (NTP, 1990e). Interestingly, the urine of workers exposed to TNM in a chemical plant manufacturing munitions was found to be positive in the Ames test (Ahlborg et al., 1988). The results of a 2-year bioassay have shown that the effects of exposure to TNM are limited to the respiratory tract. Hyperplasia of the alveolar and bronchiolar epithelium and chronic nasal inflammation were observed in exposed rats. Adenomas and carcinomas of the lung were elevated in treated rats, with carcinomas occurring in nearly all animals exposed to the highest concentration (NTP, 1990e).

The mechanism of toxicity is not clear, but may involve activation of the K-ras oncogene. In the NTP study (NTP, 1990e), DNA isolated from alveolar/bronchiolar neoplasms from mice and rats exposed to TNM was transfected into cultured fibroblasts. Morphologic transformation occurred, and the transforming gene was identified as the K-ras oncogene in both mice and rats. Approximately 40% of examined human pulmonary adenocarcinomas contain an activated K-ras oncogene (You et al., 1989) and activation of this oncogene is frequently observed in chemically induced pulmonary neoplasms in rodents (Belinsky et al., 1989). Tetranitromethane is known to nitrate hydroxyl groups of tyrosine residues and Ptitsyn et al. (1979) have shown that TNM similarly modifies tyrosine residues of deoxyribonucleoproteins *in vitro*.

2,6-Xylidine

2,6-Xylidine is widely used as a dye, a drug, and a cosmetic precursor. Administration of XL at a concentration of 10,000 ppm in the diet for 6 months produced liver enlargement in the rat (Lindstrom et al., 1963). Similar effects were observed when XL was administered orally for 20 days by

gavage at a dose of 157.5 mg/kg (Short et al., 1983), or orally for 4 weeks by gavage at a dose of 500 to 700 mg/kg/day (Magnusson et al., 1971). No microscopic lesions have been observed except for a slight decrease in centrilobular glycogen and a slight proliferation of smooth endoplasmic reticulum. In a 2-year bioassay, XL was administered in the diet at concentrations ranging from 0 to 3000 ppm (NTP, 1990f). The incidence of nasal carcinomas was about 50% in both male and female rats in the high-dose group.

The biotransformation of XL is presented in Figure 17. Lindstrom et al. (1963) have shown that XL is metabolized to 4-hydroxy-2,6-dimethylaniline and 2-amino-3-methylbenzoic acid in the rat. A more recent investigation determined that XL was metabolized principally to 4-hydroxy-2,6-dimethylaniline (a) in the rat. No 2-amino-3-methylbenzoic acid (b) was noted in the rat, but in the dog, significant quantities of 2-amino-3-methylbenzoic acid and its glycine conjugate (c) were produced (Short et al., 1989). A minor metabolite, N,2,4-trimethylaniline (d) was also seen in the rat. Repeated administration of XL did not change the profile of the metabolites in either species, but the administration of 3-methylchloanthrene caused an increase in the amount of 4-hydroxy-2,6-dimethylaniline. This finding has suggested that hydroxylation is a cytochrome P₄₄₈ mediated process. This is an interesting finding because 3-methylcholanthrene has been shown in other studies to specifically induce N-oxidation of aromatic amines (Thorgeirsson et al., 1983; 1984; Atlas et al., 1977).

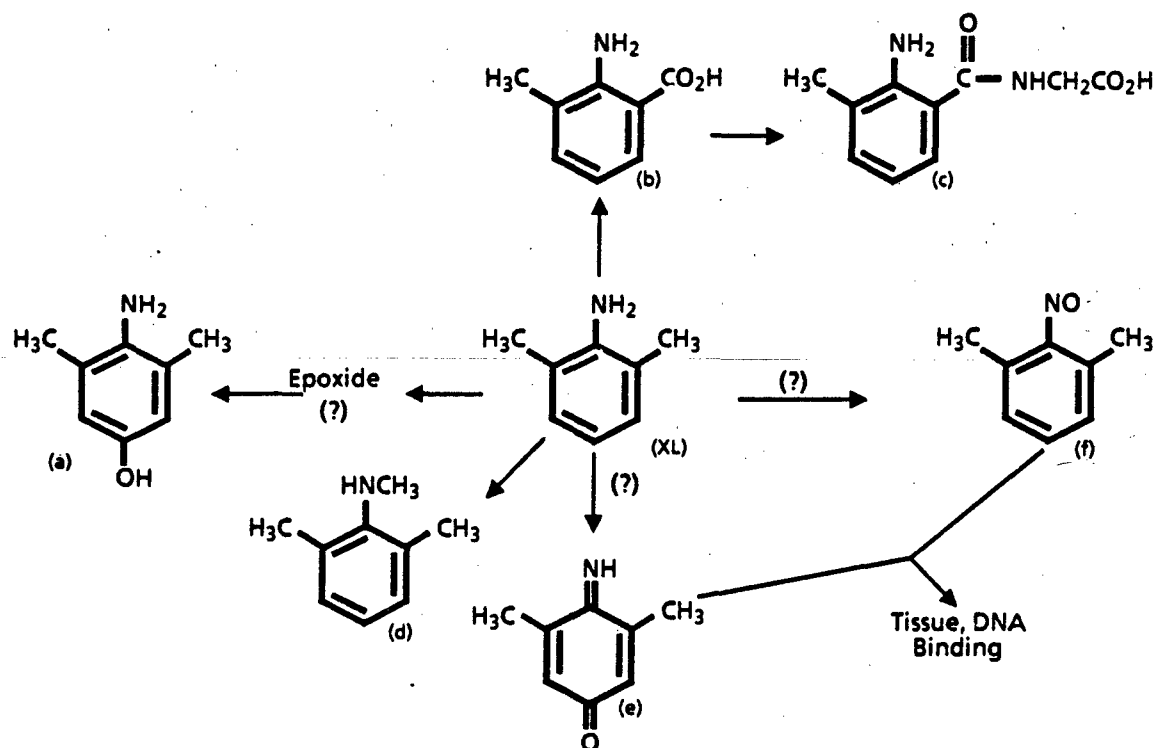


Figure 17.

There are several possibilities for the reactive species formed from XL that could be involved in the production of nasal carcinomas. 4-Hydroxy-2,6-dimethylaniline (a) could be involved if an epoxide forms as an intermediate. The formation of a quinone imine (e) could be involved because quinones have been implicated in the toxicity of a variety of aromatic compounds (Irons and Sawahata, 1985). Quinone imines are highly reactive electrophiles and can cause lipid peroxidation (Albano et al., 1985). Reduction of quinone imines also can result in the production of free radical intermediates (Rosen et al., 1985). Finally, aromatic nitroso-compounds are known to be reactive (Miller and Miller, 1981) and 2,6-dimethylnitrosobenzene (f) could be a toxic metabolite of XL.

***p*-Cresidine**

p-Cresidine is primarily used as an intermediate in the manufacturing of dyes. In long-term feeding studies, *p*-cresidine was carcinogenic to both rats and mice, the main sites of its action being the urinary bladder, nasal cavity, and liver (IARC, 1982). Positive results have been displayed in genotoxicity screening assays including the Ames test, but only after metabolic activation (IARC, 1982).

There have been no reports in the literature describing the metabolism of this chemical. Nevertheless, a proposed biotransformation pathway is presented in Figure 18. In this example, an initial oxidation of the methoxy group to yield 2-amino-*p*-cresol (a) is followed by oxidation of the methyl group to 4-aminohydroxybenzoic acid (b) which can then undergo either conjugation or acetylation of the amino functional group. The free amino group can also undergo *N*-methylation in an *S*-adenosylmethionine-dependent reaction to yield metabolites (c,d). The species responsible for the observed carcinogenicity of this chemical may be an aromatic-nitroso compound or, in a reaction similar to that of hydrazine, the *N*-acetylhydroxybenzoic acid (e) could undergo deacetylation, resulting in an acetyl radical.

DISCUSSION

The report by Huff et al. (1991) has listed 10 chemicals that have been tested by the NTP and shown to produce tumors in the nasal cavity. These chemicals were AGE, *p*-cresidine, DBCP, DBE, DMVC, DX, EB, IDG, PO, and XL. The results of the *Salmonella* reverse mutation assay (Ames test) have indicated that all of these chemicals were either weakly positive or positive, except for DX, which was negative. The tumors produced by AGE and PO were limited to the nasal cavity, whereas the others produced tumors at multiple sites.

Of the 10 chemicals listed by Huff et al. (1991), 3 were epoxides (AGE, EB, and PO). One chemical of these 10 (IDG) could undergo biotransformation to form an epoxide. Nasal tumors were found in only 2 of 49 male rats exposed to IDG by oral gavage at a dose of 250 mg/kg. There was no evidence of nasal tumors in female rats or in mice of either sex. Three other chemicals reviewed in this manuscript could form epoxides during biotransformation (BTD, NPT, and VT). Both BTD and NPT produced alveolar and bronchiolar adenomas in mice, but VT produced no evidence of carcinogenicity.

Epoxides can produce tumors, and nasal tumors were produced when AGE, EB, and PO were administered by inhalation. The administration of other chemicals by inhalation that required metabolic activation to an epoxide resulted in formation of lung tumors, but not nasal tumors. The conversion of these chemicals to reactive epoxides by nasal epithelium is probably low, suggesting that the biotransformation occurred in the lungs.

Three of the 10 chemicals listed by Huff et al. (1991) were halogenated hydrocarbons that formed reactive aldehydes during biotransformation. 1,2-Dibromo-3-chloropropane and DBE were administered by inhalation and both produced positive evidence of nasal tumors in rats and mice. In both cases, metabolic activation is required for activity but the site for this activation is unknown. The formation of alveolar and bronchiolar adenomas in both species suggests that activation occurs in the lungs. Because tumors are generally found in organs that are the site for their biotransformation to reactive intermediates (Williams and Weisburger, 1991), it is possible that activation of these agents occurred in the nasal epithelium as well. Dimethyl vinylchloride metabolism also affords a reactive aldehyde intermediate. This chemical was administered by oral gavage and clear evidence for nasal tumor formation was found in male and female rats. This suggests that activation to a reactive intermediate can occur at locations distal to the site of tumor formation but does not rule out the possibility of metabolism of blood-borne levels of DMVC by the nasal epithelium. Two other chemicals reviewed in this manuscript (MCA and CS) do not form reactive metabolites during their biotransformation and neither chemical induced nasal tumor formation.

The remaining three chemicals listed by Huff et al. (1991), and found to produce nasal tumors, were DX, XL, and *p*-cresidine. 1,4-Dioxane was administered in the drinking water. This chemical has been shown to be metabolized to a strained lactone that is excreted in the urine. This implies that the lactone ring may not be quickly metabolized and so could produce tumors at sites distant to its site of formation. Alternatively, dioxane may be absorbed to such a great extent that sufficient parent compound survives the first pass through the liver to cause tumors at other sites in the body. The principal site of biotransformation is most likely in the liver because of the large number of animals with liver adenomas and carcinomas. Both XL and *p*-cresidine were administered in the food. Liver and bladder tumors were observed for *p*-cresidine indicating that metabolism may have taken place in the liver with the formation of a stable carcinogenic metabolite excreted in the urine. As with dioxane, sufficient parent chemical may also have survived the first pass through the liver to result in tumor formation in nasal epithelium. In the case of XL, the principal findings were tumors of the nasal cavity with some neoplastic nodules in the liver of female rats that may have been related to treatment. With these last two compounds, there is little understanding of the relationship between their metabolism and the formation of tumors. The presence of free amino functional groups in both of these chemical is interesting because the amino groups could undergo reactions similar to those described for hydrazine. However, because no information in the literature exists concerning the reactivity of this group for either chemical, there is no reason to expect that they are metabolized in a similar manner to hydrazine. If the distribution and type of nasal tumors produced in animals exposed to these two chemicals is similar to that reported for hydrazine, then studies might be designed to address the metabolic pathways of both chemicals in more detail.

Four additional chemicals were reviewed in this manuscript. Cresols and MMA have produced no evidence of carcinogenicity. The metabolism of MMA clearly does not produce reactive intermediates, but it is not known whether the hydroxylation of cresols involves a direct oxygen insertion or the formation of an epoxide intermediate. The fact that cresols are not carcinogenic would tend to favor a mechanism of direct insertion, but no information exists in the literature that would answer this question. Titanocene dichloride has produced tumors of the forestomach when administered by oral gavage. The carcinogenic response has been judged as equivocal. Finally, TNM administration by inhalation produced clear evidence of alveolar and bronchiolar adenomas and carcinomas, squamous cell carcinomas, and sarcomas. This chemical is unique because it is the only chemical reviewed in this manuscript that has been shown to activate oncogenes. In this respect, it is possible that HZ may also activate oncogenes, but there is no evidence to support this hypothesis at the present time.

SUMMARY AND CONCLUSION

The biotransformation of 19 chemicals that have been shown to produce nasal toxicity in long-term carcinogenesis studies in rodents has been compared with that of HZ. The pertinent information for all 19, as well as that for HZ, has been summarized in Table 1.

Ten of the 19 chemicals reviewed produced tumors of various types in the nasal cavity. Of these, four are epoxides or can be metabolized to an epoxide, three can undergo biotransformation to reactive aldehyde intermediates, and one (DX) can be metabolized to a strained lactone ring, described as the proximate carcinogen. *p*-Cresidene and XL possess a free amino function group that may undergo reactions similar to those reported for the metabolism of HZ; however, there is no literature data to support this hypothesis. In addition, the types of tumors that arise as a consequence of exposure to HZ (squamous cell and adenocarcinoma) are unlike those reported for *p*-cresidene (neuroblastoma) or XL (carcinoma). This further suggests that HZ is metabolized to reactive intermediates that are different from those of *p*-cresidene or XL. In conclusion, there is no evidence suggesting that the mechanisms of biotransformation of the 19 chemicals reviewed in this report is similar to that described for HZ.

TABLE 1. COMPARATIVE STRUCTURE-ACTIVITY AND NASOTOXICITY SUMMARY

Chemical	Nasal Tumors	Tumor Types	Epoxide?	Aldehyde?	Other Reactive Metabolites?	Reference
1,3-Butadiene	no-inf, met yes	olf, neuroblastoma	yes		mercapturic acid	Loesch, 1982;
1,2-Epoxybutane	yes	Ad			mercapturic acid	Brown, et al., 1991
1,2-Propylene oxide	yes	Ad, hemangioma/ hemangiosarcoma	yes		mercapturic acid	Dunnick et al., 1988 NTP, 1985a
Naphthalene	no-olf, met				mercapturic acid	NTP, 1991a
Vinyl toluene	no-olf, met		yes		mercapturic acid	NTP, 1990a
Iodinated glycerol	yes	Ad	yes			NTP, 1990b
Allyl glycidyl ether	yes	SCCa, Ad, olf, AdCa	yes		possible	NTP, 1990d
Dimethyl vinylchloride	yes	Ca, usually olf		yes	mercapturic acid possible	NTP, 1985b
1,2-Dibromoethane	yes	AdCa, Ca		yes	mercapturic acid possible	NTP, 1982a
1,2-Dibromo-3-chloropropane	yes				mercapturic acid, episulfonium ion	
Monochloroacetic acid	no-inf	SCCa		yes		NPT, 1982b
2-Chlorobenzalmonitrile (CS)	no-sq met					NTP, 1992a
p-Cresol and mixed cresol isomers	no-inf, met					NTP, 1990g
Methyl methacrylate	no-inf					NTP, 1992b
1,4-Dioxane	yes	SCCa				NTP, 1986
					strained lactone	Argus et al., 1965; Hoch-Ligeti et al., 1970
Titanocene dichloride	no-inf					NTP, 1991b
Tetranitromethane	no-inf					NTP, 1990e
2,6-Xylidine	yes	Ad, Ca			possible nitroso- compounds	NTP, 1990f
p-Cresidine	yes	neuroblastoma			possible nitroso- compounds	IARC, 1982
Hydrazine	yes	SCCa, AdCa, adenomatous polyp			free radical	Vernot et al., 1985

Ad = adenoma AdCa = adenocarcinoma Ca = carcinoma inf = inflammation met = metaplasia olf = olfactory Sq = squamous SCCa = squamous cell carcinoma

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