National Toxicology Program
U.S. Department of Health and Human Services

Peer-Review Draft:
Report on Carcinogens
Monograph on *ortho*-Toluidine

August 28, 2013

Office of the Report on Carcinogens
Division of the National Toxicology Program
National Institute of Environmental Health Sciences
U.S. Department of Health and Human Services

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FOREWORD

The National Toxicology Program (NTP) is an interagency program within the Public Health Service (PHS) of the Department of Health and Human Services (HHS) and is headquartered at the National Institute of Environmental Health Sciences of the National Institutes of Health (NIEHS/NIH). Three agencies contribute resources to the program: NIEHS/NIH, the National Institute for Occupational Safety and Health of the Centers for Disease Control and Prevention (NIOSH/CDC), and the National Center for Toxicological Research of the Food and Drug Administration (NCTR/FDA). Established in 1978, the NTP is charged with coordinating toxicological testing activities, strengthening the science base in toxicology, developing and validating improved testing methods, and providing information about potentially toxic substances to health regulatory and research agencies, scientific and medical communities, and the public.

The Report on Carcinogens (RoC) is prepared in response to Section 301 of the Public Health Service Act as amended. The RoC contains a list of identified substances (i) that either are *known to be human carcinogens* or are *reasonably anticipated to be human carcinogens* and (ii) to which a significant number of persons residing in the United States are exposed. The Secretary, Department of HHS, has delegated responsibility for preparation of the RoC to the NTP, which prepares the report with assistance from other Federal health and regulatory agencies and nongovernmental institutions. The most recent RoC, the 12th Edition (2011), is available at http://ntp.niehs.nih.gov/go/roc12.

Nominations for (1) listing a new substance, (2) reclassifying the listing status for a substance already listed, or (3) removing a substance already listed in the RoC are evaluated in a scientific review process (http://ntp.niehs.nih.gov/go/rocprocess) with multiple opportunities for scientific and public input and using established listing criteria (http://ntp.niehs.nih.gov/go/15209). A list of candidate substances under consideration for listing in (or delisting from) the RoC can be obtained by accessing http://ntp.niehs.nih.gov/go/37893.

INTRODUCTION

ortho-Toluidine (*ortho*-methylaniline, CASRN 95-53-4) is a synthetic chemical that is currently used in the United States in the manufacture of rubber chemicals, of a chemical intermediate for herbicides, of dye intermediates, and of the local anesthetic prilocaine. *ortho*-Toluidine has been listed in the Report on Carcinogens (RoC) as *reasonably anticipated to be a human carcinogen* since 1983 based on sufficient evidence of carcinogenicity from studies in experimental animals. Since that time, several cancer studies in humans have been published in the peer-reviewed literature, and the International Agency for Research on Cancer (2010, 2012) has concluded that *ortho*-toluidine is carcinogenic to humans (Group 1). *ortho*-Toluidine has been selected as a candidate substance for review for possible change in listing status in the RoC based on current U.S. exposure and an adequate database of cancer studies.

Monograph contents

This RoC draft monograph on *ortho*-toluidine consists of the following components: (Part 1) the cancer evaluation component that reviews the relevant scientific information and assesses its quality, applies the RoC listing criteria to the scientific information, and recommends an RoC listing status for *ortho*-toluidine, and (Part 2) the draft substance profile containing the NTP's preliminary listing recommendation, a summary of the scientific evidence considered key to reaching that recommendation, and data on properties, use, production, exposure, and Federal regulations and guidelines to reduce exposure to *ortho*-toluidine.

The cancer evaluation component for *ortho*-toluidine provides information on the following topics: human exposure and chemical properties (Section 1), disposition and toxicokinetics (Section 2), cancer studies in humans (Section 3), cancer studies in experimental animals (Section 4), and mechanistic data and other related effects (Section 5), including studies of genetic toxicology and potential mechanisms of carcinogenicity, relevant toxicological effects. The information in Section 6 is a synthesis of Sections 2 through 5.

The information reviewed in Sections 2 through 5 must come from publicly available, peer-reviewed sources. Information in Section 1, including chemical and physical properties, analytical methods, production, use, and occurrence, may come from publicly available, peer-reviewed or non-peer-reviewed sources.

The cancer evaluation for *ortho*-toluidine focuses on the evaluation of the human cancer studies and mechanistic data.

Process for preparation of the cancer evaluation component

The process for preparing the cancer evaluation component of the monograph included approaches for obtaining public and scientific input and using systematic methods (e.g., standardized methods for identifying the literature (see Appendix A), inclusion/exclusion criteria, extraction of data and evaluation of study quality using specific guidelines, and assessment of the level of evidence for carcinogenicity using established criteria).

The Office of the Report on Carcinogens (ORoC) followed the approaches outlined in the concept document, which discusses the scientific issues and questions relevant to the evaluation of *ortho*-toluidine carcinogenicity, the scope and focus of the monograph, and the approaches to obtain scientific and public input to address the key scientific questions and issues, for preparing the cancer evaluation component of the draft monograph. The ORoC presented the draft concept document for *ortho*-toluidine to the NTP Board of Scientific Counselors (BSC) at the June 21-22, 2012 meeting that provided opportunity for written and oral public comments and is available on the RoC website (http://ntp.niehs.nih.gov/go/37898), after which the concept was finalized and *ortho*-toluidine was approved by the NTP Director as a candidate substance for review.

Key scientific questions and issues relevant for the cancer evaluation

The carcinogenicity of *ortho*-toluidine in experimental animals has been well established since the early 1980s, and no new data were identified to challenge these conclusions or to suggest that the findings in experimental animals are not relevant to humans. The monograph assesses the cancer studies in experimental animals that were not part of the original listing. The key questions and issues in the re- review of *ortho*-toluidine concern the evaluation of human cancer studies and mechanistic data.

Questions related to the evaluation of human cancer studies

- What is the level of evidence (sufficient, limited, or inadequate) for the carcinogenicity of *ortho*- toluidine from studies in humans? What are the tissue sites?
- What are the major potential confounders (i.e., co-exposures) for evaluating urinary bladder cancer risk in these studies?
- Can any association between urinary bladder cancer and exposure to *ortho*-toluidine be explained by exposure to these co-exposures or other risk factors for urinary bladder cancer?

Questions related to the evaluation of toxicological and mechanistic data

- What are the tumor sites that contribute to the sufficient evidence in experimental animals? Do the cancer studies in experimental animals published since the original listing provide additional information on the tumor sites?
- What are the potential mechanisms by which *ortho*- toluidine may cause cancer?
- Is there evidence that these mechanisms occur in humans? If so, what is the level of the evidence (strong, moderate, or weak)?

Approach for obtaining scientific and public input

Additional scientific input was obtained for exposure, human cancer studies, and disposition and toxicokinetics of *ortho*-toluidine. (Technical advisors are identified on the "CONTRIBUTORS" page.)

Public comments on scientific issues were requested at several times prior to the development of the draft RoC monograph, including the request for information on the nomination, and the request for comment on the draft concept document, which outlined

the rationale and approach for conducting the scientific review. In addition, the NTP posted its protocol for reviewing the human cancer studies for public input on the ORoC webpage for *ortho*-toluidine (available at http://ntp.niehs.nih.gov/go/37898) several months prior to the release of the draft monograph. One public comment on *ortho*-toluidine was received from the public as of the date on this document (http://ntp.niehs.nih.gov/go/37663).

Methods for writing the cancer evaluation component of the monograph

The procedures by which relevant literature was identified, data were systematically extracted and summarized, and the draft monograph was written, together with the processes for scientific review, quality assurance, and assessment and synthesis of data, are described below.

The preparation of the RoC monograph for *ortho*-toluidine began with development of a literature search strategy to obtain information relevant to the topics listed above for Sections 1 through 5 using search terms developed in collaboration with a reference librarian (see Appendix A for a detailed description of the literature search strategy). The citations (N = 2,277) identified from these searches were uploaded to a web-based systematic review software for evaluation by two separate reviewers using inclusion/exclusion criteria, and 280 references were selected for final inclusion in the draft monograph using these criteria. Studies identified from the literature searches but excluded from the review include publications on chemicals other than *ortho*-toluidine (or relevant structurally related compounds such as *ortho*-toluidine metabolites and analogues), and studies involving exposure to *ortho*-toluidine that reported results for topics not covered in this monograph (see Monograph Contents).

Information for the exposure, relevant cancer, and mechanistic sections was systematically extracted in tabular format and/or summarized in the text, following specific procedures developed by ORoC, from studies selected for inclusion in the monograph. All sections of the monograph underwent scientific review and quality assurance (QA) (i.e., assuring that all the relevant data and factual information extracted from the publications have been reported accurately) by a separate reviewer. Any discrepancies between the writer and the reviewer were resolved by mutual discussion in reference to the original data source.

Strengths, weaknesses, and study quality of the cancer studies for *ortho*-toluidine in humans (see Appendix D) or experimental animals (see Appendix E) were assessed based on a series of *a priori* questions. For the human cancer studies, these questions and the guidelines for answering the questions were available in the protocol (http://ntp.niehs.nih.gov/NTP/roc/thirteenth/Protocols/ortho-ToluidineProtocol_508.pdf), which also outlines the approach for evaluating potential confounding from occupational co-exposures or other lifestyle factors. Relevant genotoxicity and mechanistic studies were also assessed for their strengths and weaknesses.

Human exposure information was assessed to determine whether the evidence indicates that a significant number of persons residing in the United States are exposed to *ortho*-toluidine (see Foreword for information regarding the congressional mandate for the

RoC). However, for many substances, this information is not available, and typically, U.S. exposure can be inferred from data on use, production volume, occupational monitoring, environmental occurrence, estimated daily intake, and biomonitoring. Because cancer has a long latency period, past exposure is also considered in the assessment.

RoC listing criteria (see text box) were applied to the available database of carcinogenicity data to assess the level of evidence (sufficient, limited, or inadequate) for the carcinogenicity of *ortho*-toluidine from studies in humans and the level of evidence (sufficient, not sufficient) from studies in experimental animals. The approach for synthesizing the evidence across studies and reaching a level of evidence conclusion was outlined in the protocol. The initial conclusions do not integrate the human cancer, experimental cancer, and mechanistic data. The evaluation of the mechanistic data included a complete discussion and assessment of the strength of evidence for potential modes of action for *ortho*-toluidine-induced neoplasia, including metabolic activation, cytotoxicity, genetic-related effects, and epigenetic effects. The RoC listing criteria were then applied to the body of knowledge (cancer studies in humans and experimental animals and mechanistic data) for *ortho*-toluidine to reach a listing recommendation.

RoC Listing Criteria

Known To Be Human Carcinogen:

There is sufficient evidence of carcinogenicity from studies in humans*, which indicates a causal relationship between exposure to the agent, substance, or mixture, and human cancer.

Reasonably Anticipated To Be Human Carcinogen:

There is limited evidence of carcinogenicity from studies in humans*, which indicates that causal interpretation is credible, but that alternative explanations, such as chance, bias, or confounding factors, could not adequately be excluded, OR

there is sufficient evidence of carcinogenicity from studies in experimental animals, which indicates there is an increased incidence of malignant and/or a combination of malignant and benign tumors (1) in multiple species or at multiple tissue sites, or (2) by multiple routes of exposure, or (3) to an unusual degree with regard to incidence, site, or type of tumor, or age at onset, OR

there is less than sufficient evidence of carcinogenicity in humans or laboratory animals; however, the agent, substance, or mixture belongs to a well-defined, structurally related class of substances whose members are listed in a previous Report on Carcinogens as either known to be a human carcinogen or reasonably anticipated to be a human carcinogen, or there is convincing relevant information that the agent acts through mechanisms indicating it would likely cause cancer in humans.

Conclusions regarding carcinogenicity in humans or experimental animals are based on scientific judgment, with consideration given to all relevant information. Relevant information includes, but is not limited to, dose response, route of exposure, chemical structure, metabolism, pharmacokinetics, sensitive sub-populations, genetic effects, or other data relating to mechanism of action or factors that may be unique to a given substance. For example, there may be substances for which there is evidence of carcinogenicity in laboratory animals, but there are compelling data indicating that the agent acts through mechanisms which do not operate in humans and would therefore not reasonably be anticipated to cause cancer in humans.

*This evidence can include traditional cancer epidemiology studies, data from clinical studies, and/or data derived from the study of tissues or cells from humans exposed to the substance in question that can be useful for evaluating whether a relevant cancer mechanism is operating in people.

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Part 1

Draft RoC Cancer Evaluation

Properties and Human Exposure

Disposition (ADME) and Toxicokinetics

Human Cancer

Studies in Experimental Animals

Mechanistic Data and Other Relevant Effects

Overall Cancer Evaluation

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1 Properties and Human Exposure

ortho-Toluidine is a high-production-volume chemical used in the manufacture of rubber chemicals, of herbicide intermediates, of dye intermediates, and of the local anesthetic prilocaine. This section describes the chemical and physical properties of *ortho*-toluidine (Section 1.1); its uses and production (Section 1.2); exposure to *ortho*-toluidine and biomarkers for exposure (Section 1.3); exposure in the workplace (Section 1.4); potential exposure from other sources such as cigarette smoking, medical and consumer products, and food (Section 1.5); and potential for environmental exposure (Section 1.6). Section 1.7 synthesizes and summarizes the information in Sections 1.1 to 1.6. U.S. regulations and guidelines that potentially limit exposure to *ortho*-toluidine are in Appendix B. (Note: Links provided in the text connect directly to each table as it is discussed, and a link is provided at the end of each table to return to the text citing the table.)

1.1 Chemical identification and properties

ortho-Toluidine (Figure 1-1) is a synthetic chemical that exists at room temperature as a light-yellow liquid that darkens rapidly on exposure to air and light. It is described as having an aromatic odor (IPCS 1998). *ortho*-Toluidine may be classified as a monocyclic aromatic amine, arylamine, or alkylaniline (IARC 2010a, Skipper *et al.* 2010, Yu *et al.* 2002). It is slightly soluble in water; soluble in dilute acids; and miscible with ethanol, diethyl ether, and carbon tetrachloride (HSDB 2011). Toxicological studies of *ortho*-toluidine using its hydrochloride salt *(ortho*-toluidine hydrochloride) are considered relevant for the cancer evaluation of *ortho*-toluidine because the use of the salt is unlikely to alter the observed health effects of the parent chemical (IPCS 1998). In addition, the reaction of *ortho*-toluidine with stomach acid will yield the hydrochloride salt as the test article (English *et al.* 2012). *ortho*-Toluidine hydrochloride is the solid salt form of *ortho*-toluidine that exists at room temperature as a green or white crystalline solid that is very soluble in water (Akron 2012b). Table 1-1 contains some chemical identification information for *ortho*-toluidine and *ortho*-toluidine hydrochloride.

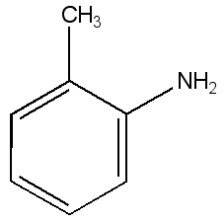

Figure 1-1. Chemical structure of *ortho*-toluidine

Table 1-1. Chemical identification of *ortho*-toluidine and *ortho*-toluidine hydrochloride

Characteristic	Information (*ortho*-toluidine)	Information (*ortho*-toluidine hydrochloride)
Chemical Abstracts index name	*ortho*-toluidine	*ortho*-toluidine hydrochloride
CAS Registry number	95-53-4	636-21-5
Molecular formula	C_7H_9N	$C_7H_9N{\bullet}HCl$
Synonyms	1-amino-2-methylbenzene, 2-aminotoluene, *o*-methylaniline	2-toluidine hydrochloride, *o*-aminotoluene hydrochloride, methylaniline

Sources: IPCS 1998, NTP 1996.

Some physical and chemical properties for *ortho*-toluidine and *ortho*-toluidine hydrochloride are listed in Table 1-2.

Table 1-2. Physical and chemical properties of *ortho*-toluidine and *ortho*-toluidine hydrochloride

Property	Information (*ortho*-toluidine)	Information (*ortho*-toluidine hydrochloride)
Molecular weight	107.2[a]	143.6[c]
Melting point	< -15ºC[a]	215ºC[d]
Boiling point	198 – 201ºC[a]	242.2ºC[d]
Vapor pressure (mm Hg)	0.33 at 25ºC[a]	0.293 at 25ºC[e]
Vapor density (air = 1)	3.69[a]	–
Density	0.998 g/cm^3 at 20ºC[a]	1.288 g/cm^3 at 20ºC[f]
Solubility water (25°C) most organic solvents	1.66×10^4 mg/L[b]	8,290 mg/L[e]
Octanol/water partition coefficient (log K_{ow})	1.32[b]	1.62[e]
Critical temperature	717ºK[b]	–
Henry's law constant	1.98×10^{-6} atm-m^3/mol at 25ºC[b]	2.10×10^{-6} atm-m^3/mol at 25ºC[e]
Conversion factors (*ortho*-toluidine, *ortho*-toluidine hydrochloride in air) parts per million (ppm) to µg/m^3 µg/m^3 to parts per million (ppm)	µg/m^3 = 4,384.5 × (ppm)[g] ppm = 2.281×10^{-4} × (µg/m^3)[g]	µg/m^3 = 5,873.2 × (ppm)[g] ppm = 1.703×10^{-4} × (µg/m^3)[g]

Sources: [a]Akron 2012a, [b]HSDB 2011, [c]NTP 1996, [d]HSDB 2005, [e]ChemIDplus 2012, [f]Akron 2012b, [g]SMARTe.org 2008.

1.2 Uses and production

Production data shown in Table 1-3 indicate that *ortho*-toluidine is a high-production-volume chemical in the United States, and historical information indicates that production exceeded 454,000 kg (1 million pounds) in the 1970s (HSDB 2005, IARC 2000a). In 2011, *ortho*-toluidine was reported to be manufactured by at least 3 companies in the United States and at least 15 companies worldwide (SRI 2012); however, in 2013 one

company reported on its website (http://www2.dupont.com/Pascagoula/en_US/products.html) that they were the only domestic producer of toluidines. The same company also reported release of *ortho*-toluidine to air in 2010 (see Section 1.6.1).

Table 1-3. Production data for *ortho*-toluidine

Category	Years covered	Quantity in pounds[a]
Chemical Data Reporting Rule[b]	2006	10 million to < 50 million
U.S. imports (recent)	2011	[58 million] (reported as 26.3 million kg)
U.S. imports (historical)	1989	[10.1 million] (reported as 4.6 million kg)
U.S. exports (recent)	2011	[3.2 million] (reported as 1.4 million kg)
U.S. exports (historical)	1989	[5.1 million] (reported as 2.3 million kg)

Sources: EPA 2012, SRI 2012, USITC 2012.
[a]From 1/2012, 3/2012, and 7/2012 Internet searches; data subject to change.
[b]Formerly called the Inventory Update Rule.

ortho-Toluidine (either directly or as an intermediate) is currently used to make dyes, rubber chemicals, herbicides, and prilocaine; however, the major uses of *ortho*-toluidine in the United States have changed over time (see Figure 1-2). Major uses of *ortho*-toluidine in the past, i.e., in the early to mid-20th century, that have not continued to the present or have greatly diminished in the United States are uses in manufacture of large quantities of dyes (1910s to 1980s) and in manufacture of 4-chloro-*ortho*-toluidine (4-COT, an intermediate in the production of the acaricide, chlordimeform, and additionally as a dye intermediate) (1930s to 1970s) (Baptista 2012, IARC 2010b, Morris and Travis 1992). The dye industry in the United States began to decline in the 1970s when the 1974 oil crisis greatly increased costs of raw materials, and by 1977 to 1982 four of the largest dye makers had exited the business (Baptista 2012, Morris and Travis 1992). Production of *ortho*-toluidine-based dye and pigment intermediates is still reported by several companies in the United States, however.

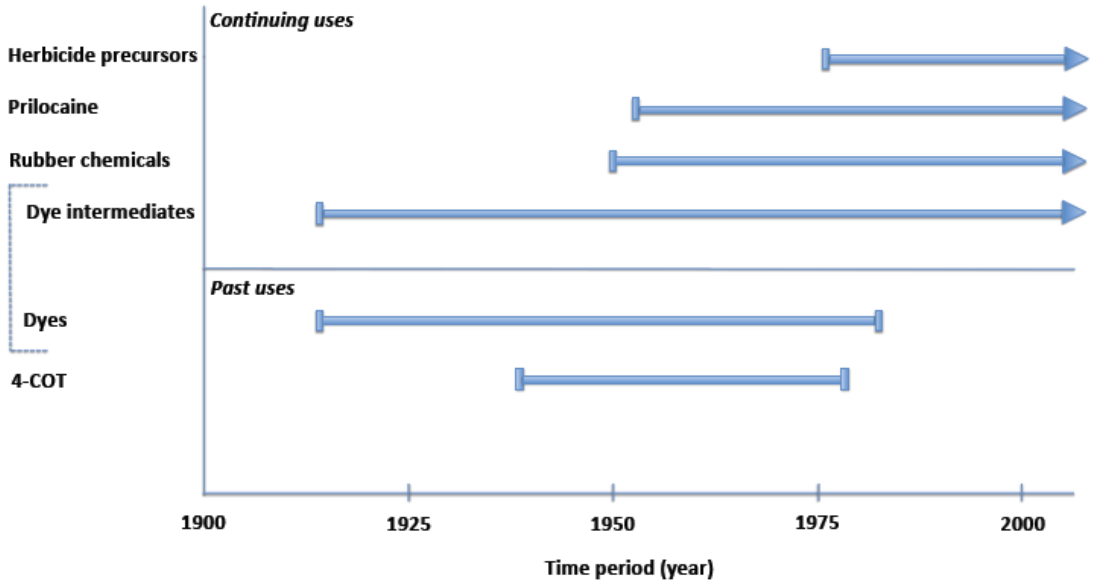

Figure 1-2. Timeline for continuing (current) and past uses of *ortho*-toluidine in the United States

Information obtained from the U.S. Environmental Protection Agency's (EPA) Toxics Release Inventory (TRI) and Chemical Data Reporting (CDR) Rule indicates that *ortho*-toluidine continues to be used in the rubber chemicals, herbicide intermediates, and dye intermediates sectors as of 2010 (TRI 2012). Based on TRI data, two of the top five *ortho*-toluidine air emitters (see Section 1.6.1) reported production of rubber chemicals, and two other companies included herbicide intermediates among their products; the remaining company in the top five emitters reported production of toluidines. Inspection of data on *ortho*-toluidine manufacture or importation reported to EPA under the CDR Rule (formerly the Inventory Update Rule or IUR) identified one additional company that produced rubber chemicals and another that produced herbicide intermediates.

The largest current use of *ortho*-toluidine has been reported to be in production of 6-ethyl-*ortho*-toluidine as a herbicide intermediate, which is used to manufacture the widely used herbicides metolachlor and acetochlor (Bowers 2011). The potential for exposure to *ortho*-toluidine as part of this production would exist only during production of 6-ethyl-*ortho*-toluidine as the intermediate; that production is indicated in Figure 1-2 as "herbicide precursors." Metolachlor was produced in the United States for more than 20 years from the late 1970s to the late 1990s (Bernard 2012), but no information on the source of the 6-ethyl-*ortho*-toluidine used during that period was identified. No export information on 6-ethyl-*ortho*-toluidine was identified. All current production of metolachlor has been reported to occur outside the United States (Bernard 2012), but no specific information on U.S. production of acetochlor was identified. No herbicides other than metolachlor and acetochlor whose intermediates are prepared from *ortho*-toluidine were identified.

Another important use for *ortho*-toluidine is as an intermediate for synthesis of rubber chemicals (e.g., the accelerant di-*ortho*-tolyl-guanidine or the antioxidant di-tolyl-phenyl-*para*-phenylenediamine) and pharmaceuticals (e.g., prilocaine) (Hanley *et al.* 2012, IARC 2012, UNEP 2004, Vardanyan and Hruby 2006). No uses of *ortho*-toluidine in the rubber chemicals manufacturing industry other than as intermediates to synthesize accelerants and antioxidants were identified. The largest release of *ortho*-toluidine to the air (68% of the total) reported to TRI in 2010 was by a company in the rubber industry (TRI 2012).

ortho-Toluidine can also be used in the manufacture of more than 90 dyes and pigments (e.g., acid-fast dyestuffs, azo pigment dyes, triarylmethane dyes, sulfur dyes, and indigo compounds) with acetoacet-*ortho*-toluidine, 3-hydroxy-2-naphthoyl-*ortho*-toluidine, 2-toluidine-5-sulfonic acid, and *ortho*-aminoazotoluene as four major intermediates (Bowers 2011). A search for producers of these intermediates identified three companies that reported use or storage of *ortho*-toluidine on site and included 2-toluidine-5-sulfonic acid or acetoacet-*ortho*-toluidine among their products. In the clinical laboratory, *ortho*-toluidine is also used as an ingredient in a reagent for glucose analysis, and for tissue staining (IARC 2012a).

1.3 Exposure to *ortho*-toluidine

Evidence for exposure to *ortho*-toluidine comes from biological monitoring data demonstrating worldwide exposure to *ortho*-toluidine in both occupationally and non-occupationally exposed individuals and in both smokers and non-smokers. Methods for biological indices for exposure to *ortho*-toluidine include measurement of *ortho*-toluidine and its *N*-acetyl-metabolites in urine and *ortho*-toluidine hemoglobin adducts in blood (Brown *et al.* 1995, Ward *et al.* 1996, Teass *et al.* 1993). Urinary levels provide an assessment of recent exposure, whereas assessment of hemoglobin adducts likely reflects cumulative dose to *ortho*-toluidine because of the 120-day half-life of human red blood cells. Table 1-4 reports studies measuring urine and hemoglobin adducts among occupationally and non-occupationally exposed people in the United States and other counties. (No analyses of *ortho*-toluidine in blood, serum, or urine specimens from the National Health and Nutrition Examination Survey (NHANES) have been identified.) The highest exposures were found for people exposed in the workplace (see Section 1.4), although low levels were reported among workers at a German chemical factory. In addition to the studies in Table 1-4, other studies detected *ortho*-toluidine in breast milk (DeBruin *et al.* 1999, as cited in IARC 2012), hemoglobin adducts in blood (Gaber *et al.* 2007, IARC 2012) and DNA–releasing adducts in urinary bladder tissue or tumors (Böhm *et al.* 2011). Potential for exposure from non-occupational sources include cigarette smoking, medical and consumer products, food (see Section 1.5), and the environment (see Section 1.6).

Table 1-4. *ortho*-Toluidine in urine and Hb adducts in different populations

Population	Urine or Hb adduct levels (#): Smokers	Urine or Hb adduct levels (#): Non-smokers	Reference
***o*-Toluidine: Urine**			
Volunteers, U.S.A.	6.3 ± 3.7 μg/24 hr (16) [6300 ± 3700 ng/24 hr]	4.1 μg/24 hr (12) [4100 ng/24 hr]	El-Bayoumy *et al.* 1986
Volunteers, Germany	204 ± 59 ng/24 hr (10)	105 ± 26 ng/24 hr (9)	Riedel *et al.* 2006
Volunteers, Germany	0.13–173 μg/L (145) [130–173,000 ng/24 hr]	0.03–34 μg/L (856) [30–34,000 ng/24 hr]	Kutting *et al.* 2009
Volunteers, Europe	179 ± 491 ng/24 hr (1148)	64 ± 128 ng/24 hr (395)	Lindner *et al.* 2011
Chemical factory, Germany	0.6 ± 1.0 μg/L (22) [600 ng/L]	0.4 ± 1.1 μg/L (21) [400 ng/L]	Riffelmann *et al.* 1995
Rubber factory, Germany	14.5 μg/L (mean) (36) [14,500 ng/L]	38.6 μg/L (mean) (15) [38,600 ng/L]	Korinth *et al.* 2007[a]
NIOSH rubber chemical cohort, U.S.A.[b]	Exposed (post-shift) 132 ± 153 μg/L (15) [132,000 ± 153,000 ng/L] Nonexposed (post-shift) 3.0 ± 1.0 ng/L (9) [3,000 ± 1,000 ng/L]	Exposed (post-shift) 80 ± 94 μg/L (27) [80,000 ± 94,000 ng/L] Nonexposed (post-shift) 3.0 ± 2.0 μg/L (16) [3,000 ± 2,000 ng/L]	Ward *et al.* 1996 (see also Brown *et al.* 1995, Stettler *et al.* 1992)
***o*-Toluidine: Hb adducts**			
Volunteers, U.S.A.	0.10 ± 0.03 ng/g Hb (12)	0.03 ± 0.01 ng/g Hb (10)	Stillwell *et al.* 1987
Volunteers, Italy	290–329 pg/g Hb (means) (41) [0.290–0.329 ng/g Hb]	188 pg/g Hb (mean) (19) [0.188 ng/g Hb]	Bryant *et al.* 1988
Pregnant women, Germany	289 ± 25 pg/g Hb (27) [0.289 ± 0.025 ng/g Hb]	237 ± 65 pg/g Hb (73) [0.237 ± 0.065 ng/g Hb]	Branner *et al.* 1998
Children, Germany		487–632 pg/g Hb (220) [0.487–0.632 ng/g Hb]	Richter *et al.* 2001
Patients, 24 hr post prilocaine administration, Germany	21 ± 15 ng/g Hb (8)	23 ± 12 ng/g Hb (17)	Gaber *et al.* 2007
Rubber factory, Germany	287 ng/L (mean) (36)	432 ng/L (mean) (15)	Korinth *et al.* 2007[a]
NIOSH rubber chemical cohort, U.S.A.[b]	Exposed (post-shift)[c] 40830 ± 32518 pg/g Hb (46) [30.830 ± 32.518 ng/g Hb] Nonexposed (post-shift) 3515 ± 6036 pg/g Hb (27) [3.515 ± 6.036 ng/g Hb]		Ward *et al.* 1996 (see also Stettler *et al.* 1992)

[a]Air levels of *ortho*-toluidine higher among nonsmoking group, according to authors.
[b]See also Section 3.
[c]Smokers and nonsmokers had similar values; combined group reported in table.

1.4 Characterization of exposure in the workplace

ortho-Toluidine is synthesized from toluene by a two-step process (Bowers 2011, IARC 2010a) (see Figure 1-3 and Appendix C). Mononitration of toluene produces three isomers (*ortho*-, *meta*-, and *para*-) of nitrotoluene, which can be separated by distillation prior to reduction of the nitro- group to an amine. Reduction of *ortho*-nitrotoluene to *ortho*-toluidine can be accomplished by several methods, but the most common method currently is a continuous vapor-phase hydrogenation process with a catalyst such as Raney nickel, copper, molybdenum, tungsten, vanadium, noble metals, or various supported metals.

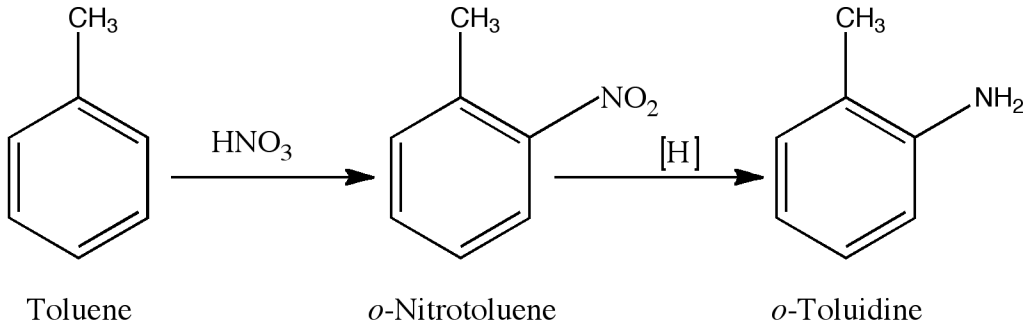

Figure 1-3. Chemical synthesis of *ortho*-toluidine from toluene

Occupational exposure to *ortho*-toluidine can occur by inhalation or skin contact (IARC 2010a) during its production, or during its use in production of chemical intermediates for pesticides, of rubber chemicals, or of intermediates for dyes and pigments. As small amounts of *ortho*-toluidine are also used in laboratory work, medical and laboratory personnel are exposed to low air concentrations of *ortho*-toluidine (EPA 1984, Kauppinen *et al.* 2003, as cited in IARC 2012).

Limited information is available on exposure to *ortho*-toluidine in the various industries where *ortho*-toluidine is used or produced. Most of the exposure information found is from the human cancer studies, and details on the exposure conditions of those individual studies is presented in Appendix C, which is provided as background information to interpret the epidemiological studies. Exposure levels across industries are presented in Table 1-5 and biomonitoring data were presented in Table 1-4. No information was found on levels of exposure to *ortho*-toluidine during production of the pesticide intermediates (such as 6-ethyl-*ortho*-toluidine or 4-chloro-*ortho*-toluidine). The highest levels of exposures (air) were reported from a study of workers at a chemical plant in the former Soviet Union where *ortho*-toluidine was produced via reduction of *ortho*-nitrotoluene. Concentrations of *ortho*-toluidine in the air were 2- to 7-fold higher than the maximum permissible concentration for the USSR of 3 mg/m^3 [0.7 ppm] (Khlebnikova, *et al.* 1970, as cited in IARC 2012). Dermal exposures also were reported (IARC 2012). Most of the air-monitoring data in the United States suggest that occupational exposure levels to *ortho*-toluidine are usually less than 1 ppm (e.g., up to 0.5 ppm in the dye and pigment industry), but may have been higher in the past.

Table 1-5. Exposure to *ortho*-toluidine in various industries

Industry (Year)	TWA (range), ppm[a]	Number of samples	Reference
ortho-Toluidine production - distillation and extraction processes	[5.7 – 6.5][b]	–	Khlebnikova *et al.* 1970[c]
Rubber chemical industry	[0.1][d]	7	Ward 1996
Dye and pigment industry - thioindigo production worker (1940)	< 0.5	–	Ott and Langner 1983
OSHA sampling data (1985-6, 1988, 1997, 2001)[e]	0.06–0.11	26[f]	OSHA 2011

[a]Values shown in brackets converted to ppm using conversion factor in Table 1-2.
[b]Reported as 25 – 28.6 mg/m^3.
[c]As cited in IARC 2012.
[d]Reported as 516 µg/m^3.
[e]OSHA Chemical Exposure Health Dataset.
[f]Only 6 samples from 1 facility in the rubber industry had detectable levels.

The most detailed exposure information was found for the rubber chemical industry. Air monitoring data were available from both a NIOSH assessment of a rubber chemical manufacturing plant carried out in 1990 (Figure 1-4) and company data from three intervals covering the period from 1976 to 2004 (Figure 1-5) (Hanley *et al.* 2012). NIOSH TWA breathing zone air sampling data or company-collected data for the rubber chemicals department (i.e., antioxidant, accelerant, and recycle process, and maintenance workers) indicate that the geometric mean breathing zone concentrations for *ortho*-toluidine for antioxidant production workers and maintenance personnel were similar and approximately twice those for accelerant production. Exposure levels among rubber chemical workers have decreased over time from a high of 0.1 ppm (time period from 1976 to 1979) to < 0.02 ppm (time period from 1995 to 2004). Data reported for the same operations, e.g., “Maintenance,” are higher for the results from the NIOSH survey compared with the company-reported data, but the time periods covered differ, and the NIOSH data were based on fewer samples for each process.

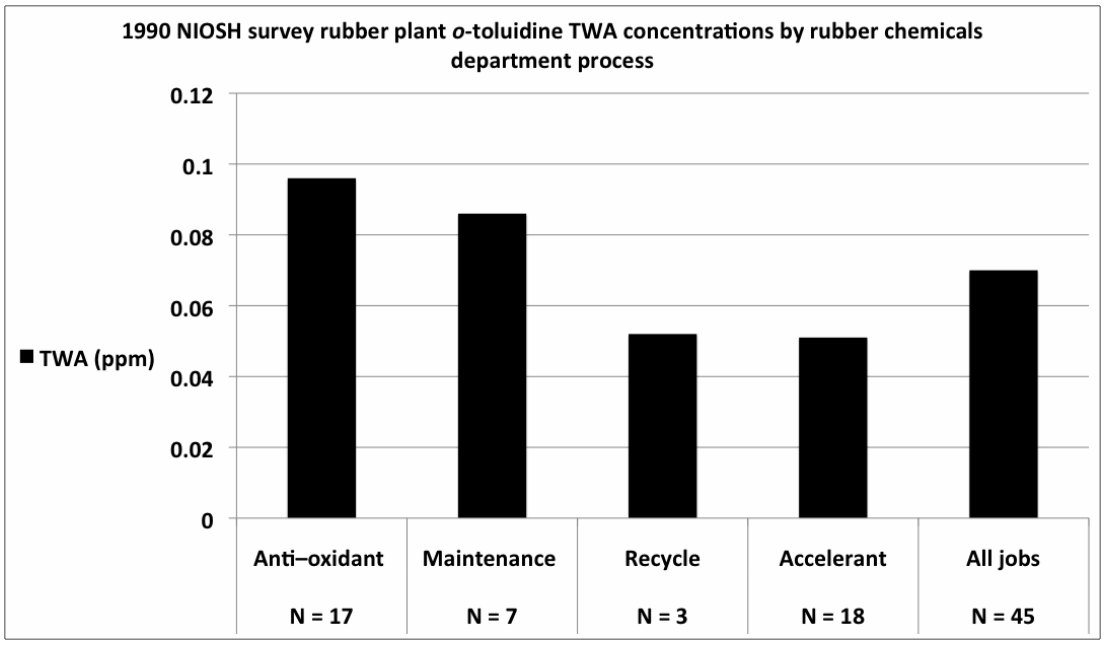

Figure 1-4. Air monitoring data (TWA breathing zone, geometric means) for *ortho*-toluidine collected by NIOSH in 1990 for processes in the rubber chemicals department

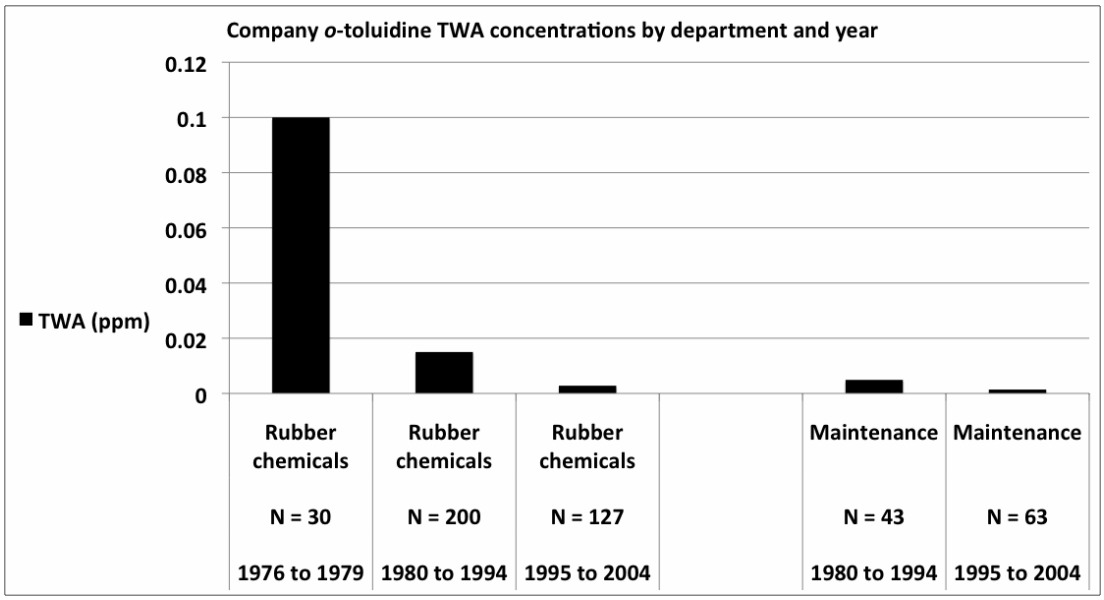

Figure 1-5. Air monitoring data (TWA breathing zone, geometric means) collected by the company by department and time period

The continued use of *ortho*-toluidine in the rubber chemicals industry and for production of the herbicide intermediate and dye intermediates indicate that workers in the United States are currently exposed, although no current information is available on the number of workers in each industry. Data from the NIOSH National Occupational Exposure Survey (NOES), conducted between 1981 and 1983, estimated that about 30,000 workers, including approximately 15,500 women, were potentially exposed to *ortho*-toluidine

during that time period (NIOSH 1990a). (Note: The NOES database has not been updated since July 1, 1990, and NIOSH has not conducted any national surveys of occupational exposure since that time.)

NIOSH recommends that worker exposure to *ortho*-toluidine be minimized through the use of engineering controls, work practices, and personal protective equipment (NIOSH 1991).

1.5 Potential for exposure from other sources: cigarette smoking, medical and consumer products, and food

ortho-Toluidine (and other arylamines) have been detected in the urine of non-occupationally exposed individuals in several studies (see Table 1-4); the sources proposed for the exposure underlying these levels include combustion products, passive smoking, dyestuffs in cosmetics and clothing (Riffelmann *et al.* 1995), and food (el-Bayoumy *et al.* 1986), but no data were identified to document contributions by any of these potential sources. *ortho*-Toluidine–releasing adducts were detected in 11 of 12 urinary bladder tumor samples (8.72 ± 4.49 fmol/μg DNA) as well as in 13 of 46 urinary bladder epithelial tissue samples (0.24 ± 0.63) and 10 of 46 urinary bladder submucosal tissue samples (0.27 ± 0.70) obtained from sudden death victims in Germany (Böhm *et al.* 2011). The authors reported that the subjects had no known occupational exposure to aromatic amines and that smoking status had no significant effect on the adduct levels detected. *ortho*-Toluidine adducts to hemoglobin (Hb) were already detected in 25 patients before treatment with prilocaine as a local anesthetic (see below) (Gaber *et al.* 2007, IARC 2012). Several lines of evidence suggest that exposure to *ortho*-toluidine occurs for non-occupationally exposed individuals from sources such as cigarette smoking, medical products (e.g., the local anesthetic prilocaine), some consumer products (e.g., hair dyes), and possibly food.

ortho-Toluidine has been measured in mainstream cigarette smoke at 9 to 144 ng per cigarette (Stabbert *et al.* 2003, as cited in IARC 2012). *ortho*-Toluidine urinary concentrations and hemoglobin adducts have generally been reported to be somewhat higher in non-occupationally exposed smokers than in non-smokers (el-Bayoumy *et al.* 1986, Riedel *et al.* 2006, Riffelmann *et al.* 1995), although in many studies the influence of smoking was weak (Kütting *et al.* 2009) (see Table 1-4). Among workers exposed to *ortho*-toluidine, there was little difference between exposure levels (urinary concentration or hemoglobin adducts) among workers that smoked compared with non-smoking workers (Ward *et al.* 1996, Korinth *et al.* 2007, Riffelmann *et al.* 1995).

Exposure to *ortho*-toluidine from medical products can occur from a product used for anesthesia. Prilocaine, a widely used local or topical anesthetic is required by U.S. Pharmacopeia standards to contain no more than 0.01% *ortho*-toluidine, but once in the body, prilocaine can be metabolized to release *ortho*-toluidine. Humans exposed to prilocaine excreted 0.75% of the dose as *ortho*-toluidine and 36.9% as hydroxylated *ortho*-toluidine (NTP 2000). The average amount of *ortho*-toluidine adducts to hemoglobin (Hb) increased 41-fold, from 0.54 ± 0.95 ng/g Hb before treatment to 22 ± 13.2 ng/g Hb at 24 hours after surgery in 25 patients who received prilocaine for local anesthesia (Gaber *et al.* 2007, IARC 2012). Information on sales of dental local anesthetics in the United States in the 11-year period from 1997 to 2008 indicate average

sales of approximately 18 million cartridges of prilocaine per year (Garisto *et al.* 2010), and recommended doses range from 1 to 8 72-mg cartridges per dental procedure (DrugsArea 2007). No specific information on the number of people exposed to prilocaine annually in the United States was identified, but based on the sales figures, a relatively small percentage of the population could be treated with prilocaine (assuming one cartridge per person, no more than 6% of the population could be exposed). Based on the current U.S. population of 314 million, potential exposure to this source of *ortho*-toluidine could still affect several million people. The actual percentage of people could be lower, depending on the use of multiple doses for individual dental patients, but that would result in increased exposure levels for those patients. Prilocaine is also present with lidocaine in a topical local anesthetic cream used to numb the skin for needle insertion or minor surgical procedures; although these products for both prescription and over-the-counter sales are widely advertised on the Internet, no sales or use data for this preparation were found.

Exposure to *ortho*-toluidine can potentially result from exposure to dyes in consumer products, including some hair dyes. Akyüz and Ata (2008, as cited in IARC 2012) reported finding *ortho*-toluidine in 34 of 54 hair dyes tested in Turkey, at levels up to 1,547 µg/g. Hair dyes in Turkey were identified as available for sale on the Internet, but no information on the *ortho*-toluidine content of the dyes was identified (Alibaba 2013, Allbiz 2013). Currently, 11 *ortho*-toluidine-based dyes are listed in the Colour Index as having commercial products, ranging from 2 to 193 depending on the dye (Freeman 2012). Most of the manufacturing involving these dyes occurs outside the United States and Europe, mainly in China and India. Many current commercial organic pigments, including Pigment Red 95, Pigment Red 148, and Pigment Red 253, are derived from *ortho*-toluidine. Pigment Red 95, Pigment Red 148, and Pigment Red 253 require the product from the reaction of *ortho*-toluidine with beta-oxynaphthoic acid for their production. The *ortho*-toluidine-based colorant Pigment Yellow 14 (193 commercial product listings in the Colour Index) requires production of the ortho-toluidine-based precursor acetoacet-ortho-toluitide. No information on specific use of these dyes in the United States was identified, but they are available from a number of suppliers, primarily in China and India, and no U.S. import restrictions were found.

In a German survey of primary and secondary amines in the human environment, a number of foods were examined; < 0.1 ppm of *ortho*-toluidine was detected in a sample of broken beans; however, it was not found in 9 other samples of preserved vegetables, or in more than 16 other foods tested (Neurath *et al.* 1977, as cited in HSDB 2011). Also, aminotoluene (toluidine), isomer unspecified, was found in shelled peas at a concentration of 0.4 ppm, in red cabbage at a concentration of 0.2 ppm, in kale at a concentration of 1.1 ppm, in carrots at a concentration of 7.2 ppm, and in celery at a concentration of 1.1 ppm (HSDB 2011). As cited in IARC 2012, Vitzthum *et al.* (1975) reported that *ortho*-toluidine has been detected as a volatile in black tea (IARC 2012). No information for *ortho*-toluidine was identified in the U.S. Food and Drug Administration's Total Diet Study (TDS) for market baskets 1991–3 through 2003–4 collected between September 1991 and October 2003 (FDA 2006).

In summary, although exposure levels from all of these sources are lower relative to occupational exposures, almost everyone would be affected by exposure through food. In

contrast, about 19% of U.S. adults smoked in 2010 (CDC 2012), and estimates for use of hair dye "indicate that more than one-third of women over age 18 and approximately 10% of men over age 40 use some type of hair dye" (Huncharek and Kupelnick 2005). Based on 2010 U.S. census data (Howden and Meyer 2011), approximately 43 million individuals or a little less than 15% of the U.S. population would be exposed to hair dyes of all types. As noted above, exposure to *ortho*-toluidine from the use of prilocaine as a dental anesthetic is estimated to occur to 6 percent or less of the U.S. population.

1.6 Potential for environmental exposure

People in the United States are potentially exposed to *ortho*-toluidine from the environment via releases into the atmosphere, as documented by TRI data (see Section 1.6.1), and data regarding people living close to emitting facilities (see Table 1-6). Occurrence data support these conclusions (see Section 1.6.2). In addition, *ortho*-toluidine hemoglobin adducts were found to be higher among children residing in cities compared with children residing in a largely rural environment in Germany suggesting the potential for environmental exposure because it is unlikely that food or personal products use differs in the three geographical areas. *ortho*-Toluidine hemoglobin adducts were lower in children from smoking homes compared with non-smoking homes.

1.6.1 Release of *ortho*-toluidine to the environment

ortho-Toluidine's production and use in the production of textile dyes or rubber vulcanization accelerators and antioxidants, and as an intermediate in organic synthesis results in its release to the environment through various waste streams (HSDB 2011). According to the TRI, total reported on- and off-site release of *ortho*-toluidine was slightly over 6,600 pounds from 15 facilities in 2010 (TRI 2012). Releases to air accounted for 77.4% of total releases, disposal by underground injection for 19.6%, and releases to water for 3.0%. No releases were reported to either land or off-site disposal. Figure 1-6 shows a color-coded map of sites reporting on-site *ortho*-toluidine releases into the air, water, and ground to TRI in 2010 (TOXMAP 2012). The color of each circle indicates the amount of total on-site release for calendar year 2010. (See below for estimates of the numbers of individuals living near facilities reporting release of *ortho*-toluidine to the air.) Based on the visual depiction of *ortho*-toluidine releases in Figure 1-6, *ortho*-toluidine has been released at industrial facilities mostly in the northeast and southeast regions of the United States. The highest reported *ortho*-toluidine release is from a facility in Niagara Falls, NY, which is the site of the rubber chemical plant studied by NIOSH (see Section 1.4).

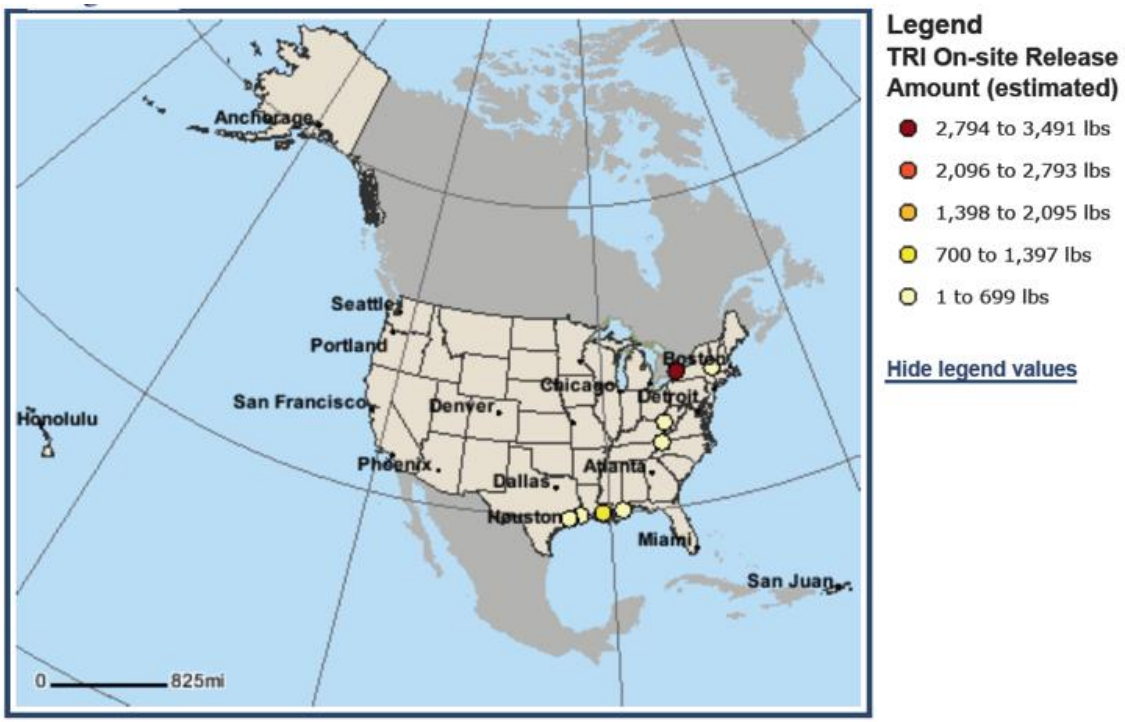

Figure 1-6. Map of reported TRI on-site *ortho*-toluidine releases for 2010

The top 5 *ortho*-toluidine-emitting facilities released approximately 5,000 pounds of *ortho*-toluidine to the air, accounting for approximately 98% of total *ortho*-toluidine air emissions reported to TRI in 2010 (TRI 2012). Table 1-6 presents demographic data from EPA's EJView website based on U.S. Census data for 2000 for areas within 0.5 mile and 1 mile of the top 10 *ortho*-toluidine-emitting facilities in 2010. Based on these data, approximately 1,400 people lived within 0.5 mile of these facilities, and 8,800 people within 1 mile of these facilities. These facilities are engaged in production of rubber chemicals, pesticide intermediates, dye intermediates, or *ortho*-toluidine. The numbers could be underestimates because census data are for residential populations and would not include workers who do not live within these boundaries. No data were identified for concentrations of *ortho*-toluidine in air near any of these sites.

Table 1-6. Demographic data for areas within 0.5 mile and 1 mile of the top 5 *ortho*-toluidine-emitting facilities in 2010

City	State	*ortho*-Toluidine air emissions (pounds)	Total persons within 0.5 Mile	Total persons within 1 Mile
Niagara Falls[a]	NY	3,491	763	4,428
Pasadena	TX	673	0	0
Geismar	LA	609	0	6
Pascagoula	MS	139	0	13
Kingsport	TN	111	137	2,942
Total		**5,023**	**900**	**7,389**

Sources: EjView2012a-j, TRI 2012.
[a]This plant is the same one assessed by Hanley *et al.* 2012 for exposure to *ortho*-toluidine and aniline.

Figure 1-7 shows a map of Superfund sites on the National Priorities List (NPL) where *ortho*-toluidine was listed as a site contaminant (TOXMAP 2012). Based on Figure 1-7, Superfund sites where *ortho*-toluidine was listed as a site contaminant also appear to be located primarily in the northeast and southeast United States.

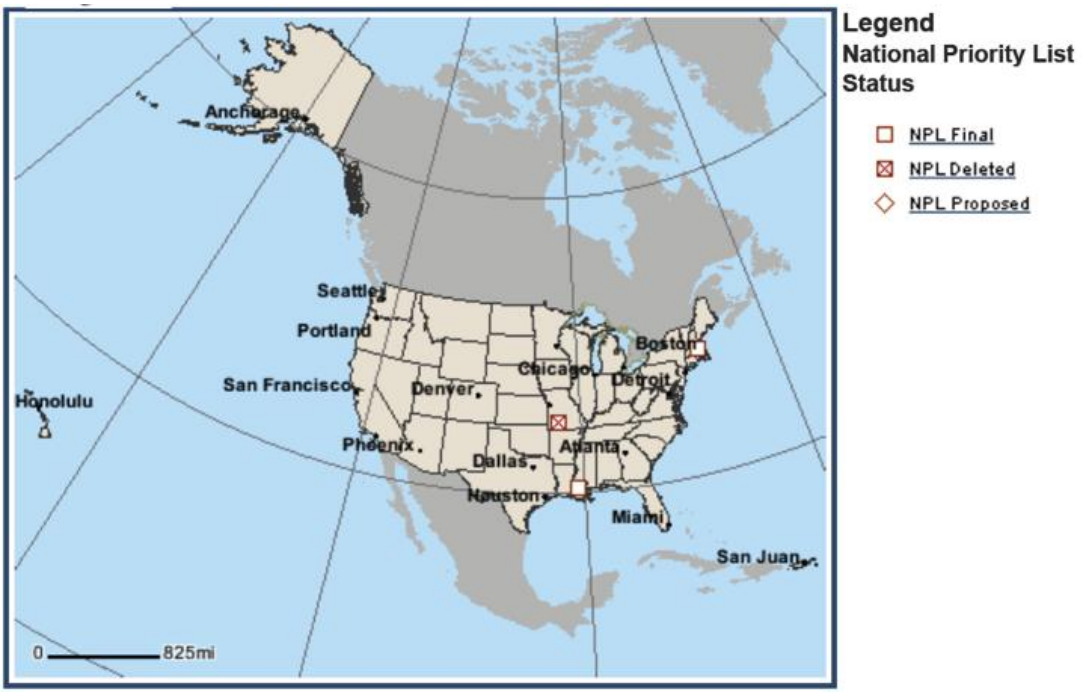

Figure 1-7. Map of Superfund sites at which *ortho*-toluidine was listed as a site contaminant

1.6.2 Fate and occurrence

Environmental exposure to *ortho*-toluidine is possible based on its occurrence in water and sediment worldwide. However, no data for *ortho*-toluidine concentration levels in ambient air or soil have been identified. Table 1-7 presents concentration level data identified for *ortho*-toluidine in water and sediment. The highest levels occurred in sediment or water close to industrial areas.

Table 1-7. *ortho*-Toluidine groundwater, surface water, and sediment concentration levels

Location	Number of samples/frequency of detection	Mean conc. (range), ppb	References[a]
Groundwater			
Hoe Creek coal gasification project, Northeastern WY	3	– (0.06–9.2)[b]	Stuermer *et al.* 1982
Surface Water			
Rhine River, Netherlands	6% of samples	0.03 (1.8 max)	Wegman and Dekorte 1981

Location	Number of samples/frequency of detection	Mean conc. (range), ppb	References[a]
Rhine River tributaries, Netherlands	8% frequency of detection	– (0.07–2.4)	Wegman and Dekorte 1981
River Waal, Netherlands	Not reported	0.7 (–)	Meijers and Vanderleer 1976
Japan, industrial areas between 1974 and 1976	8 out of 68 samples	20 (–)	Kubota 1979
Sediment			
Japan, industrial areas between 1974 and 1976	27 out of 68 samples	72 (–)	Kubota 1979

– = no data available.
[a]As cited in HSDB 2011.
[b]Combined concentration of 2- and 4-aminotoluene (*ortho*- and *para*-toluidine), sampled 15 months after completion of project.

1.7 Synthesis and summary

Several lines of evidence indicate that a significant number of people living in the United States are exposed to *ortho*-toluidine. This evidence includes widespread use, production, or imports of large amounts of *ortho*-toluidine (ranging from 10 million to 50 million pounds in 2006 and importation of 58 million pounds in 2011), and biological monitoring data demonstrating exposure in both occupationally and nonoccupationally exposed individuals and in both smokers and nonsmokers.

The highest exposure to *ortho*-toluidine occurs in the workplace; urinary exposure levels were over 26-fold higher among workers exposed to *ortho*-toluidine than among unexposed workers (Ward *et al.* 1996). Exposure via inhalation and dermal contact also can occur in the workplace through the production and use of *ortho*-toluidine in the chemical industry.

Exposure occurs through these occupational uses, but the presence of *ortho*-toluidine in urine and as hemoglobin adducts in individuals without known occupational exposure supports more widespread exposure. One source of this exposure is tobacco smoking, but exposure from consumer products (e.g., hair dyes), dental products (e.g., prilocaine), and food is also possible. Although nonoccupational exposure levels are lower than occupational exposure levels, these exposures are common, indicating that more people living in the United States are potentially exposed to *ortho*-toluidine from these sources than occupationally. No direct evidence for exposure of the general population to *ortho*-toluidine from environmental sources was identified, but TRI data indicate that production- and use-related releases of *ortho*-toluidine have occurred at numerous industrial facilities in the United States, and a biological monitoring study in Europe reported that exposure levels in children varied with geographical residence (lower in a largely rural environment) suggesting the importance of environmental sources.

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2 Disposition and Toxicokinetics

The available data on the absorption, distribution, and excretion of *ortho*-toluidine in humans and experimental animals are summarized in Section 2.1, and metabolism is discussed in Section 2.2. Toxicokinetic data for *ortho*-toluidine were limited and are briefly reviewed in Section 2.1.1. Mechanistic implications of the processes of absorption, distribution, metabolism, and excretion are discussed further in Section 5.

2.1 Absorption, distribution, and excretion

2.1.1 Experimental animals

ortho-Toluidine is well absorbed following oral exposure based on studies in male rats (IARC 2000, 2010a). Absorption data for female rats, other species, or other routes of exposure were not available. Once absorbed, *ortho*-toluidine is rapidly distributed, metabolized, and excreted (Brock *et al.* 1990, Cheever *et al.* 1980, Son *et al.* 1980). Distribution data were available from rats exposed by subcutaneous (s.c.) injection or oral gavage. These studies show general agreement regarding tissues with the highest concentrations. In male F344 rats exposed to 50 or 400 mg/kg *ortho*-[methyl-^{14}C]toluidine (2 animals per dose) by s.c. injection, radioactivity was detected in the liver, kidney, lung, spleen, colon, and urinary bladder 48 hours later (Son *et al.* 1980). The highest concentrations occurred in the liver; however, compared with the increase in dose, disproportionate increases of ^{14}C occurred in all tissues examined. These data imply saturation of some metabolic pathway(s) at the higher dose. Brock *et al*. (1990) reported more extensive tissue distribution data in male Crl:CD® BR rats 72 hours after receiving a single 500 mg/kg oral dose of radiolabeled *ortho*-[ring-U-^{14}C]toluidine (Figure 2-1). The dose was selected as an approximate equivalent of the dietary level that produced tumors in the long-term carcinogenicity studies (see Section 4). The highest concentrations were found in whole blood, spleen, kidneys, and liver. Peak blood levels of undifferentiated radioactivity were reached at 24 hours, and the half-life for plasma elimination ranged from about 12 to 15 hours. The kinetic studies are of limited use in that it is unknown what percentage of the radioactivity in plasma is due to [^{14}C]-*ortho*-toluidine. The major tumor sites in animals administered *ortho*-toluidine in feed (see Section 4) were the urinary bladder, spleen, and abdominal organs and connective tissue in rats and liver and blood vessels in mice. The urinary bladder also is the tumor site of interest in humans (see Section 3). Most of these tissues were among those with the highest accumulation of radioactivity in both distribution studies in rats.

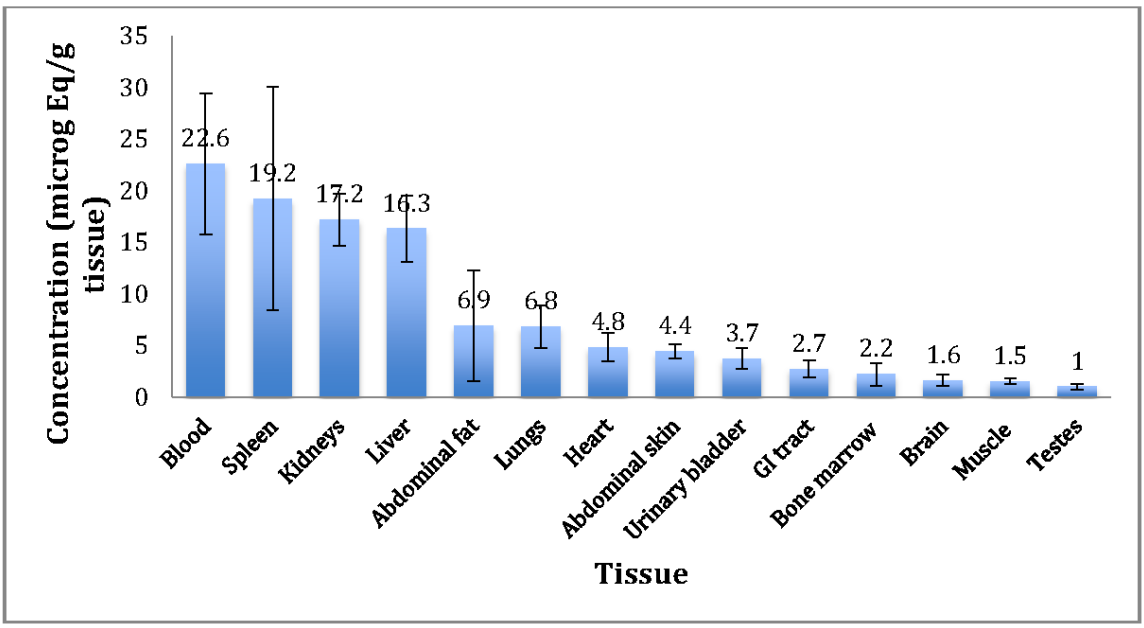

Figure 2-1. Tissue distribution of orally administered *ortho*-toluidine in male rats
Source: Brock *et al.* (1990) (mean ± SD from four rats; samples collected at 72 h).

The primary route of excretion in rats was the urine regardless of exposure route. Following a single subcutaneous dose of either 50 or 400 mg/kg, 75% to 84% was excreted in the urine within 48 hours (Son *et al.* 1980) while more than 92% of an oral dose of 50 mg/kg was excreted in the urine within 24 hours (Cheever *et al.* 1980). Subcutaneous administration forces 100% absorption of the dose. The observation that urinary excretion is about the same for both routes implies near 100% absorption of the oral dose. The saturation of metabolic pathways is not as apparent in the urinary excretion data. Excretion via the lungs and feces were approximately 1% and 3%, respectively (Son *et al.* 1980). The amount of unmetabolized compound detected in the urine ranged from about 3.6% to 5.1% in male F344 rats administered 0.82 mmol/kg (about 88 mg/kg) (Kulkarni *et al.* 1983) or 400 mg/kg *ortho*-toluidine by s.c. injection (Son *et al.* 1980). The amount of unchanged toluidine excreted in rat urine also depended on the dose and isomer administered (Cheever *et al.* 1980). Male Sprague-Dawley rats administered a single oral dose (500 mg/kg) of *meta*- or *para*-toluidine excreted only 2.5% of the dose as the parent compound compared with 21% for *ortho*-toluidine, even though there were no major differences in the primary metabolic pathways (ring hydroxylation followed by sulfate or glucuronide conjugation) (see Section 2.2). Rats administered a lower oral dose of *ortho*-toluidine (50 mg/kg) excreted 36% of the dose unchanged.

2.1.2 Humans

The primary routes of exposure to *ortho*-toluidine in humans are the respiratory tract and skin (IARC 2000). Evidence that *ortho*-toluidine is absorbed following inhalation exposure comes from studies that measured *ortho*-toluidine in urine and/or as hemoglobin adducts in occupationally exposed workers (Korinth *et al.* 2007, 2006, Ward *et al.* 1996). Studies in different populations of rubber industry workers reported that *ortho*-toluidine concentrations in workplace air correlated significantly with

concentrations in the urine (Brown *et a*l. 1995). A series of studies of *ortho*-toluidine exposed and non-exposed workers in the rubber chemicals industry reported that exposed workers had approximately 25 times higher post-shift urinary levels of *ortho*-toluidine–compared with non-exposed workers and that the post-shift urinary exposure levels among exposed workers were 6-fold higher than the pre-shift levels (Stettler *et al.* 1992). Pre-shift urinary levels of exposed workers were also higher than those of non-exposed workers suggesting that *ortho*-toluidine is not completely eliminated from the bodies of the exposed workers between work shifts (Brown *et al*. 1995, Stettler *et al.* 1992). *ortho*-Toluidine has been detected in the urine of non-smoking individuals with no known occupational exposure to *ortho*-toluidine, which implies possible absorption from contaminated food and water (El-Bayoumy *et al.* 1986).

Several *in vitro* studies reported that *ortho*-toluidine (either as neat compound or in a solution with phosphate buffer and 5% ethanol) was readily absorbed through excised human skin mounted on diffusion cells (Lüersen *et al.* 2006, Wellner *et al.* 2008). About 15% of the applied dose penetrated over 7 hours and 50% penetrated within 24 hours (Lüersen *et al.* 2006). Dermal absorption of *ortho*-toluidine was shown to be significant in studies of rubber industry workers (Korinth *et al.* 2007, Korinth *et al.* 2006). These studies monitored workplace air concentrations of *ortho*-toluidine, measured internal exposure based on either hemoglobin adducts or urinary excretion, and documented skin conditions of the workers. These studies demonstrated that the relative internal exposure depended more on the skin condition of the workers than on the concentrations of *ortho*-toluidine in the air. Internal exposure was significantly higher in workers with skin lesions (burns, erythema, or eczema) compared with workers with healthy skin. Furthermore, frequent use of skin barrier creams was shown to enhance dermal absorption of *ortho*-toluidine. Korinth *et al.* (2008) confirmed that skin barrier creams actually enhanced dermal absorption of *ortho*-toluidine *in vitro* using diffusion cells and excised human skin. The highest mean enhancement factors (based on maximum fluxes from the same skin donor in the same experimental series for untreated and treated skin) ranged from 6.2 to 12.3.

No tissue distribution studies were identified for humans.

2.2 Metabolism

Few studies have investigated *ortho*-toluidine metabolism in experimental animals or humans or have identified the specific cytochromes P450 involved. This section provides a brief review of the metabolism of aromatic amines and *ortho*-toluidine. Metabolism studies in experimental animals and humans are reviewed in Sections 2.2.1 and 2.2.2, respectively, and metabolic enzymes are discussed in Section 2.2.3.

2.2.1 Experimental animals

The only metabolism studies identified that were specific for exposure to *ortho*-toluidine were in male rats (Kulkarni *et al.* 1983, Son *et al.* 1980). Son *et al*. used solvent extraction and chromatography on several absorbants to isolate metabolites. Nonextractable conjugated metabolites were hydrolyzed enzymatically and the aglycones were isolated by chromatography. GC/MS was used to identify the aglycones. The major metabolic pathways of *ortho*-toluidine in rats were *N*-acetylation and hydroxylation at the 4 position (*para* to the amine group), followed by glucuronide or sulfate conjugation.

Glucuronidation, acetylation, and oxidation are competing metabolic reactions in most species (Freudenthal *et al.* 1999). Sulfate and glucuronide-conjugated urinary metabolites comprised about half of the administered dose (Table 2-1). The ratio of sulfates to glucuronides was approximately 6:1. Minor metabolic pathways included hydroxylation at the 6 position (*ortho* to the amine group), oxidation of the methyl group, and oxidation of the amine group. A double acid conjugate of 4-amino-*meta*-cresol (thought to be the *N*-glucuronide of 4-amino-*meta*-cresyl sulfate) was identified but the amount was not reported. A subsequent study by Kulkarni *et al*. (1983) identified *N*-hydroxy-*ortho*-toluidine in rat urine using HPLC with an electrochemical detector. They noted that this metabolite might play a role in urinary bladder carcinogenicity (see Section 5.2.1). Cheever *et al.* (1980) reported that ring hydroxylation was a major metabolic pathway in rats with about half of the administered dose recovered as conjugates of 4-amino-3-methylphenol (4-amino-*meta*-cresol).

Table 2-1. Metabolites of *ortho*-toluidine detected in rat urine

Metabolite	Relative amount (% of dose)[a]
Ether-extractable metabolites	
ortho-Toluidine	3.6[b]–5.1
Anthranilic acid	0.3
N-Acetyl-anthranilic acid	0.3
N-Acetyl-*ortho*-toluidine	0.2
N-Acetyl-*ortho*-aminobenzyl alcohol	0.3
N-Acetyl-4-amino-*meta*-cresol	0.3
4-Amino-*meta*-cresol	0.06
ortho-Azoxytoluene	0.2
ortho-Nitrosotoluene	≤ 0.1
N-Hydroxy-*ortho*-toluidine	0.1[b]
Acid-conjugated metabolites	
4-Amino-cresyl sulfate	27.8
N-Acetyl-4-amino-*meta*-cresyl sulfate	8.5
2-Amino-*meta*-cresyl sulfate	2.1
4-Amino-*meta*-cresyl glucuronide	2.6
N-Acetyl-4-amino-*meta*-cresyl glucuronide	2.8
N-Acetyl-*ortho*-aminobenzyl glucuronide	1.3
Unidentified conjugated metabolites	5.9

Sources: Kulkarni *et al.* 1983, Son *et al.* 1980.
[a]Measured 24 hours after a single s.c. dose of 400 mg/kg unless otherwise noted.
[b]Measured 6 hours after a single s.c. dose of 0.82 mmol/kg [~88 mg/kg].

In addition to the metabolites listed in Table 2-1, Gupta *et al*. (1987) predicted the existence of several metabolites based on data from other aromatic amines. These included *N*-acetoxy-*ortho*-toluidine (formed by acetylation of *N*-hydroxy-*ortho*-toluidine), *N*-acetyl-*N*-hydroxy-*ortho*-toluidine (formed by oxidation of *N*-acetyl-*ortho*-toluidine), *N*-acetoxy-*N*-acetyl-*ortho*-toluidine (formed by acetylation of *N*-acetyl-*N*-hydroxy-*ortho*-toluidine), 2-hydroxy-6-methyl-acetanilide (formed by acetylation of 2-amino-*meta*-cresol), and *ortho*-azotoluene (formed through a reaction of *ortho*-toluidine with *ortho*-nitrosotoluene). *N*-acetoxy-*ortho*-toluidine could undergo non-enzymatic breakdown to form several reactive electrophilic species (i.e., nitrenium ions, nitrene, and free radicals) that could bind to macromolecules. Another pathway involves oxidation of unconjugated phenolic metabolites to form reactive quinone imines (English

et al. 2012, Skipper *et al.* 2010). Metabolic pathways of *ortho*-toluidine are shown in Figure 2-2.

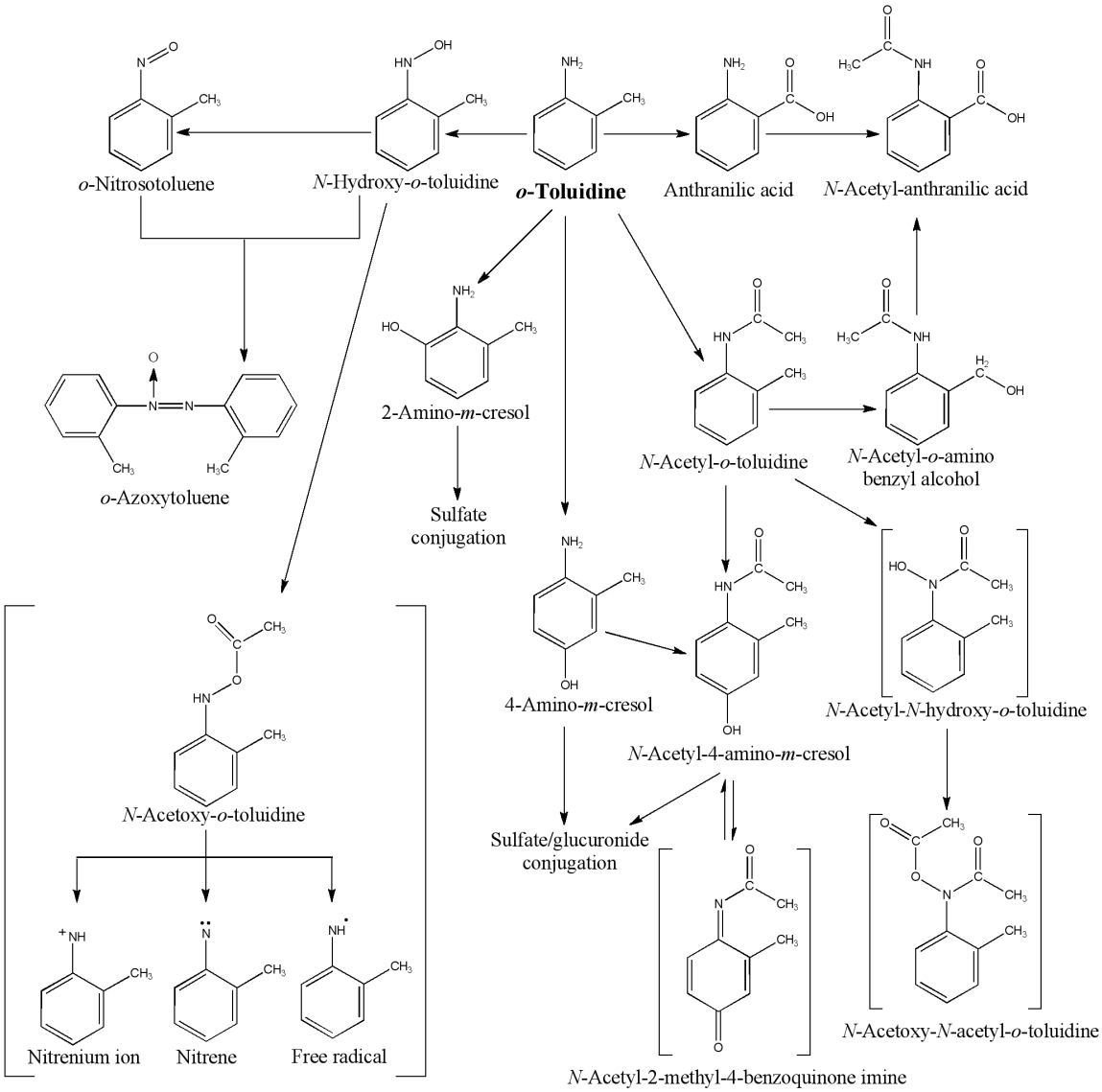

Figure 2-2. Metabolism of *ortho*-toluidine in rats

Sources: English *et al.* 2012, IARC 2000, Skipper *et al.* 2010, Son *et al.* 1980.
Brackets indicate postulated proximate or reactive metabolites based on data from other aromatic amines.

Toxicity studies of various aromatic amines in rats, mice, guinea pigs, rabbits, dogs, and monkeys show significant species differences in sensitivity to the carcinogenic effects of these chemicals (Freudenthal *et al.* 1999). The differences in species responses were related to differences in metabolism, particularly the ability of each species to *N*-acetylate aromatic amines, which is considered to be a detoxification step for urinary bladder cancer but an activating step for liver cancer. The mechanistic implications of these species differences in metabolism are discussed in Sections 5.2.1 and 5.2.2.

2.2.2 Humans

No studies of *ortho*-toluidine metabolism in humans were identified; however, metabolic pathways are expected to be similar to those reported in experimental animals based on studies of other aromatic amines and knowledge of the key metabolizing enzymes. *ortho*-Toluidine also is a major metabolite of the commonly used local anesthetic prilocaine (Gaber *et al.* 2007).

Ward *et al.* (1996) monitored aromatic amine exposure in workers at a chemical plant and reported that base hydrolysis was used to convert *N*-acetyl-*ortho*-toluidine to the parent compound prior to analysis, thus, indicating that *N*-acetylation of *ortho*-toluidine occurred in humans. Lewalter and Korallus (1985) noted that acetylation is a common metabolic pathway for aromatic amines but that only free, nonacetylated aromatic amines could lead to formation of hemoglobin (protein) adducts. Based on data for other aromatic amines, an oxidized metabolite (nitroso form) can come in contact and bind to hemoglobin in the blood (Skipper *et al.* 2010, Skipper and Tannenbaum 1994). Several studies have detected *ortho*-toluidine hemoglobin adducts in humans (Seyler *et al.* 2010, Korinth *et al*. 2006, 2007, Richter and Branner 2002, Richter *et al.* 2001, Ward *et al*. 1996, Bryant *et al.* 1988). The presence of hemoglobin adducts can be used as a biomarker of aromatic amine bioactivation to their ultimate carcinogenic form (Richter and Branner 2002, Skipper and Tannenbaum 1994). Gaber *et al.* (2007) also reported that *ortho*-toluidine–releasing hemoglobin adducts were increased up to 360-fold after prilocaine treatment. Prilocaine also is a well-known methemoglobin inducer (Gaber *et al.* 2007, Hjelm 1965). Methemoglobin is one of the principal acute effects observed in humans exposed to *ortho*-toluidine (English *et al.* 2012). The probable metabolic pathway leading to methemoglobinemia is metabolism of *ortho*-toluidine by hepatic cytochrome P450 enzymes to *N*-hydroxy-*ortho*-toluidine. Further oxidation of the *N*-hydroxy metabolite to nitrosotoluene occurs in the blood, thus generating methemoglobin.

2.2.3 Metabolic enzymes

Cytochromes P450 (possibly CYP1A2 and CYP1A1) are responsible for *N*-hydroxylation of aromatic amines (Delclos and Kadlubar 1997, Windmill *et al.* 1997). Mammalian peroxidases also can catalyze oxidative metabolism of aromatic amines (Delclos and Kadlubar 1997, English *et al.* 2012). In humans, CYP1A2 is expressed constitutively in the liver but not in other tissues, while CYP1A1 is predominantly expressed in extrahepatic tissues. However, no definitive studies on the participation of CYPs in *ortho*-toluidine metabolism have been conducted, and some studies in rats and humans suggest that CYP1A2 does not play a significant role in the metabolic activation of this compound (Gaber *et al.* 2007, IARC 2010a). Some data suggest that the ring-hydroxylation of *ortho*-toluidine is catalyzed by CYP2E1 (Diaz Gómez *et al.* 2006).

Jodynis-Liebert and Matuszewska (1999) studied the effects of toluidines and dinitrotoluenes on caffeine metabolism in rats and showed that *ortho*-, *meta*-, and *para*-toluidine induced CYP1A2 in the liver. CYP1A2-catalyzed *N*-hydroxylation is known to lead to bioactivation of many carcinogenic aromatic amines. Other studies have shown that recombinant human cytochromes P450 (CYP2A6, CYP2E1, CYP1A1, CYP2B6, CYP2D6, or CYP3A4) can metabolize the aromatic amines 2,6-dimethylaniline and *ortho*-anisidine and might play a role in their bioactivation (Gan *et al.* 2001, Stiborová *et*

al. 2005). Most of these P450s are expressed in the liver; however, CYP1A1 primarily is expressed in extrahepatic tissues, while 2E1, 2B6, 3A4, and 2D6 also have extensive extrahepatic activity. CYP1A1, 2D6 and 2E1 mRNA expression has been reported in human urinary bladder tissue and 1A1 also is expressed in human urinary bladder malignancies (Brauers *et al.* 2000).

In addition to P450-mediated *N*-hydroxylation, mammalian peroxidases (e.g., prostaglandin H synthase or myeloperoxidase) can metabolize ring-hydroxylated metabolites of aromatic amines to reactive quinone imines (Skipper *et al.* 2010). Phase II metabolic steps include *N*-acetylation, *O*-acetylation, *N*,*O*-transacetylation, *O*-sulfation, and glucuronidation (Woo and Lai 2004). Cytosolic arylamine *N*-acetyltransferases (NATs) catalyze *N*-acetylation, *O*-acetylation, and *N*,*O*-transacetylation reactions. Two mammalian cytosolic NATs have been identified in a variety of species, while three have been identified in mice (Delclos and Kadlubar 1997). Both of the NAT isozymes (NAT1 and NAT2) in humans are polymorphic and have different substrate specificities. NAT1 is expressed in most human tissues while NAT2 is predominantly expressed in liver, small intestine, and colon (Hein 2009). *O*-Sulfation reactions are catalyzed by cytosolic sulfotransferases (SULTs) (Windmill *et al.* 1997) and glucuronidation is catalyzed by UDP-glucuronosyltransferases in the endoplasmic reticulum (Woo and Lai 2004).

2.3 Synthesis

ortho-Toluidine can be absorbed after exposure in the air, on the skin, or through the gastrointestinal tract. Its distribution and excretion have been studied primarily in rodents where *ortho*-toluidine was detectable in blood, spleen, liver, kidneys, urinary bladder, and other tissues; excretion was mainly in the urine for all exposure routes with much smaller amounts eliminated through the lungs and in the feces.

ortho-Toluidine metabolism has only been investigated in male rats, thus, specific information on species and/or sex differences were not available. However, metabolism and toxicity data for various aromatic amines indicate that metabolic differences are important for species differences in toxicity. Cytochromes P450-mediated oxidation and acetylation, and glucuronide/sulfate conjugation reactions are the primary metabolic steps in all mammalian species studied. *N*-Hydroxylation has been identified as a key bioactivation step. The majority of the administered dose of *ortho*-toluidine is excreted as metabolites. More than half of a subcutaneous dose in rats was recovered in the urine as sulfate or glucuronide conjugates with smaller amounts of the parent molecule or acetylated metabolites.

Studies in the rat indicate that nitrosotoluene is formed from *N*-hydroxy-*ortho*-toluidine (Figure 2-2). Further metabolism of this molecule may lead to formation of reactive metabolites such as nitrenium ions, nitrene, and free radicals. Although no specific metabolism studies were available, there is indirect evidence based on formation of hemoglobin adducts and methemoglobin that nitrosotoluene is a metabolite of *ortho*-toluidine in humans. *N*-hydroxy-*ortho*-toluidine would be a likely intermediate in the formation of nitrosotoluene.

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3 Human Cancer Studies

Introduction

Human exposure to *ortho*-toluidine occurs mainly among industrial populations, where it is used primarily in the rubber chemical industry, as an intermediate in the manufacture of pesticides and of a variety of dyes and pigments, and in pharmaceuticals manufacturing (see Section 1, "Human Exposure"). While exposure to *ortho*-toluidine can also occur via tobacco smoke, the environment, and consumer products, all of the available human studies have been conducted among occupationally exposed populations.

The human cancer studies section describes and evaluates the available epidemiological data on exposure to *ortho*-toluidine and cancer, reaching a level of evidence conclusion according to the approach outlined in the "Protocol: Evaluation of Human Cancer Studies on Exposure to *ortho*-Toluidine for the Report on Carcinogens" (hereafter referred to as "Protocol," available at http://ntp.niehs.nih.gov/NTP/roc/thirteenth/Protocols/ortho-ToluidineProtocol_508.pdf). The steps in the cancer evaluation process, listed below, are captured in the following subsections or appendices.

1. Selection of the relevant literature included in the cancer evaluation (Section 3.1 and Appendix A, and in the Protocol).
2. Description of the study design, methodologies, and characteristics of the individual studies and identification of the tumor sites of interest (Section 3.2 and Appendix D)
3. Assessment of study quality (Section 3.3, Table 3-2; Appendix D, Tables D-3 and D-4)
4. Cancer assessment (Section 3.4): (i) evaluation of the cancer findings from the individual studies (Table 3-3) and (ii) synthesis of the evidence for human carcinogenicity across studies.
5. Preliminary recommendation for the level of evidence of carcinogenicity (sufficient, limited, or inadequate) of *ortho*-toluidine from human studies (Section 3.5).

3.1 Selection of the relevant literature

Details of the procedures used to identify and select the primary studies and supporting literature for the human cancer evaluation are detailed in Appendix A and in the Protocol. The primary epidemiological studies considered for the cancer evaluation had to meet the following criteria: (1) was a peer-reviewed, primary research study on potential exposure to *ortho*-toluidine, (2) provided exposure-specific analyses for *ortho*-toluidine or evidence that potential exposure to *ortho*-toluidine was highly likely based on author's report or inferred using relevant knowledge of industrial processes, and (3) provided risk estimates for cancer endpoints or information needed to calculate risk estimates. Studies identified that met these criteria included six occupational historical cohort studies of

cancer, and two population-based case-control studies (urinary bladder cancer and childhood acute lymphoblastic leukemia).

Studies excluded from the review were one case-control study of renal-cell cancer among paperboard printing workers (Sinks *et al.* 1992) that did not provide qualitative or quantitative evidence of potential exposure (although pigments containing *ortho*-toluidine and other chemicals were reportedly used in the past) and several case-series of urinary bladder cancer, primarily among dyestuff manufacturers, that did not report or permit the calculation of risk estimates for potential exposure to *ortho*-toluidine (Conso and Pontal 1982, Genin *et al.* 1978, Khlebnikova *et al.* 1970, Oettel *et al.* 1968, Uebelin and Pletscher 1954; for a historical review of earlier case series, see e.g., Michaels 1988). In general, no exposure data were reported in these studies, with the exception of the study of *ortho*-toluidine manufacturing workers in the former USSR by Khlebnikova *et al.* (1970), who reported ambient concentrations ranging from 0.5 to 28.6 mg/m^3 of *ortho*-toluidine and dermal exposure (see IARC 2010a).

3.2 Overview of the methodologies and study characteristics of the selected epidemiologic studies and identification of cancer endpoints

This section provides an overview of the characteristics and methodologies of the individual studies included in the review (see Table 3-1) and identifies the primary cancer endpoint(s) of interest. For each of the reviewed studies, detailed data on study design, methods, and findings were systematically extracted from relevant publications, as described in the study Protocol, into Tables D-1 and D-2 in Appendix D and Table 3-4 in Section 3.4. Background exposure information for some of these epidemiologic studies is available in Appendix C.

Table 3-1. Human cancer studies of potential exposure to *ortho*-toluidine

Primary reference	Name of study	Exposure assessment	Cancer endpoints
Cohort studies			
Case and Pearson 1954[a]	U.K. dye workers	Exposure assigned based on company rolls of magenta manufacturing workers	Mortality (SMR): urinary bladder cancer
Pira *et al.* 2010	Italian dye workers	Individual exposure assessment based on work history in departments producing *ortho*-toluidine, fuchsin, or safranine T dyes	Mortality (SMR): urinary bladder cancer
Ott and Langner 1983	U.S. dye workers	Individual exposure assigned by history and duration of employment in departments producing bromindigo and thioindigo dyes	Mortality (SMR): All causes, all cancers, digestive, respiratory, urinary bladder,
Stasik 1988	4-COT production workers	Employment in department producing or processing 4-chloro-*ortho*-toluidine	Mortality (SMR): All causes, stomach, urogenital, brain cancers Incidence (SIR): Urinary bladder cancer

Primary reference	Name of study	Exposure assessment	Cancer endpoints
Carreón *et al.* 2010	NIOSH (U.S.A.) rubber chemical workers	Individual exposure classified as definitely, possibly, and probably not *exposed to ortho*-toluidine based on work history and occupational hygiene data	Incidence/mortality (SMR, SIR, SRR): All causes (SMR) All cancers (SMR) 8 specific sites (SMR) Urinary bladder cancer (SMR, SRR, RR)
Sorahan 2008	U.K. rubber chemical workers	Individual exposure assigned by history and 3 levels of duration of employment in department producing "Sopanox" rubber chemical agent	Incidence/mortality (SMR, SIR, SRR) All causes (SMR) All cancers and > 30 specific cancers (SMR) (Sorahan *et al.* 2000) Urinary bladder cancer (SMR, SRR, RR)
Population- or hospital-based case-control studies			
Richardson *et al.* 2007	Canadian case-control study	Job-exposure matrix based on self-reported occupational questionnaire and NIOSH NOES Survey data	Incidence (OR) Urinary bladder cancer
Castro-Jiménez and Orozco-Vargas 2011	Colombian case-control study	Parental exposure to hydrocarbons including *ortho*-toluidine	Incidence (OR) Childhood acute lymphoblastic leukemia

4-COT = 4-chloro-*ortho*-toluidine; JEM = job-exposure matrix; NIOSH = National Institute for Occupational Safety and Health; NOES = National Occupational Exposure Survey (1983-1986); OR = odds ratio; RR = relative risk; SIR = standardized incidence ratio; SMR = standardized mortality ratio; SRR = standardized rate ratio.

[a]Although *ortho*-toluidine was not specifically mentioned in the study by Case and Pearson, exposure among magenta manufacturing workers is likely based on knowledge of the industrial process. In the U.K., the process for manufacturing magenta, resulting mainly in the production of magenta III (new fuchsin), involved condensation of *ortho*-toluidine and formaldehyde in the presence of *ortho*-nitrotoluene (Howe 1977).

Six occupational historical cohort studies of cancer among *ortho*-toluidine-exposed workers were identified: three cohort mortality studies were conducted among workers in the dyestuffs industry, two incidence/mortality studies in the rubber chemicals industry, and one incidence study in a plant manufacturing 4-chloro-*ortho*-toluidine (4-COT) (Table 3-1). Each of the studies conducted external or internal analyses on urinary bladder cancer risk, and four of the studies reported on some or all other cancer sites

Two standardized cohort mortality studies of dyestuff workers were conducted among male workers manufacturing magenta: a study in the United Kingdom, hereinafter referred to as the U.K. dye workers study (Case and Pearson 1954) and a second study in Italy hereinafter referred to as the Italian dye workers study (Pira *et al.* 2010) (see Table 3-1). In the U.K. study, exposure to *ortho*-toluidine was inferred based on knowledge of the industrial process in the United Kingdom during that time period. Findings of the

Italian dye workers study were reported in an initial mortality analysis to 1976 (Rubino *et al.* 1982) and in two follow-up studies to 1989 (Piolatto *et al.* 1991) and to 2003 (Pira *et al.* 2010). Exposure was assessed via individual work history. A third standardized mortality study was conducted among male workers engaged in the manufacture of thio- and bromindigo dyes in the United States (Ott and Langner 1983), hereinafter referred to as the U.S. dye workers study. Exposure to *ortho*-toluidine occurred only during the manufacture of thioindigo dyes and there was limited quantitative data documenting *ortho*-toluidine exposure.

A standardized urinary bladder cancer incidence analysis among male workers in Germany engaged in the manufacture of the azo dye and chlordimeform pesticide intermediate 4-COT, in which *ortho*-toluidine is used as a precursor, has been reported by Stasik (1988) (hereafter referred to as the 4-COT production workers study).

Two standardized mortality and incidence studies in the rubber chemical industry, in the United States (conducted by NIOSH, hereinafter referred to as NIOSH rubber chemical workers) and United Kingdom (hereinafter referred to as the U.K. rubber chemical workers) were identified. Findings from the NIOSH rubber chemical workers were reported in a series of publications involving two different exposure assessments. An analysis of urinary bladder incidence (Ward *et al.* 1991) and mortality (Prince *et al.* 2000) was conducted among male and female workers with a follow-up from 1973 through 1988, using the initial exposure assessment. Urinary bladder cancer cases and deaths identified in the 1991 analysis were subsequently re-analyzed by Carreón *et al.* (2010), based on a reclassification of exposure categories. Both (1991 and 2010) incidence analyses included internal analyses of duration of employment and time since first employment. Additional urinary bladder cancer cases in this cohort have been reported but not analyzed (Markowitz 2005, Markowitz and Levin 2004). Air monitoring and biological monitoring of a subset of workers for *ortho*-toluidine and co-exposures were also conducted and an updated, detailed exposure survey of ambient levels of *ortho*-toluidine and co-exposures was conducted by Hanley *et al.* (2012). The United Kingdom study evaluated standardized cancer mortality and incidence among male rubber chemical manufacturing workers. Findings of an initial follow-up to 1986 were reported by Sorahan and Pope (1993), follow-ups to 1992 (incidence) and 1996 (mortality) by Sorahan *et al.* (2000), and follow-up to 2005 by Sorahan (2008). Analysis by duration of employment was conducted for this cohort but no quantitative data on *ortho*-toluidine exposure were reported.

Two case-control studies were identified: a population-based Canadian cancer registry study of male urinary bladder cancer in which job-exposure matrices of exposure to a range of occupational agents were applied (Richardson *et al.* 2007) (hereafter referred to as the Canadian case-control study) and a hospital-based case-control study in Colombia of childhood acute lymphoblastic leukemia (ALL) in association with parental exposure to a range of hydrocarbons, again using a job-exposure matrix (hereafter referred to as the Colombian case-control study) (Castro-Jiménez and Orozco-Vargas 2011).

The available database is only adequate to evaluate urinary bladder cancer. Urinary bladder cancer has been the primary focus of concern in human studies, driven in part by early case reports of increased numbers of these cancers among workers in the dyestuffs

industry, in *ortho*-toluidine or 4-COT manufacturing, and in other amine manufacturing processes in which *ortho*-toluidine is used as an intermediate (see Section 3.1). Reporting is limited or absent for the majority of other tumor sites among the available cohort studies. The available case-control studies on exposure to *ortho*-toluidine reported on only one other tumor site, childhood ALL, in the Colombian case-control study (Castro-Jiménez and Orozco-Vargas 2011; see Appendix D, Table D-2) in addition to the Canadian case-control study of urinary bladder cancer by Richardson *et al.* (2007). A statistically significant increase in ALL was observed among children whose parents were both estimated to have had potential occupational exposure to *ortho*-toluidine; however, potential confounding by one of a number of other hydrocarbons that were associated with an increase in ALL risk could not be ruled out. The available database on this cancer endpoint is inadequate to evaluate the relationship between exposure to *ortho*-toluidine and ALL.

3.3 Assessment of the quality of the individual studies

Each primary study was assessed for its ability to inform hazard identification including the potential for biases and the adequacy of the "ability to detect an effect" and analytical methods, following the approach outlined in the Protocol for evaluating human cancer studies on exposure to *ortho*-toluidine. Details on the assessment of study quality are presented in Appendix D and in Table D-3 and details on the description of the study elements are in Appendix D, Tables D-1 and D-2. Section 3.3.1 reports on the assessment of biases and other factors of study quality, Section 3.3.2 focuses on the assessment of potential confounding, and Section 3.3.3 integrates these assessments, reaching decisions on the utility of the individual studies to inform cancer identification.

3.3.1 Assessment of potential bias, analytical methods, and other study quality characteristics

Selection and attrition bias

Selection bias is not generally a major concern in cohort studies, with the exception of the potential for a healthy worker effect in studies using external (non-occupational) comparison groups (e.g., standardized mortality and incidence studies). Both the healthy worker hire effect and healthy worker survival effect tend to bias towards the null, so that positive associations are unlikely to be biased upward. The potential for a healthy worker hire effect can be indirectly assessed based on observed differences between all-cause and all-cancer mortality or incidence rates; no strong evidence of a healthy worker hire effect was identified in any of the cohort studies. No analyses were done in the studies to determine whether there was a healthy worker survival effect.

Overall, selection bias was not a major concern (i.e., potential for bias is not probable) in any of the studies with the exception of the 4-COT production worker study (Stasik 1988) (see Appendix D, Table D-3). The potential for a healthy worker effect was considered to be unlikely or minimal for analyses using internal controls in the two rubber chemical workers studies (Sorahan 2008, Carreón *et al.* 2010) and possible in the three dye worker cohort studies (Case and Pearson 1954, Ott and Langner 1983, Pira *et al.* 2010). The 4-COT production workers study (Stasik 1988) was initiated based on the findings of two urinary bladder cancer incident cases that were identified as a result of an earlier mortality study, and there is potential (probable) for a systematic bias, most likely

towards finding a positive effect in this subcohort. The potential for selection bias in the Canadian case-control study (Richardson *et al*. 2007) was considered to be possible based on the use of cancer cases as controls and a low participation rate (60%). It is difficult to predict whether using cancer cases as the referent group would bias the risk estimate towards the null because it is not known whether *ortho*-toluidine is a risk factor for other types of cancers.

Attrition bias was assessed via loss to follow-up in the cohort studies. Where reported, loss to follow-up was generally low and the potential for this type of bias was considered unlikely/minimal (Ott and Langner 1983, Sorahan 2008, Carreón *et al.* 2010) or possible (Pira *et al.* 2010). Information on follow-up was not available in two studies (U.K. dye workers and 4-COT production workers). Although loss to follow-up was higher (12%) in the Italian dye workers study (for the total cohort, but unknown for *ortho*-toluidine-exposed workers), there is no *a priori* reason to suspect that loss to follow-up would be related to exposure or disease status, and thus any potential bias would most likely be towards the null (Pira *et al.* 2010).

Information bias: exposure endpoints

The adequacy of the characterization of exposure to *ortho*-toluidine and potential for misclassification was assessed based on quality of information provided to document exposure to *ortho*-toluidine at the individual level. Studies considered to have good or adequate exposure characterization were the two rubber chemical cohort studies and the Italian dye worker study. The most detailed, and best characterization of exposure was conducted in the NIOSH rubber chemical cohort (Carreón *et al.* 2010) because of the extensive ambient exposure measurements and biomonitoring data for a sample of workers, and expert judgment (Hanley *et al.* 2012). An earlier publication of the study had assigned workers to exposure probability categories (definitely, possibly, and probably not exposed) based on the department in which they worked (Ward *et al.* 1991). The revised exposure assessment, which included a review of records, plant walkthroughs, and interviews with company personnel, found that workers in some departments (primarily maintenance workers) had been misclassified regarding *ortho*-toluidine exposure (Carreón *et al.* 2010, Hanley *et al*. 2012). (See Appendix C, Table C-1 and Section 1, Figures 1-4 and 1-5 for more information on *ortho*-toluidine exposure levels among the different types of workers.)

Exposure assessment was based on individual work histories specific process information provided by the authors and expert judgment in the U.K. rubber chemical (Sorahan 2008) and Italian dye worker (Pira *et al.* 2010) studies (see Appendix B); although no quantitative exposure data were provided There is a higher potential for non-differential misclassification of exposure in these studies compared with the Carreón *et al.* (2010) study, but overall the exposure assessment was considered to be adequate to inform the evaluation of carcinogenicity.

The potential for misclassification of exposure was more of a concern in the U.K. and U.S. dye workers studies, 4-COT-production workers study, and the Canadian case-control study. In the U.K. dye worker study (Case and Pearson 1954), exposure to *ortho*-toluidine was inferred via knowledge of magenta manufacturing in the United Kingdom during the study time period. Although there was some limited ambient air and

biomonitoring data in the U.S. dye worker study (Ott and Langner 1983), the potential for exposure misclassification was considered to be probable in this study because exposed workers (those producing thioindigo dyes) were grouped together with workers without potential exposure to *ortho*-toluidine (those producing bromindigo dyes). In addition, there were four alternative manufacturing processes, and *ortho*-toluidine might not have been used in all processes (see Appendix C). It also seems likely that not all 4-COT production and process workers were exposed to *ortho*-toluidine (Stasik 1988). In the Canadian case-control study (Richardson *et al*. 2007), exposure to *ortho*-toluidine was assessed via self-reported occupational history and a job-exposure matrix (JEM); however, the quality of the JEM was limited because it was based on a walk-through exposure survey in one calendar year in a different country, and did not include information on specific jobs.

Information bias: disease endpoints

The assessment of the potential for misclassification of urinary bladder cancer deaths or incident cases was based on the accuracy and completeness of ascertainment of vital status and diagnosis. Mortality data are typically less informative than incidence data for long survival cancers such as urinary bladder cancer, and the use of underlying cause of death from death certificates may underestimate cases of bladder cancer among deceased cohort members. In addition, cancer registries provide potentially greater diagnostic precision compared with death certificates; however, any cases that are not registered or occur outside of the state/region or time period covered may be missed. Non-differential misclassification of cases, tending to bias the findings toward the null, was considered unlikely or minimal in the studies reporting cancer incidence (the two rubber chemical worker cohorts and the Canadian case-control study), but possible in the NIOSH and U.K. rubber chemical mortality analyses and the Italian and U.S. dye workers studies reporting mortality data. In the 4-COT production workers and U.K. dye workers studies, methods used to ascertain urinary bladder cancer cases (4-COT production workers) or deaths (U.K. dye workers) might have differed between the cohort and reference group, leading to the potential for a systematic (differential) misclassification of disease.

Ability to detect an effect and adequacy of analytical methods

Factors influencing a study's ability to detect an effect include statistical power, levels, duration, level or range of exposure to *ortho*-toluidine, and length of follow-up in cohort studies. The statistical power to detect a two-fold increased risk of urinary bladder cancer was limited in all the cohort studies but good in the Canadian case control study; of the cohort studies, the NIOSH cohort study (Carreón *et al.* 2010) had the highest statistical power. All the cohort studies had adequate length of follow-up which, based on U.S. and European data on the latency of urinary bladder cancer, is considered to be 20 years. With respect to level, range, and duration of exposure, the ability to detect an effect was considered to be good for the NIOSH rubber chemical workers, adequate for the cohorts of U.K. rubber chemical workers (Sorahan 2008), Italian dye workers (Pira *et al.* 2010), and U.K. dye workers (Case and Pearson 1954), and limited for the Canadian case-control study and cohort studies of U.S. dye workers (Ott and Langner 1983), and 4-COT production workers (Stasik 1988).

The adequacy of analytical methods was assessed based on whether the analyses included internal analyses, evaluated exposure-response relationships or time since first exposure, or adjusted for (or considered) potential confounding. Exposure-response relationships were evaluated in three studies: the two rubber chemical worker studies (Sorahan 2008, Carreón *et al.* 2010) and the Canadian case-control study (Richardson *et al.* 2007). Only two studies had formal statistical methods to evaluate confounding. The U.K. rubber chemical workers cohort study (Sorahan 2008) adjusted for occupational co-exposures but not for occupation risk factors for urinary bladder cancer, whereas the case-control study adjusted for some non-occupational risk factors but not occupational co-exposures. Although the NIOSH rubber chemical workers cohort study (Carreón *et al.* 2010) did not adjust for co-exposures in its analysis, it included an internal analysis, which helps to mitigate potential confounding, and collected other information to evaluate potential confounding (see Sections 3.3.2 and 3.3.3). The U.K. rubber chemical workers study also conducted internal analyses. The three dye worker cohort studies excluded individuals with co-exposure to some known human bladder carcinogens (Case and Pearson 1954, Pira *et al*. 2010) or to known human carcinogens (Ott and Langner 1983). Although the Canadian case-control study conducted exposure-responses analyses, there is a high probability of misclassification to each of the exposure categories, and no information was provided in the number of cases and control for each exposure category. A strength of the study is that it controlled for cigarette smoking; however, no information on co-exposures was reported and no analyses controlling for any other occupational co-exposures were conducted. Analyses of the studies on dye workers (all three studies) and the 4-COT production workers were limited to external analyses with no consideration of exposure categories or accounting for potential confounders.

3.3.2 Assessment of potential confounding by occupational co-exposures to known or suspect carcinogens

Workers in both the dyestuffs industry and rubber chemical manufacturing industry may be exposed to a number of other chemicals, some of which may cause urinary bladder cancer or other cancers. In general, most studies did not assess exposure to potential confounders at the individual level or consider them in analytical models; however, in some cases the relative level of exposure to other chemicals compared with exposure to *ortho*-toluidine can be predicted from knowledge of the industrial process. The approach and conclusions of the evaluation of whether confounding from co-exposures is a concern in each study is captured in the table below and includes the following steps:

1. A list of chemicals in each study of potential concern (e.g., reasonable potential of worker exposure) and identification of co-exposures that may cause urinary bladder cancer (blue and orange font) or other cancers (green font). (Table 3-3; see Appendix D, Table D-4 for background information regarding the potential carcinogenicity of the various co-exposures.)
2. Methods for assessing exposure to other chemicals or estimates of exposure compared to *ortho*-toluidine (Table 3-2).
3. Analytical methods to consider or adjust for exposure to co-exposures (Table 3-2).
4. Overall assessment of the potential for confounding.

The U.S., U.K., and Italian dye workers were potentially exposed to several suspected or known animal carcinogens, one of which, *ortho*-aminoazotoluene, causes urinary bladder cancer in animals. The U.K. and Italian dye workers were involved in magenta production, which is classified as carcinogenic to humans (IARC 2012); *ortho*-toluidine is one of the suspected co-exposures. Exposure data are lacking in each of the dye workers cohorts, however, and there is limited or no available evidence for the human carcinogenicity of the individual agents used in the dye production processes.

The German 4-COT production workers were exposed to 4-chloro-*ortho*-toluidine, for which there is some evidence of urinary bladder carcinogenicity in humans. The author noted that exposure to 4-COT was the predominant exposure, and it is not possible to separate potential effects of *ortho*-toluidine from those of 4-COT. It is also not clear whether workers in the U.S. dye workers study would also have been exposed to this substance as an intermediate in the thioindigo dye manufacturing processes.

With respect to potential confounding by co-exposures in the NIOSH cohort of rubber chemical workers, levels of 4-aminobiphenyl (the only known human bladder carcinogen with potential exposure in this population) were detected at very low levels and were similar in *ortho*-toluidine–exposed and unexposed workers, which argues against 4-aminobiphenyl being a potential confounder. Workers were exposed to aniline, which is an animal carcinogen; however, exposure levels relative to *ortho*-toluidine were low. The U.K. rubber chemical workers were likely to be exposed to several other chemicals if they worked in other departments, including aniline, phenyl-β-naphthylamine (PBN), and 2-mercaptobenzothiazole (MBT), but evidence of carcinogenicity in humans of these substances is limited or inadequate for evaluation. In addition, internal analyses were conducted in which risk estimates for urinary bladder cancer incidence were adjusted for these co-exposures.

In the Canadian case-control study of bladder cancer, it is not clear whether individual observed cases were exposed to other chemicals; no adjustments were made in the analysis for multiple chemical exposures.

Table 3-2. Co-exposures and potential for confounding (see also Appendix D, Table D-4.)

Study	Co-exposures[a]	Exposure assessment and levels and methods to evaluate potential for confounding	Potential for confounding
U.K. dye workers cohort Case *et al.* 1954, Case and Pearson 1954	*High probability*: Magenta *Potential exposure*[b] *o*-Nitrotoluene, formaldehyde	No exposure assessment at the individual level. Levels of potential co-exposures relative to *ortho*-toluidine cannot be evaluated. Excluded workers with exposure to auramine, benzidine, α-naphthylamine, or β-naphthylamine.	Exposure to other known human urinary bladder carcinogens unlikely; exposure to animal or human carcinogens probable. Magenta production is a known human bladder carcinogen per IARC; however, any effects from magenta cannot be separated from its co-exposures (of which *ortho*-toluidine is a major suspect); studies of magenta in experimental animals are inadequate.
Italian dye workers cohort Piolatto *et al.* 1991, Pira *et al.* 2010, Rubino *et al.* 1982[c]	*High probability*: *o-Toluidine and 4,4´-methylene bis(2-methylaniline) production: ortho*-Nitrotoluene; 4,4´-methylene-bis(2-methylaniline) *Fuchsin and safranine T production:* aniline, *ortho*-aminoazotoluene, 2,5-diaminotoluene, fuchsin, safranine T	No exposure assessment at the individual level. Levels of *o*-nitrotoluene and 4,4´-methylene-bis(2-methylaniline are predicted to be similar to that of *o*-toluidine.[d] Exposure to other chemicals probably lower. Excluded workers with exposure to benzidine, α-naphthylamine, or β-naphthylamine.	Exposure to other known human urinary bladder carcinogens unlikely; exposure to animal urinary bladder carcinogens possible, exposure to animal carcinogens probable. See comment for Case and Pearson for magenta (e.g., fuchsin) production.
U.S. dye workers cohort Ott and Langner 1983	*Potential exposure:* Nitrobenzene; 4-chloro-*ortho*-toluidine; 4-chloro-acetyl-*o*-toluidine; thioindigo dyes; 1,2-dihydroacenaphthylene; 2-aminobenzoic acid	No exposure assessment at the individual level. Odor of nitrobenzene reported. Excluded individuals with high exposure to arsenicals, vinyl chloride, or asbestos.	Exposure to animal carcinogens or suspect human urinary bladder carcinogen (4-chloro-*ortho*-toluidine) probable for some workers in cohort.
4-COT production workers cohort (Germany) Stasik 1988	*High probability:* 4-chloro-*ortho*-toluidine *Potential exposure:* 6-chloro-*ortho*-toluidine; *N*-acetyl-*ortho*-toluidine	No exposure assessment at the individual level. Authors state exposure to 4-chloro-*o*-toluidine was predominant.	High probability of potential confounding from exposure to a suspected human bladder carcinogen (4-chloro-*o*-toluidine). Study methods do not allow for attributing any observed effects to *ortho*-toluidine.

Study	Co-exposures[a]	Exposure assessment and levels and methods to evaluate potential for confounding	Potential for confounding
NIOSH (U.S.) rubber chemical workers cohort Carreón *et al.* 2010, Hanley *et al.* 2012, Ward *et al.* 1991, Ward *et al.* 1996	*High probability:* aniline *Potential exposure:* 4-aminobiphenyl (trace)	Air sampling of co-exposure available for *ortho*-toluidine exposure groups but not at the individual level; biomonitoring data available on subgroup of workers but not used in risk calculations. *Definitely exposed jobs:* Aniline: Breathing zone GM: slightly lower than *o*-toluidine; urine and Hb adducts lower than *o*-toluidine. Nitrobenzene: Breathing zone GM: approx 2.5 lower than *o*-toluidine; non-detectable in most samples. 4-Aminobiphenyl: observed in air at trace levels; Hb adducts found at similar (low) levels in *ortho*-toluidine and unexposed workers. Other co-exposures: levels NR, but evidence from process descriptions (Hanley *et al.* 2012) suggest low or minimal potential exposure. Internal analyses (duration of exposure).	No evidence that exposure to 4-aminobiphenyl (a known human bladder carcinogen) was a potential confounder in this study; exposure to other animal carcinogens possible.
U.K. rubber chemicals workers cohort Sorahan 2008, Sorahan *et al.* 2000, Sorahan and Pope 1993	*High probability:* "Sopanox" (1-tolylbiguanidine) *Potential exposure*[e]*:* aniline; MBT; PBN	Quantitative exposure assessment to MBT; duration of exposure to aniline and PBN. Analysis of bladder cancers among *o*-toluidine exposed workers adjusted for exposure to MBT and PBN in internal analysis.	Exposure to other known human bladder carcinogens unlikely; methods to evaluate potential confounding adequate.
Canadian case-control study Richardson *et al.* 2007	Other potential co-exposures among cases associated with *ortho*-toluidine exposure not reported.	No adjustment of case-control analysis for other occupational co-exposures was conducted.	Co-exposure to other carcinogens possible; inadequate data to evaluate potential confounding from co-exposures.

GM = geometric mean; MBN = 2-mercaptobenzothiazole; ND = non-detectable; PBN = phenyl-β-naphthylamine.

[a]Co-exposures include those where there is a reasonable potential for exposures, does not include co-exposure to very low or trace levels unless that chemical is a known human bladder carcinogens; blue font = known or potential human urinary bladder carcinogens, orange font = animal urinary bladder carcinogen; green font = animal or human carcinogen, not urinary bladder.
[b]Based on knowledge of manufacturing process (see Section 1). According to Howe (1977), U.K. magenta manufacture mainly resulted in Magenta III, produced by condensing *ortho*-toluidine with formaldehyde in the presence of *ortho*-nitrotoluene.
[c]According to the authors (Rubino *et al*. 1982), *ortho*-toluidine and 4,4´-methylene-bis (2-methylaniline) were made in one department and New Fuchsin (new magenta or Magenta III) was produced in a second by heating *ortho*-toluidine, 4,4´-methylene-bis (2-methylaniline) with *ortho*-nitrotoluene; workers in the second department also made safranine T by oxidizing ortho-toluidine and 2,5-diaminotoluene in the presence of aniline, with *ortho*-aminoazotoluene as an intermediate of the reaction (see Section 1). Workers in the *ortho*-toluidine-exposed subcohort worked in one or other of these departments.
[d]Based on knowledge of manufacturing process (see Section 1).
[e]Some workers may have been exposed to these chemicals via working in other departments.

3.3.3 Assessment of potential confounding by other risk factors

In addition to the healthy worker effect and industrial co-exposures discussed above, exposed workers may differ from the comparison group with respect to demographic, lifestyle, or other risk factors. With the exception of smoking, there are few known non-occupational risk factors for bladder cancer other than radiation and some chemotherapy drugs, and these would be unlikely to be related to *ortho*-toluidine exposure. There is strong evidence to suggest that smoking is an independent risk factor for urinary bladder cancer. In addition, *ortho*-toluidine has been detected in tobacco smoke (IARC 2010a). The NIOSH study (Ward *et al.* 1991, 1996) was the only cohort study to examine the effect of smoking on bladder cancer risk, first by assessing smoking status among an approximately 12% sample of workers and measuring *ortho*-toluidine, aniline, or 4-aminobiphenyl in urine and hemoglobin (Hb) adducts in a sample of smokers and nonsmokers, and secondly by calculating the effect of the difference in smoking status among workers in comparison with the U.S. population on expected urinary-bladder cancer risk (using the method of Axelson and Steenland 1988). No differences were observed between smokers and non-smokers for *ortho*-toluidine in urine or Hb adducts (Ward *et al.* 1996), and the difference in smoking status between workers and the U.S. population was estimated to increase the risk of urinary bladder cancer incidence by 5% (Ward *et al.* 1991). The U.K. rubber chemical worker study reported a SMR for lung cancer for the overall cohort, which provides some indirect information on evaluating potential confounding from cigarette smoking. In the case-control study, analyses were adjusted for smoking, alcohol consumption, and demographic variables. In the Canadian case-control study, ethnicity, marital status, education, questionnaire respondent, alcohol, and smoking variables were analyzed by backwards stepwise conditional logistic regression.

3.3.4 Summary of the utility of the studies to inform the cancer evaluation

Based on the methodological evaluation of the adequacy of study design, adequacy of exposure and disease assessment of cancer incidence or mortality, and ability to detect an effect of *ortho*-toluidine on urinary-bladder cancer risk, the NIOSH and U.K. rubber chemical worker cancer incidence studies and the Italian dye workers cohort mortality study are considered to be of high or moderate utility to inform the cancer evaluation. The NIOSH cohort is considered to be the most informative study because it provides the best exposure assessment of *ortho*-toluidine and co-exposures. Exposure was not as well characterized (by e.g., ambient air monitoring or biomonitoring) in the U.K. rubber chemical and Italian dye workers studies; however, detailed job histories were available, and thus we can reasonably conclude that each worker was exposed to *ortho*-toluidine, although the levels of exposure are unknown. Strengths of the U.K. rubber chemical study are analysis by duration of employment and internal adjustment of potential confounding. The Italian dye workers study is of moderate but more limited utility due to the possibility of potential confounding, the smaller numbers of exposed workers, and higher overall number of workers lost to follow-up.

The cohort studies of U.K. and U.S. dye workers and the Canadian case-control study are of more limited utility because of the potential for misclassification of exposure and confounding by co-exposures. The U.S. dye workers study only has sufficient statistical power to detect a large effect. In addition, only 23% of the dye workers had more than 5

years of employment and *ortho*-toluidine was used to make only one of the two types of dyes included in the potentially exposed group. Although the Canadian case-control study used a job-exposure matrix to assess exposure at the individual level, there is still potential for misclassification due to the limited quality of the exposure assessment and data are inadequate to evaluate potential confounding from occupational co-exposures in this study.

In the German 4-COT production worker study, it is not possible to reliably distinguish the potential effect of *ortho*-toluidine from that of 4-COT, a suspect human bladder carcinogen, and there is a risk of positive selection bias in this cohort; therefore the study was considered to be methodologically inadequate for inclusion in the synthesis.

3.4 Cancer assessment: urinary bladder cancer

This section summarizes and interprets the findings from the individual studies and synthesizes the evidence for urinary bladder cancer across the body of studies. Five cohort studies and one case-control study were considered adequate for inclusion in the evaluation of the level of evidence of carcinogenicity of *ortho*-toluidine from studies in humans. As noted in Section 3.3.4 ("Summary of the utility of the studies to inform the cancer evaluation"), based on the methodological strengths and limitations of these studies, the two (U.K. and NIOSH) rubber chemical cohorts of bladder cancer incidence and mortality and, to a lesser extent, the Italian dye workers cohort mortality study are considered the most informative for the evaluation of the overall findings, while the U.K. and U.S. dye workers cohort studies and the Canadian case-control study are of more limited utility. When both incidence and mortality data were available for the same study, incidence was considered to be more informative for evaluating urinary bladder cancer risk.

The key question for evaluating the level of evidence across the body of studies is whether any observed associations between *ortho*-toluidine exposure and urinary bladder cancer could be explained by chance, bias, or confounding by co-exposures or other risk factors. Several of the guidelines developed by Austin Bradford Hill (1965) are relevant to the evaluation of the level of evidence for human carcinogenicity, including the magnitude (strength) and consistency of any observed associations across studies; evidence for exposure-response relationships and associations with appropriate latency; and the degree to which chance, bias, and confounding could plausibly explain observed associations. Observed associations from methodologically limited studies or negative findings from such studies are given less weight in the overall evaluation than findings from methodologically strong studies.

3.4.1 Individual studies

The findings for the six studies evaluating urinary bladder cancer and exposure to *ortho*-toluidine are summarized in Table 3-3 below. The interpretation of the studies, including the conclusions of the findings, whether they can be explained by confounding, and the overall quality of the evidence, is presented in the "Interpretation" column.

Table 3-3. Urinary bladder cancer among *ortho*-toluidine-exposed workers

Reference	Study Name Design/ population Exposure assessment	Exposure group (N)	External analysis: SMR or SIR (95% CI); # Obs deaths or cases	Internal analysis: OR SRR, or RR (95%CI); # Obs cases	Interpretation
Studies with high or moderate utility					
Carreón *et al.* 2010 (reanalysis of Ward *et al.* 1991) incidence data and Prince *et al.* 2000 mortality analysis United States	U.S. (NIOSH) rubber chemical workers (1749) Historical cohort cancer mortality and incidence study of urinary bladder cancer Exposure assessment based on work history and industrial hygienist surveys; quantitative evidence of exposure	Exposure probability Definitely (962) Possibly (187) Probably not (600) Definitely exposed Employment duration (yr) < 5 (678) 5–9 (95) ≥ 10 (189) P_{trend} Time since first employment (yr) < 10 (78) 10–19 (250) ≥ 20 (634) P_{trend} Exposure probability Definitely (708) Possibly (291) Probably not (750)	Incidence (SIR) 5.84 (2.91–10.45); 11 1.86 (0.05–10.39); 1 0.87 (0.02–4.86); 1 1.25 (0.03–6.97); 1 3.67 (0.09–20.44); 1 11.09 (5.07–21.05); 9 $P < 0.001$ 3.63 (0.09–20.23); 1 2.77 (0.34–10.02); 2 9.02 (3.89–17.76); 8 $P < 0.001$ Mortality (SMR) 1.98 (0.05–11.05); 1 0 observed deaths 3.0 (0.08–16.71); 1	Incidence (SRR) 1.00 (1) 2.0 (0.13–32.05); 1 6.07 (0.77–48.17); 9 $P < 0.0001$ 1.00 1.05 (0.09–12.38); 2 3.39 (0.40–29.03); 8 $P = 0.12$	Potential co-exposures unlikely to explain increase in risk Potential confounding by smoking unlikely: estimated increase in SIR due to smoking = 1.05 based on 5% sample of smoking data, compared with national rates (Ward *et al.* 1991) High risk estimates in incidence study Evidence of exposure-response relationship not explained by bias or confounding Overall quality of evidence: high

Reference	Study Name Design/ population Exposure assessment	Exposure group (N)	External analysis: SMR or SIR (95% CI); # Obs deaths or cases	Internal analysis: OR SRR, or RR (95%CI); # Obs cases	Interpretation
Sorahan 2008 United Kingdom	U.K. rubber chemical workers (2160) Historical cohort cancer mortality and incidence study of urinary bladder cancer Qualitative exposure assessment based on detailed job history and industrial hygienist's knowledge of manufacturing processes	*o*-Toluidine-exposed subcohort (53) Employment duration (yr) Ref 0.1–4.9 ≥ 5 P_{trend} (Continuous)	SIR = 5.56 (1.51–14.22); 4 SMR = 11.16 (2.30–32.61); 3	Combined incidence and mortality: Adjusted RR[d] 1.00 3.72 (1.21–11.4); NR 3.38 (0.67–17.0); NR $P < 0.05$	No clear evidence of effect of duration of employment High risk estimates Significantly elevated risk after adjustment for co-exposures Overall quality of evidence adequate to high
Pira *et al.* 2010 Italy	Italian dye workers (906) Historical cohort mortality study Qualitative evidence of exposure based on work history matched to expert knowledge of processes	Fuchsin, safranine T, or *ortho*-toluidine mfr (47)	SMR = 22.5 (8.3–49.0); 6	NR	Confounding by co-exposures unlikely but cannot be ruled out High risk estimate but based on small numbers Overall quality of evidence: adequate

Reference	Study Name Design/ population Exposure assessment	Exposure group (N)	External analysis: SMR or SIR (95% CI); # Obs deaths or cases	Internal analysis: OR SRR, or RR (95%CI); # Obs cases	Interpretation
Studies with lower utility					
Ott and Langner 1983 United States	U.S. dye workers (275) Historical cohort mortality study Exposure based on working in a production area associated with exposure to *o*-toluidine, but extent of exposure is unclear and misclassification likely	Bromindigo or thioindigo mfr (117)	Deaths 0 observed deaths (Expected not reported; 1.2 expected in total cohort)	NR	Limited power to detect effect due to potential exposure misclassification and low statistical power No excess mortality Overall quality of evidence: limited
Case and Pearson 1954 United Kingdom	U.K. dye workers (4622) Historical cohort mortality study of urinary bladder cancer Exposure inferred via manufacturing process	Magenta production (85)	SMR = [23.0 (5.87–62.8)]; 3	NR	Indirect but plausible evidence of exposure to *ortho*-toluidine No clear evidence of carcinogenicity of co-exposures High risk estimate but based on small numbers Overall quality of evidence:

Reference	Study Name Design/ population Exposure assessment	Exposure group (N)	External analysis: SMR or SIR (95% CI); # Obs deaths or cases	Internal analysis: OR SRR, or RR (95%CI); # Obs cases	Interpretation
					limited
Richardson *et al*. 2007 Canada	Canadian case-control study Cancer registry-based case-control study of urinary bladder cancer 1062 cases, 805 Qualitative evidence of *ortho*-toluidine exposure (JEM based on NIOSH survey); concerns about quality of JEM) 7 cancer controls	Ever exposed to *o*-toluidine (39) *Probability of exposure* Low (NR) Medium (NR) High (NR) P_{trend}		OR = 1.01 (0.71–1.44); 39 1.49 (0.89–2.52); NR 0.46 (0.20–1.07); NR 1.10 (0.62–1.94); NR 0.79	Limited power to detect effect because of potential for exposure misclassification No excess risk Overall quality of evidence: limited

SMR = standardized mortality ratio; SIR = standardized incidence ratio; SRR = standardized rate ratio; OR = odds ratio; NR = Not reported; JEM = job exposure matrix. Numbers in [ ] calculated by RoC.

Studies of rubber chemical workers

In the updated analysis of the NIOSH rubber chemical workers (Carreón *et al.* 2010), a highly statistically significant increased SIR was found among definitely exposed workers (SIR = 5.84; 95% CI = 2.91 to 10.45, N = 11, $P < 0.001$), and there was evidence, from external or internal incidence analyses, of positive exposure-response relationships among definitely exposed workers by duration of employment (SIR for employment duration of < 5 to > 10 years SIR $P_{trend} < 0.001$ and SRR $P_{trend} < 0.0001$) and by time since first exposure (Table 3-2) (Carreón *et al.* 2010). In the updated analysis, 254 workers that had been assigned to the possibly or probably not exposed category in an earlier analysis (Ward *et al.* 1991) were reclassified as definitely exposed in the updated exposure classification of this cohort (Carreón *et al.* 2010, see Appendix C for details of the reclassification); the risk estimate was slightly higher in the earlier analysis (6.48; 90% CI = 2.61 to 13.35, N = 7). Overall, the finding of an increased risk of urinary bladder cancer remained robust with two different exposure assessments.

A subsequent follow-up of urinary bladder cancer cases in the NIOSH cohort has been conducted by Markowitz and Levin (2004, 2005) based on detailed examination of employment and medical records, and using the original exposure classification of Ward *et al.* (1991). Of 19 new cases identified between 1991 and 2000 (except for one diagnosed in 1982 and not included in the Ward *et al.* [1991] analysis), 10 were considered definitely exposed and 6 possibly exposed to *ortho*-toluidine (Table 3-4). Although no formal statistical analysis was performed, these findings strongly suggest a continuing pattern of excess urinary bladder cancers among *ortho*-toluidine–exposed workers. Of the 16 new definitely or possibly exposed cases, 75% were identified 31 or more years after first exposure, yielding a mean latency of 32 years and suggesting that determination of the full extent of urinary bladder cancer risk, at least in this cohort, will depend on the forthcoming follow-up of 40 or more years.

Table 3-4. Additional urinary bladder cancer cases from the NIOSH cohort[a]

Exposure category (Ward *et al.* 1991)	Newly identified cases[a]	Previously reported cases[b]
Definitely exposed (708)	10	7
Possibly exposed (288)	6	4
Probably not exposed (753)	3	2
Total (1749)	19	13

[a]Markowitz 2005, Markowitz and Levin 2004; follow-up from 1989 through 2003 (including one case from 1982 not identified by Ward *et al.* 1991).
[b]Ward *et al.* 1991; follow-up from 1973 through 1988.

It is unlikely that the increased risk of urinary bladder cancer in the NIOSH cohort could be explained by selection and information biases or confounding. There is no clear evidence of selection, ascertainment, or attrition bias (see Section 3.2, Table 3-2), and the high magnitude of the observed risk estimate mitigates against a risk of these types of biases. Based on detailed industrial hygiene data, biomonitoring data, individual work histories, and extensive use of records to reclassify exposure, there is documented evidence of substantial exposure to *ortho*-toluidine in the NIOSH cohort among workers in the "definitely exposed" category. It is unlikely that co-exposure to known or

suspected carcinogenic substances or other risk factors could explain the observed associations between exposure to *ortho*-toluidine and urinary bladder cancer risk in the NIOSH cohort study. As noted, 4-aminobiphenyl (4-ABP) is the only co-exposure that has been clearly established as a urinary bladder carcinogen in humans; however, exposure to 4-ABP was very low (< 1 ppm) (Hanley *et al.* 2012, Viet *et al.* 2009, Ward 1997, Ward *et al.* 1996), intermittent (1972 and 1985) (Ward *et al.* 1994, Ward 1997), and not correlated with *ortho*-toluidine exposure (as assessed by hemoglobin adducts (Ward *et al.* 1996). Although workers were also exposed to aniline, it is unlikely that aniline can explain the association between *ortho*-toluidine and urinary bladder cancer. The available epidemiologic studies have not found an association between aniline exposure and urinary bladder cancer (Case and Pearson 1954, EPA 1994, IARC 1987, Sorahan 2008). Although aniline is an animal carcinogen (Group 3), it has not caused urinary bladder cancer in animals and it is considered a less potent animal carcinogen than *ortho*-toluidine (see Section 5, "Other Relevant Data"). Smoking is also unlikely to explain the excess risk of urinary bladder cancer. As noted in Section 3.3.2, smokers and non-smokers had similar levels of *ortho*-toluidine that were not related to their occupational exposure status, and, when compared with national rates, smoking prevalence differences were estimated to potentially increase urinary bladder cancer risk in this cohort by only 5%, compared with the approximately 6-fold observed increase in association with *ortho*-toluidine exposure.

Statistically significant increased risks of urinary bladder cancer incidence (SIR = 5.56; 95% CI = 1.51 to 14.22, N = 4) and mortality (SMR = 11.2, 95% CI = 2.30 to 32.61; 3 deaths) were observed in the U.K. rubber chemical cohort study. The major limitations of this study are the small number of exposed cases and the lack of quantitative information on exposure levels; however, neither of these limitations would create a false positive. Internal analyses showed a significant positive trend (continuous measure, $P < 0.05$) for cumulative duration of employment in the *ortho*-toluidine department. Similar to the NIOSH study, there was no evidence of a potential for selection bias, and the potential for nondifferential exposure misclassification, is mitigated by the use of individual work histories to assign person-years at risk.

The U.K. rubber workers were also potentially exposed to 2-mercaptobenzothiazole (MBT), phenyl-β-naphthylamine (PBN) and aniline, if they rotated to other departments of the plant where these chemicals were used, which approximately 74% of the *ortho*-toluidine-exposed workers did (Sorahan *et al.* 2000). Confounding by these exposures is considered to be unlikely. MBT and PBN have not been clearly associated with urinary bladder cancer in other epidemiologic studies (Collins *et al.* 1999, Veys 1996), although they were associated with increased risks of urinary bladder cancer incidence in the U.K. rubber chemical cohort in an unadjusted analysis. However, the relative risks were strongly attenuated and no longer statistically significant after simultaneous adjustment for co-exposure to *ortho*-toluidine, aniline, and either MBT or PBN in internal analyses. In contrast, the risk for *ortho*-toluidine was modestly reduced but still statistically significant (Table 3-3) after adjusting for aniline, MBT, and PBN. Although there was no information on cigarette smoking in this study, there was no excess risk of lung cancer among workers in the overall (not restricted to *ortho*-toludine exposed workers) cohort (SMR = 0.91, 95% CI = 0.75 to 109; 120 deaths), suggesting that smoking habits among workers were not substandially different than the general population (reference group).

Other studies: dye workers and case-control study

A large excess mortality was found in both studies of dye workers involved in magenta manufacturing: the Italian study (SMR = 22.5; 8.3 to 49.0, N = 6) and the U.K. study ([SMR = 23.0; 95% CI = 5.87 to 62.8], N = 3); however, exposure to *ortho*-toluidine in the U.K. study is inferred via industrial process and not definitely established. The use of individual work histories to assign person-years at risk helps mitigate the potential for misclassification of exposure in the Italian cohort. Workers in the Italian dye workers cohort who made *ortho*-toluidine were likely exposed at similar levels to *ortho*-nitrotoluene and 4,4´-methylene-bis (2-methylaniline), both of which are listed as reasonably anticipated to be human carcinogens (NTP 2011a,b) based on sufficient evidence of carcinogenicity from studies in experimental animals; however, these chemicals did not cause cancer of the urinary bladder, although site concordance between animals and humans is not always observed. Workers who made fuchsin or safranine T were possibly exposed to the intermediate *ortho*-aminoazotoluene, for which there is some evidence of bladder tumors in animal studies. Three urinary bladder cancer deaths were reported among workers in the section making *ortho*-toluidine and two among workers in the dyemaking section (the location of the most recent death was not reported), with no overlap in exposure, according to the authors, suggesting that *ortho*-toluidine was the only common exposure. Effect modification cannot completely be ruled out, however, since co-exposures are mostly other aromatic amines that share common metabolic activation pathways.

In contrast to these studies, no association was found among U.S. dye workers who were involved in thioindigo manufacturing processes (Ott and Langner 1983); however, the study had low statistical power to detect an effect; only 8 cancer deaths (from all cancers) were expected in the subcohort, only 1.2 cases of urinary cancer were expected in the entire cohort of dye workers, and approximately 77% of workers had short-term employment (of 4 years or less). Thus, this study only had statistical power to detect large risk estimates. In addition, it is not known how many of the 117 workers were potentially exposed to *ortho*-toluidine because the subcohort also included workers who manufactured bromindigo dyes, who presumably were not exposed to *ortho*-toluidine. In summary, no firm conclusions can be drawn from the absence of observed urinary bladder cancer deaths in this cohort.

No association between *ortho*-toluidine and urinary bladder cancer was observed in the Canadian case-control study. Although the study had adequate statistical power to detect an effect, non-differential exposure misclassification is probable.

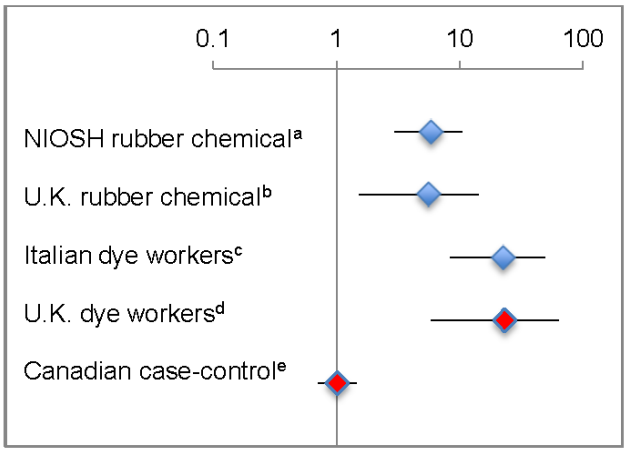
3.4.2 Synthesis of evidence across the body of studies

Overall, there is credible evidence of an association between increased urinary-bladder cancer risk and exposure to *ortho*-toluidine based on consistent findings across studies, the presence of an exposure-duration response relationship in two studies studies (Carreón *et al.* 2010, Sorahan *et al.* 2008), and large magnitudes of effect across studies.

An increased risk of urinary-bladder cancer (incidence or mortality) was consistently observed in all four studies with adequate latency that used statistical or other methods capable of detecting an association (Case and Pearson 1954, Sorahan 2008, Carreón *et al.*

2010, Pira *et al.* 2010) (see Figure 3-1). Both rubber chemical cohort studies (NIOSH and U.K.) of urinary bladder cancer incidence reported high and statistically significant increased SIRs of similar magnitude (approximately five-fold) among exposed workers. Urinary bladder cancer mortality findings also point to an increase in urinary bladder cancer risk, although they vary across studies. In the rubber chemical cohorts, an 11-fold significantly elevated risk was observed in the U.K. study but not in the NIOSH study (Prince *et al.* 2000); however, this analysis was based on few expected/observed deaths. These findings are supported by large and statistically significant increases (approximately 22-fold) in urinary bladder cancer mortality observed in two cohorts of magenta dye makers (U.K. and Italian) exposed to *ortho*-toluidine, both of which had a long follow-up period; both of these studies, as noted, have methodological limitations. Two studies did not find an excess of urinary-bladder cancer mortality among *ortho*-toluidine–exposed workers; however, the statistical power to detect an effect was low in the U.S. dye workers study (Ott and Langner 1983), and misclassification of exposure is a serious concern in both the U.S. dye workers cohort and the Canadian case-control study (Richardson *et al.* 2007).

Figure 3-1. Risk estimates (SIR, SMR or OR) for urinary-bladder cancer



Risk estimates and 95% confidence incidences for four of the five studies that were considered in the assessment. Relative risks for urinary-bladder incidence (SIRs or OR) were reported when available (NIOSH and U.K. rubber chemical workers and Canadian case-control study); in the absence of incidence data, relative risks for urinary-bladder cancer mortality (SMR) were reported (Italian and U.K. dye workers). No deaths were observed in the U.S. dye worker study (Ott and Langer 1983). Blue represents study with high to moderate quality and red represents studies with lower quality.

One of the limitations of the database is the limited number of methodologically adequate studies, and the small number of observed urinary bladder cancer deaths or cases, which are associated with imprecise risk estimates. The findings of the two cohort studies reporting cancer incidence confirm the greater utility of incidence data relative to mortality data for long latency and long survival cancers of this type. The large magnitudes of the risk estimates help reduce concerns that the findings are due to chance. The subsequent report of further cases among exposed workers in the NIOSH cohort suggests a continuing pattern of excess urinary bladder cancer risk.

The next key question is whether the excess risk of urinary-bladder cancer observed in these cohort studies can be attributed to exposure to *ortho*-toluidine or other factors. The NIOSH study provides strong evidence that the exposed cases/deaths were actually exposed to *ortho*-toluidine, and based on the authors' documentation and knowledge of

the industrial processes, it is reasonable to assume that most, if not all, of the exposed cases or deaths in the other informative studies were exposed to *ortho*-toluidine (Pira *et al.* 2010, Sorahan *et al*. 2008). In addition, the large magnitude of the risk estimates help rule out bias due to exposure misclassification.

Another limitation is the lack of formal methods to evaluate confounding from exposure to smoking or other occupational carcinogens in many of the studies. Smoking can reasonably be ruled in the NIOSH study, in which information was only available for a subset of workers. The large magnitude of risk estimates also provides high confidence for ruling out smoking across studies.

The most challenging issue is potential confounding from other occupational co-exposures. In the most informative study, the NIOSH cohort of rubber chemical workers, there is substantial evidence that *ortho*-toluidine is the most plausible agent causally related to the observed increase in urinary-bladder cancer risk among workers considered to be definitely or probably exposed to *ortho*-toluidine (see Section 3.4), and these conclusions are supported by the study of U.K. rubber chemical workers. Potential confounding by aniline, the principal common co-exposure in these two studies, can be reasonably ruled out because aniline has not been shown to cause urinary-bladder cancer in experimental animals or humans in other studies, and was not related to an increase in risk among the U.K. rubber chemical workers. Also, in the NIOSH cohort, workers were exposed to approximately three times higher levels of *ortho*-toluidine (which is a more potent animal carcinogen) than aniline, according to Ward *et al.* (1996). Potential confounding from occupational co-exposures is of greater concern for the two cohorts manufacturing magenta dyes (see Section 3.4). Magenta manufacturing has been classified by IARC as a known human carcinogen based largely on these two studies; however, IARC was unable to identify the specific chemical exposures, which include *ortho*-toluidine, responsible for the increased risk of urinary-bladder cancer. In addition, urinary-bladder cancer deaths were observed in both subgroups of workers in the Italian dye workers cohort study who were exposed to different process chemicals except for *ortho*-toluidine, strongly suggesting that *ortho*-toluidine is the common causal agent. Finally, the finding of urinary-bladder cancer among rubber chemical workers who are not exposed to many of the chemicals found in the dye workers studies argues that *ortho*-toluidine contributes to the excess urinary-bladder cancer among dye workers. In addition, there is no independent evidence that the other co-exposures cause urinary-bladder cancer in humans, although some are animal carcinogens. The possibility of effect modification may exist and may help explain the observed large risk estimates, however.

Overall, the finding of increased urinary-bladder cancer risk in separate cohorts with different exposure conditions and co-exposures lends strong support to the conclusion that *ortho*-toluidine is the common causal risk factor.

3.5 Preliminary level of evidence recommendation

There is sufficient evidence of carcinogenicity from studies in humans. Several epidemiologic studies have found an increased risk of urinary bladder cancer that is unlikely to be explained by chance, bias or confounding.

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4 Studies of Cancer in Experimental Animals

ortho-Toluidine has been listed as *reasonably anticipated to be a human carcinogen* in the Report on Carcinogens (RoC) since 1983 based on sufficient evidence of carcinogenicity in experimental animals. This section reviews and assesses carcinogenicity studies in experimental animals exposed to *ortho*-toluidine. The steps in the cancer evaluation process are (1) identifying new studies published since, or not included in the original listing in 1983 (hereafter referred to as "new" studies) (Section 4.1), (2) assessing the quality of all studies (Section 4.2), (3) synthesizing the findings across studies (Section 4.3), and (4) reaching a preliminary conclusion on the level of evidence of carcinogenicity of *ortho*-toluidine from these studies (Section 4.4).

4.1 Identification and overview of the studies

The studies that formed the basis for the 1983 listing of *ortho*-toluidine in the RoC include (1) two feed studies in different strains of rats, one in male CD rats (Weisburger *et al.* 1978) and the other in male and female F344 rats (NCI 1979), and (2) two feed studies in different strains (Albino CD-1 [HaM/ICR] and B6C3F$_1$) of male and female mice (NCI 1979, Weisburger *et al.* 1978) (see Table 4-1 for a brief overview of these studies). All of these feeding studies were two-year carcinogenicity studies that used two different exposure groups in addition to untreated controls. Rats and mice were exposed in the diet for two years in the NCI studies and for 18 months in the studies reported by Weisburger and colleagues (see Table 4-1).

Cancer studies in experimental animals published since the review (or not included in the review) were identified by searching databases, comprehensive reviews, and citations from studies retrieved from the literature searches as described in Appendix A. Five publications published after the 1983 evaluation met the inclusion/exclusion criteria requiring that included studies evaluated exposure specifically to *ortho*-toluidine and either (1) report neoplastic lesions, or non-neoplastic or preneoplastic lesions relevant to carcinogenicity, or (2) are subchronic studies that provide information on dose selection (see Appendix A). These publications reported on seven studies including (1) three feed studies, two in male rats (Hecht *et al.* 1982, NTP 1996), and one in dogs (Pliss 2004), (2) three parenteral studies, all by subcutaneous injection, in rats (Pliss 2004), mice (Pliss 2004), and hamsters (Hecht *et al.* 1983), (3) and one tumor initiation study in genetically altered fish (Anders *et al.* 1991). An additional feed study (Takayama *et al.* 1989) in rats was identified in the literature search but was excluded from the review because exposure was to a mixture of 39 chemicals including *ortho*-toluidine hydrochloride.

All of the studies in rodents exposed animals to only one dose of *ortho*-toluidine. In the feeding study reported by Hecht *et al.* (1983) female rats were exposed to *ortho*-toluidine in the diet for 73 weeks and held for a total of 93 weeks. The NTP (1996) reported on short-term exposure experiments using three different conditions: 13-week continuous exposure, 13-week exposure and held for a total of 26 weeks, and 26-week continuous exposure (NTP 1996). Five dogs (between 2 and 3 years) were exposed to *ortho*-toluidine, first in the food and later by gavage, for up to 9 years in the study reported by

Pliss (2004); however, there were no untreated controls and two dogs died of non-cancer related deaths within three years of the study onset.

The subcutaneous studies in mice and rats were two-year carcinogenicity studies with animals receiving weekly subcutaneous injections for the entire study duration (Pliss 2004). The study in hamsters was shorter; the animals were injected weekly for 52 weeks and observed up to 87 weeks (Hecht *et al.* 1983).

The study by Anders *et al.* (1991) reported on melanomas (external evaluation) in genetically modified fish dosed for 4 months.

Table 4-1. Overview of studies of exposure to *ortho*-toluidine in experimental animals

Route of exposure	Species (sex)	Exposure/observation duration	Reference
Studies included in the 1983 evaluation[a]			
Feed	F344 rat (male and female)	101–104 wk	NCI 1979
Feed	CD rat (male)	18 mo/24 mo	Weisburger *et al.* 1978
Feed	B6C3F$_1$ mouse (male and female)	101–104 wk	NCI 1979
Feed	Albino CD-1 (HaM/ICR) mouse (male and female)]	18mo/24 mo	Weisburger *et al.* 1978
Studies published after (or not included) in the 1983 evaluation[b]			
Feed	F344 rat (male)	73 wk/93 wk	Hecht *et al.* 1982
Feed	F344 rat (male)	13wk/26 wk	NTP 1996
Feed	Dog (female)[c]	9 yr	Pliss 2004
Subcutaneous	Syrian golden hamster (male)	52 wk/87 wk	Hecht *et al.* 1983
Subcutaneous	Rat (male and female)[c]	2 yr	Pliss 2004
Subcutaneous	CC$_{57}$BR mice (male and female)	2 yr	Pliss 2004
Per os	Genetically altered fish	4 wk	Anders *et al.* 1991

[a]All studies for the 1983 evaluation tested *ortho*-toluidine at two dose levels.
[b]All studies listed below tested *ortho*-toluidine at only one dose level.
[c]Strain or breed not specified.

4.2 Quality assessment of studies

The eleven studies published after 1983 identified from the literature search and studies included in the previous evaluation were systematically evaluated in a two-step process by first evaluating whether the level of detail reported for key elements of study design,

experimental procedures, and cancer endpoints was adequate for evaluating its quality and interpreting its results. The reporting quality of key elements for 2 of the 11 studies was considered to be inadequate for cancer evaluation: the study in mice exposed to *ortho*-toluidine by subcutaneous injection (Pliss 2004) and the tumor initiation study in genetically altered fish (Anders *et al.* 1991).

The nine remaining studies, which were adequately reported, were further evaluated for concerns for study quality, using *a priori* criteria, which might negatively impact the ability to assess carcinogenicity. Key factors considered in the quality assessment include characterization of the chemistry of the substance, dosing regimen, exposure and observation period, number of animals per exposure group, monitoring of animal health, and assessment for neoplasm endpoints. Details of each study assessment and quality criteria are reported in Appendix E.

Eight of the remaining nine studies – the four feed studies in rats (Weisburger *et al*. 1978, NCI 1979, Hecht *et al.* 1982, NTP 1996), two feed studies in mice (Weisburger *et al*. 1978, NCI 1979), two subcutaneous studies, one in hamsters (Hecht *et al.* 1983) and one in rats (Pliss 2004) – were considered to have adequate quality to inform the carcinogenicity assessment. The feeding studies in rats and mice were considered to be more informative (e.g., had minimal concerns for most study quality elements) (Hecht *et al.* 1982, NTP 1996) than the two subcutaneous studies in rodents (Hecht *et al.* 1983, Pliss 2004). One of the feeding studies in rats, the NTP feed study in male rats, was a subchronic study, which by virtue of its design (e.g., short exposure and duration period) would usually not be considered able to detect tumors, due to the long latency period usually required for tumor development. Despite such limitations, preneoplastic and neoplastic findings were reported, and the study was included in the cancer assessment. One of the remaining nine studies, a feeding study in dogs, was considered to be inadequate to inform the cancer evaluation, primarily because no untreated control group of dogs was tested and there were also concerns about other study elements as described in Appendix E.

Overall, the studies in rodents provide an adequate database for evaluating the carcinogenicity of o*rtho*-toluidine. Although some limitations in study design or reporting were observed in some studies, most of the limitations would bias towards not finding an effect (type-I error) and would not necessarily bias towards finding a “false” positive effect (type-II error).

4.3 Assessment of neoplastic findings

The studies in rats and mice previously evaluated for the 1983 listing of *ortho*-toluidine in the RoC provided sufficient evidence for its carcinogenicity based on tumors of the connective tissue (sarcoma) in the spleen and other organs in both sexes of rats, urinary bladder in female rats, mesothelium and subcutaneous tissue in male rats, blood vessels in both sexes of mice, and liver in female mice. This section integrates the findings across the new (two feeding studies in male F344 rats and two subcutaneous studies), and earlier studies (two feeding studies each in rats and mice). Findings from the four feeding studies in rats are reported in Tables 4-2 (urinary-bladder neoplasms), 4-3 (sarcoma), and 4-4 (other neoplasms); the two feeding studies in mice are reported in Table 4-5, and the

two subcutaneous injection studies in rodents in Table 4-6. All studies are discussed below.

4.3.1 Feed studies: rats

The new feeding studies also support the conclusions of the original listing that dietary exposure to *ortho*-toluidine causes neoplasms of the urinary bladder, connective tissue, subcutaneous tissue, mammary gland, and mesothelium in rats (see Table 4-3). These conclusions are based on studies that are considered to be of adequate quality to inform a cancer evaluation and thus increase the confidence in the conclusions. Strengths of the studies were lifetime exposure to doses approaching toxicity and performance of complete histopathological examination ofall major organs. The Hecht study, which is a "new" study, was conducted in the same strain of male rats as one of the original studies (the NCI study) and, in general, confirmed the findings of the NCI study. The other "new" feeding study, the NTP subchronic study, was informative for the evaluation of neoplasms of the mesothelium. The new studies also provide some support that *ortho*-toluidine causes urinary-bladder neoplasms and mammary tumors in male rats in addition to females. Some types of neoplasms were observed in both male and female rats (urinary-bladder connective tissue, mammary gland), whereas other neoplasms may be sex specific (subcutaneous tissue and mesothelium). Some types of neoplasms may be strain specific (connective tissue, mesothelium, and mammary gland), although differences in study design (e.g., shorter exposure and observation period in the CD rat study compared with the F344 rat study) may also account for the differences in findings. Details on the findings of these tumor sites that support these conclusions are discussed below.

Urinary-bladder cancer is a potential target site in human cancer studies. The collective data from the four feeding studies in experimental animals provide strong evidence that *ortho*-toluidine exposure causes urinary-bladder neoplasms in female rats (a conclusion of the 1983 evaluation), with weaker evidence observed for male rats (Table 4-2) (conclusion supported by the new studies). In female F344 rats, dietary exposure to *ortho*-toluidine caused a dose-related statistically significant increased incidence of urinary-bladder cancer (transitional-cell carcinoma) in both exposure groups with the incidence reaching 47% in the high-exposure group. This was considered to be a robust finding because spontaneous urinary-bladder neoplasms in rats are rare; no carcinomas were observed in 989 female F344 rats from 20 feed studies (NIH-07 diet, which includes data up to 1999). In addition, the time to first observed tumor was shorter in high-dose females (65 weeks) compared with low-dose females (103 weeks). In male rats, dietary exposure to *ortho*-toluidine induced low incidences of urinary-bladder neoplasms (statistically non-significant) in two species of rats. Similar to females, spontaneous urinary-bladder neoplasms are rare in both male F344 and CD rats: (1) 3 neoplasms (carcinoma or papilloma) and 1 carcinoma were observed in 991 rats from 20 studies using NIH-07 diet of F344 rats, and (2) 6 urothelial (transitional-cell) papilloma or carcinoma were observed in 30 studies of Charles River Crl:CD rats published between 1989 and 2002. The results in the chronic studies in rats are supported by the findings of a statistically significant increased incidence of transitional-cell hyperplasia of the urinary bladder in F344 male rats in the NTP subchronic study (13-week interim study and 26-week exposure study). NCI noted that there appeared to be a dose-related progression,

especially in female rats, from transitional-cell hyperplasia to transitional-cell carcinoma of the urinary bladder.

Table 4-2. Studies of dietary exposure to *ortho*-toluidine in rats: urinary-bladder hyperplasia and neoplasm incidence

Reference Strain, Sex Study Duration	Exposure, ppm (# rats)	Hyperplasia	Papilloma	Carcinoma	Carcinoma or papilloma (combined)	Comments
Weisburger *et al.* 1978 CD [Sprague-Dawley], Male 18 mo exposed (24 mo total)	0 (111)[a] 0 (25)[b] 8,000–4,000 (25)[c] 16,000–8,000 (25)[c]			5/111 (4.5) 0/16[d] 3/23 (13) 4/24 (22)		*o*-Toluidine HCl (97%–99% pure). Survival similar between concurrent controls and exposed groups (16/25, 23/25, 24/25). Food consumption not reported for individual animals.
NCI 1979 F344, Male 101–104 wk	0 (20) 3,000 (50) 6,000 (50) Trend[e]	0/20 9/50 (18) 7/44 (16) NR		0/20 3/50 (6) 0/44 (0) $P > 0.05$	0/20 3/50 (6) 1/44 (2) $P > 0.05$	Technical grade (> 99% pure, with one contaminant < 1%). Body weights of both sexes of exposed rats lower than controls and dose-related. Dose-related trends in mortality observed in both sexes; steep decreases in mortality occurred after 70 wk in high-dose males, 75 wk in low-dose males, 80 wk in high-dose females and 90 wk in low-dose females. Food consumption not reported for individual animals.
NCI 1979 F344, Female 101–104 wk	0 (20) 3,000 (50) 6,000 (50) Trend[e]	0/20 21/45 (47)*** 13/47 (28)** NR		0/20 9/45 (20)* 22/47 (47)*** $P < 0.001$	0/20 10/45 (22)* 22/47 (47)*** $P < 0.001$	

Reference Strain, Sex Study Duration	Exposure, ppm (# rats)	Hyperplasia	Papilloma	Carcinoma	Carcinoma or papilloma (combined)	Comments
Hecht *et al.* 1982 F344, Male 72-wk exposure (93 wk total)	0 (30) 4,000[f] (30)		0/27 3/30	0/27 1/30		*o*-Toluidine HCl (purified, but purity not reported). Survival at week 22 was 18/30 for controls and 6/30 for exposed. Body weight of exposed reported as "somewhat lower than control group."
NTP 1996 F344, Male 13-wk interim sacrifice 13-wk stop exposure[g] 26-wk continuous exposure	 0 (10) 5,000[h] (20) 0 (10), 5,000[h] (20) 0 (10) 5,000[h](20)	 0/10 10/20** 0/10 0/20 0/10 17/18**				*o*-Toluidine HCl (100% pure). Survival 100% in all groups. Mean body weights were 82%–89% lower in exposed groups than control group.

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$ (compared with concurrent controls by Fisher's exact test); [] = Statistical significance calculated by NTP using Fisher's exact test.
[a]Pooled controls, controls from all compounds tested in study.
[b]Concurrent controls.
[c]Body weights in exposed groups < 10% of concurrent control weights by 12 wk; doses reduced for remaining 60 wk. Low dose reduced from 8000 to 4000 mg/kg food, and high dose reduced from 16,000 to 8000 mg/kg food.
[d]Six cases of subcutaneous fibroma or fibrosarcoma occurred along with transitional-cell carcinoma of the male rat urinary bladder.
[e]Trend calculated using Cochran-Armitage trend test.
[f]Mean Daily Dose: 62 mg/rat; Total dose of *o*-toluidine HCl: 31.3 g/rat; Average exposure of *o*-toluidine HCl per body weight per day of animals not reported.
[g]Rats exposed for 13 wk and observed for another 13 wk.
[h]Exposure (mg/kg/d) = 301 for 13-wk interim sacrifice, 304 for 13-wk stop exposure, and 285 for 26-wk continuous exposure.

Increased incidences of sarcoma in the spleen and other tissue sites were observed in rats of both sexes (NCI 1979) and in male rats in two different studies (NCI 1979, Hecht *et al.* 1982). In the NCI study, *ortho*-toluidine exposure caused significant dose-related increased incidences of (1) multiple types of sarcoma (fibrosarcoma, angiosarcoma, osteosarcoma, and sarcoma NOS [not otherwise specified]) in the spleen and other abdominal organs in rats of both sexes, (2) specific sarcomas in multiple organs (fibrosarcoma in males, and osteosarcoma in females), and (3) multiple types of sarcoma and angiosarcoma in the spleen of females. The NCI (1979a) noted that the histologic appearance of each type of sarcoma was similar regardless of the organs involved; they were of mesenchymal origin, closely related, and poorly differentiated. There was also a high incidence of invasion into adjacent organs and soft tissues and/or metastasis to other sites, suggesting that they were highly malignant. In the Hecht study, statistically significant increased incidences of sarcoma in the peritoneum and fibroma (benign neoplasm) in the spleen occurred in male F344 rats. Sarcoma in the spleen is a rare tumor in F344 rats; the historical control data for untreated rats from NTP oral studies using NIH-07 diet (which was also the diet used in the Hecht study) ranged from 0% to 0.4% (based on 1003 tumors) for males and 0% to 0.1% in females depending on the specific type of sarcoma (http://ntp.niehs.nih.gov/go/15482).

Increased incidences of mesothelioma (*tunica vaginalis* or abdominal cavity and organs) were observed in males in all three studies of F344 rats but were only statistically significant in the NCI chronic study. In the NCI chronic study, the incidence of mesothelioma (multiple organs/*tunica vaginalis*) was higher (34%) in the low-dose exposure group than the high-dose exposure group (18%) and most of the mesotheliomas were located in the *tunica vaginalis*. The historical control rate for mesothelioma for the study laboratory in the NCI study was reported to be 0.4% (1/285). A small, but not statistically significant, excess of malignant mesothelioma (located in the peritoneal cavity) was observed in the exposed male F344 rats (16.6%) compared with the controls (7.4%) in the Hecht study, and thus the finding in this study is weaker than in the NCI study. The NTP subchronic study provides supporting evidence that dietary exposure to *ortho*-toluidine causes mesothelioma; malignant mesothelioma and mesothelial hyperplasia of the epididymides occurred in male rats exposed in the diet for only 13 weeks, and held for an additional 13 weeks (stop-exposure). Although the findings were not statistically significant they are considered to be of biological significance because of the short exposure and observation duration (NTP 1996).

Table 4-3. Studies of dietary exposure to *ortho*-toluidine in rats: sarcomas

Reference Strain, Sex Study Duration	Exposure, ppm (# rats)	*Multiple tissues (multiple types)*	*Multiple tissues (specific types)*	*Spleen (multiple types)*	Spleen (specific types)	Comments[a]
Weisburger *et al.* 1978 CD [Sprague-Dawley], male 18 mo exposed (24 mo total)	0 (111)[b] 0 (25)[c] 8,000–4,000 (25)[d] 16,000–8,000 (25)[d]	Not reported	Not reported	Not Reported	Not Reported	
NCI 1979 F344, male 101–104 wk	0 (20) 3,000 (50) 6,000 (50) Trend[e] 0 (20) 3,000 (50) 6,000 (50) Trend[e]	0/20 15/50 (30)** 37/49 76)*** *P* < 0.001	*Fibrosarcoma* 0/20 8/50 20/49*** *P* < 0.001 *Sarcoma NOS* 0/20 3/50 (6) 11/49 (22)* *P* = 0.003	0/20 8/49 (16) 4/42 (10) *P* > 0.05	*Fibroma* 0/20 10/49 (20)* 2/42 (5) *P* > 0.05	Multiple types of poorly differentiated sarcoma primarily include sarcoma, NOS (not otherwise specified), fibrosarcoma, angiosarcoma, or osteosarcoma in multiple organs or spleen
NCI 1979 F344, female 101–104 wk	0 (20) 3,000 (50) 6,000 (50) Trend[e]	0/20 3/50 (6) 21/49 (43)*** *P* < 0.001	*Osteosarcoma* 0/20 0/50 18/49 (37)** *P* < 0.001	0/20 9/49 (18)* 2/49 (24)** *P* = 0.018	*Angiosarcoma* 0/20 7/49 (14) 9/49 (18)* *P* = 0.045	Multiple types: sarcoma, NOS, angiosarcoma or osteosarcoma
Hecht *et al.* 1982 F344, male 72 wk exp. (93 wk total)	0 (30), 4,000 (30)[f]		*Peritoneal cavity: sarcoma* 0/27 9/30 (30)**		*Fibroma* 0/27 10/30 (33)***	

Reference Strain, Sex Study Duration	Exposure, ppm (# rats)	*Multiple tissues (multiple types)*	*Multiple tissues (specific types)*	*Spleen (multiple types)*	Spleen (specific types)	Comments[a]
NTP 1996 F344, male 13-wk interim sacrifice; 13-wk stop exposure[g]; 26-wk continuous exposure	0 (10) 5,000 (20)	None observed under any conditions	None observed under any conditions	None observed under any conditions	None observed under any conditions	

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$ (compared with concurrent controls by Fisher's exact test); [] = Statistical significance calculated by NTP using Fisher's exact test.
[a]See Table 4-2 for information on purity, survival, body weight, or feed consumption.
[b]Pooled controls, controls from all compounds tested in study.
[c]Concurrent controls.
[d]Body weights in exposed groups < 10% of concurrent control weights by 12 wk; doses reduced for remaining 60 wk. Low dose reduced from 8000 to 4000 mg/kg food, and the high dose reduced from 16,000 to 8000 mg/kg food.
[e]Trend calculated using the Cochran-Armitage trend test.
[f]Mean daily dose: 62 mg/rat; Total dose of *o*-toluidine HCl: 31.3 g/rat; average exposure of *o*-toluidine HCl per body weight per day of animals not reported.
[g]Rats exposed for 13 weeks and observed for another 13 weeks.

Fibroma or fibrosarcoma of the subcutaneous tissues was observed in all three chronic feed studies (Hecht *et al.* 1982, NCI 1979, Weisburger *et al.* 1978) including two different strains of male rats (CD and F344). In male CD rats, statistically significant increased incidences of fibroma or fibrosarcoma were observed in both the low- and high-dose groups, but no further pathological information or stratification of incidence by type of neoplasm was provided (Weisburger *et al.* 1978). Increased incidences of fibroma were observed in male F344 rats in both the low- and high-dose groups in the NCI study; in addition to fibroma, a few osteosarcoma, myxosarcoma, fibrosarcoma, and unspecified sarcoma were also observed. The Hecht study reported a high incidence (83%) of fibromas occurring in the skin (presumably the subcutaneous tissue of the skin) in male F344 rats at the only dose tested.

Statistically significant increased incidences of fibroadenoma of the mammary gland were found in male F344 rats in the Hecht *et al.* (1982) study and in high-dose female F344 rats in the NCI (1979a) study; a non-statistically significant excess of fibroadenoma was found in the low-exposure group males in the NCI (1979a) chronic study. In general, fibroma and fibroadenoma regardless of tissue origin, are benign, well-localized neoplasms with few mitotic figures that do not usually progress to malignancy.

Table 4-4. Studies of dietary exposure to *ortho*-toluidine in rats: mesothelium, subcutaneous tissue and mammary gland neoplasm incidence (%)

Reference Strain, Sex Study Duration	Exposure, ppm (# rats)	Mesothelium: various body cavities *Mesothelioma*	Subcutaneous tissue *Fibroma, Fibrosarcoma*	Mammary gland *Fibroadenoma*	Comments
Weisburger *et al.* 1978 CD [Sprague-Dawley], male 18-mo exposed (24 mo total)	0 (111)[a] 0 (25)[b] 8,000–4,000 (25)[c] 16,000–8,000 (25)[c]		*Fibroma and fibrosarcoma* 18/111 (16) 0/16 18/23 (78) [***] 21/24 (88) [***]		See Table 4-2 for information on purity, survival, and feed consumption
NCI 1979 F344, male 101–104 wk	0 (20) 3,000 (50) 6,000 (50) Trend[d]	*Tunica vaginalis* / *Multiple organs*[e] 0/20 / 0/20 10/50 (20) [*] / 17/50 (34)*** 6/49 (12) / 9/49 (18)* NR / $P > 0.05$	*Fibroma*[f] 0/20 28/50(56)*** 27/49(55)*** $P = 0.001$	*Fibroadenoma* 0/20 7/50 (14) 1/49 (2) $P > 0.05$	See Table 4-2 for information on purity, survival, body weight, and feed consumption
NCI 1979 F344, female 101–104 wk	0 (20) 3,000 (50) 6,000 (50) Trend[d]		*Fibroma* 0/20 4/50 (8) 2/49 (4) $P > 0.05$	*Fibroadenoma* 6/20 20/50 (40) 35/49 (71)** $P < 0.001$	
Hecht *et al.* 1982 F344, male 72 wk exp. (93 wk total)	0 (30) 4,000 (30)[g] 0 (30) 4,000[g]	*Peritoneal*[h] 2/27 (7) 5/30 (17)	*Fibroma* 1/27 (3) 25/30 (83)***	*Fibroadenoma* 0/27 11/30 (37)*** *Adenocarcinoma* 0/27 2/30 (7)	See Table 4-2 for information on purity, survival, body weight, and feed consumption

Reference Strain, Sex Study Duration	Exposure, ppm (# rats)	Mesothelium: various body cavities ***Mesothelioma***	Subcutaneous tissue ***Fibroma, Fibrosarcoma***	Mammary gland ***Fibroadenoma***	Comments
NTP 1996 F344, male 13-wk stop exposure[i]	0 (10) 5,000 (20) [j]	*Epididymis* 0/10 2/20 (10)[j] No tumors in 13-wk interim sacrifice or 26-wk continuous exposure studies			See Table 4-2 for information on purity, survival, body weight, and feed consumption 2/20 mesothelial hyperplasia of the epididymis in stop-exposure study

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$ (compared with concurrent controls by Fisher's exact test); [] = Statistical significance calculated by NTP using Fisher's exact test.
[a]Pooled controls, controls from all compounds tested in study.
[b]Concurrent controls.
[c]Body weights in exposed groups < 10% of concurrent control weights by 12 wk; doses reduced for remaining 60 wk. Low dose reduced from 8000 to 4000 mg/kg food, and the high dose reduced from 16,000 to 8000 mg/kg food.
[d]Trend calculated using the Cochran-Armitage trend test.
[e]Mesothelioma included malignant mesothelioma and mesothelioma NOS in *tunica vaginalis* and in other organs in the abdominal cavity.
[f]Malignant subcutaneous tumors including osteosarcoma, myxosarcoma, fibrosarcoma, sarcoma NOS were also observed in exposed males.
[g]Mean daily dose: 62 mg/rat; Total dose of *o*-toluidine HCl: 31.3 g/rat; average exposure of *o*-toluidine HCl per body weight per day of animals not reported.
[h]Located in muscular wall and organs of abdominal cavity.
[i]Rats exposed for 13 weeks and held for another 13 weeks.
[j]Exposure = [304 mg/kg/d].

4.3.2 Feed studies: mice

No new studies with adequate design and reporting were identified in mice, and the conclusions, based on the two feed studies in two different strains of mice (NCI 1979, $B6C3F_1$ strain; Weisburger *et al.* 1978, Albino CD-1 (HaM/ICR) strain) are the same as the 1983 evaluation. These studies were considered to be informative for cancer evaluation because they exposed animals to doses approaching toxicity for close to their lifetime and conducted complete histopathological examination on all major organs. Neoplasms of the blood vessels (hemangioma and hemangiosarcoma combined) were observed in both studies and liver cancer was observed in one study (Table 4-4). In the NCI study, a significant dose-related trend was observed in male but not female $B6C3F_1$ mice; most of the neoplasms observed in both the low and high doses were malignant neoplasms (hemangiosarcoma). Although the increases in incidences of the blood vessel neoplasms in male $B6C3F_1$ mice were not statistically significant, they were considered exposure related because they were outside the historical control range (hemangioma and hemangiosarcoma combined). The increased incidences of blood vessel neoplasms in male and female Albino CD-1 (HaM/ICR) mice were statistically significant in both the low- and high-dose groups; these doses were much higher than the dose used in the NCI study. Statistically significant dose-related increases in liver neoplasms (hepatocellular carcinoma and adenoma combined) were also observed in *ortho*-toluidine exposed $B6C3F_1$ females but not in Albino CD-1 (HaM/ICR) females; most of the neoplasms observed were carcinomas.

4.3.3 Subcutaneous injection studies in rodents

No evidence of carcinogenicity was observed in studies of rats and hamsters administered *ortho*-toluidine by subcutaneous injection; however, the data are inadequate to conclude whether these negative findings are due to study design issues, species differences, or route of exposure. No increases in specific neoplasm incidences were found in any of the studies. The incidence of all neoplasms in rats was reported to be statistically higher than in unexposed controls, but these findings have little biological meaning. As discussed in Section 4.1, these studies were considered to have limited ability to inform a cancer evaluation, and most of the limitations (e.g., less than lifetime exposure and observation duration, smaller numbers of animals, and uncertainty about whether necropsies were completed on all major organs) would decrease the sensitivity for detecting a neoplastic response. In addition, subcutaneous injection is a less relevant route of exposure for human carcinogenicity.

4.4 Preliminary level of evidence conclusion

There is significant evidence for the carcinogenicity of *ortho*-toluidine from studies in experimental animals based on increased incidences of malignant or combined and malignant tumors in rats and mice at multiple tissue sites. Increased incidences in benign tumors of the mammary gland (fibroadenoma) in male (Hecht *et al.* 1982) and female (NCI 1979) rats were also reported. Although these tumors do not usually progress to malignancy they support the findings of sufficient evidence of the carcinogenicity of *ortho*-toluidine from studies in experimental animals.

Table 4-5. Summary of dietary *ortho*-toluidine hydrochloride studies in mice: neoplasm incidence (%)

Reference Strain; Sex Study Duration	Doses: ppm, (# animals)	Blood vessels Hemangiosarcoma (HS) or hemangioma		Liver Hepatocellular adenoma or carcinoma		Comments
Weisburger *et al.* 1978 Albino CD-1 (HaM/ICR; male 18 mo exp/6 mo obs. (24 mo total)	0 (99)[a] 0 (25)[b] 16,000–8,000 (25)[c] 32,000–16,000 (25)[c]		*Combined* 5/99 (5) 0/14 (0) 5/14 (36)* 9/11 (82)*			*ortho*-Toluidine hydrochloride (97%–99% pure) Survival was similar between concurrent controls and exposed groups (Males: 14/25, 14/25, 11/25; Females: 15/25, 18/25, 21/25). Body weights decreased by > 10% of concurrent control weights at 12 wk
Weisburger *et al.* 1978 Albino CD-1 (HaM/ICR); female 18 mo exp/6 mo obs. (24 mo total)	0 (102)[a] 0 (25)[b] 16,000–8,000 (25)[c] 32,000–16,000 (25)[c]		*Combined* 9/102 (8.8) 0/15 (0) 5/18 (28)* 9/21 (43)*			
NCI 1979 B6C3F$_1$,; male 2 yr (101–104 wk)	0 (20) 1,000 (50) 3,000 (50) Trend[d]	*HS*[e]- 1/19 (5) 1/50 (2) 10/50 (20) *P* = 0.004	*Combined* 1/19 (5)[f] 2/50 (4) 12/50 (24) *P* = 0.002	*Carcinoma* 4/19 (21) 16/50 (32) 11/50 (22) *P* > 0.05	*Combined* 5/19 (26) 19/50 (38) 14/50 (28) *P* > 0.05	*o*-Toluidine hydrochloride (Technical grade, > 99% pure, one contaminant < 1%) No significant dose-related trends were found for mortality. Body weights were lower in exposed mice of both sexes and were dose related. Food consumption not reported for individual animals.
NCI 1979 B6C3F$_1$; female 2 yr (101–104 wks)	0 (20) 1,000 (50) 3,000 (50) Trend[d]		*Combined* 1/20 (5) 1/49 (2) 3/50 (6) *P* > 0.05	*Carcinoma* 0/20 2/49 (4) 7/15 (14) *P* = 0.015	*Combined* 0/20 (0)[g] 4/49 (8) 13/50 (26)** *P* = 0.001	

*$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$ (compared with concurrent controls by Fisher's exact test).
[a]Pooled controls, controls from all compounds tested in study.
[b]Concurrent controls.
[c]Body weights in exposed groups decreased to < 10% of concurrent control weights by 12 wk; doses reduced for remaining 60 wk. Low dose was reduced from 16,000 to 8000 mg/kg food, and the high dose from 32,000 to 16,000 mg/kg food.
[d]Trend calculated using Cochran-Armitage trend test.

[e]Neoplasms of the blood vessels were predominantly located in either the periuterine or periepididymal fat in the abdominal viscera.
[f]Incidence in historical control male mice is 4% for hemangiosarcoma and 5% for hemangiosarcoma and hemangioma combined; the probability (in 50 animals) is less than 0.001 for obtaining 10 or more hemangiosarcoma and 12 or more combined neoplasms.
[g]Incidence of hepatocellular neoplasms in historical control female mice is 4.3% (range 0% to 11%).

Table 4-6. Summary of neoplasm incidence in subcutaneously injected *ortho*-toluidine studies in rats, and hamsters

Reference Species (Strain; Sex Study Duration	Exposure interval and period Dose (# of animals)	Neoplasm Incidence (%) or findings	Comments
Pliss 2004 Rat (strain/source not reported); Male and female Up to 2 yr	1 d/wk, 18–24 mo mg/injection 0 (25 Male/25 Female) 30 (25 Male/25 Female) Total maximum dose/animal: 3.25 g [estimated dose at study start: 300–375 mg/kg bw]	Combined neoplasm[a,b] 4/38 (10.5) 12/30 (40)** Individual neoplasms not reported.	*o*-Toluidine (99.7% pure, with 0.2% *p*-toluidine) Survival of exposed rats (30/50) at time of first neoplasm (19.6 mo) in exposed rats was lower than controls (38/50) at time of first neoplasm (23 mo). Neoplasm incidences were not reported by sex or by tissue type.
Hecht *et al.* 1983 Hamster (Syrian Golden); Male 87 wk	1 d/wk, 52 wk mmol [mg]/kg/wk 0 (15) 1.9 [203] (15) Total maximum dose/animal: 99 mmol/kg [10.6 g/kg bw]	No statistically significant increase in neoplasm incidence in exposed hamsters compared with controls. Neoplasm incidence data not reported.	*o*-Toluidine pure as analyzed by TLC and gas chromatography; details not provided. Mean survival time (wk) in exposed hamsters (males 61.3) and females 57.8) were lower than controls (males 75.5, females 68.7).

$*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$ (compared with concurrent controls by Fisher's exact test).
bw = body weight.
[a]Neoplasms in control rats included 2 mammary fibroadenomas, 2 leucoses.
[b]Neoplasms in exposed rats included: 4 mammary fibroadenomas, 2 sarcomas and fibromas at the injection site, and 1 hepatic sarcoma, 1 renal plasmocytoma, 1 testicular lymphohemangioma, and 3 leucoses.

5 Mechanistic Data and Other Relevant Effects

This purpose of this section is to review data that identify or elucidate potential mechanisms of action for the carcinogenic effects discussed in Sections 3 and 4. These data include, but are not necessarily limited to: (1) genetic and related effects, (2) relevant toxicological effects (effects that may be associated with carcinogenicity or are a key feature of a proposed carcinogenic mechanism), (3) mechanistic considerations, and (4) carcinogenic effects of metabolites and analogues.

5.1 Genetic and related effects

The genetic and related effects of *ortho*-toluidine have been extensively investigated and reviewed (Danford 1991, IARC 2000, 2010a). Many of the data came from two international collaborative studies of short-term tests for carcinogens (Ashby *et al.* 1985, de Serres and Ashby 1981). The first of these studies included 42 coded chemicals and the second included 10 uncoded chemicals; *ortho*-toluidine was included in both studies. Some important features of these studies included the following: (1) more than 35 assays were used to represent all available types of short-term tests claimed to have potential as carcinogen prescreens, (2) multiple laboratories participated in the studies; (3) chemicals were prepared in pure form and dispatched to the participating laboratories from the same batch; (4) a common S9 preparation was provided but its use was optional; (5) all participating investigators were required to submit protocols prior to the beginning of the studies but no attempt was made to standardize protocols; (6) standard defined criteria were used to evaluate assay performance; and (7) data reporting was limited because of the number of chemicals involved.

Overall, the data show that *ortho*-toluidine has a wide range of genetic effects; however, there is substantial variation in results between different laboratories as well as minor variations in protocols. Data are presented for bacterial systems (Section 5.1.1), non-mammalian eukaryotes (Section 5.1.2), *in vitro* mammalian systems (Section 5.1.3), *in vivo* studies (Section 5.1.4), and genotoxicity studies of *ortho*-toluidine metabolites (Section 5.1.5). Results for genetic and related effects are synthesized in Section 5.1.6. All tables for this section, with the exception of the overall summary table, are provided in Appendix F.

5.1.1 Bacterial systems

ortho-Toluidine has a mutagenicity profile similar to other arylamines, with weakly positive results in bacteria and requiring special assay conditions to demonstrate positive effects. *ortho*-Toluidine has been tested for reverse and forward mutations (using plate incorporation, preincubation, and fluctuation protocols) and prophage induction in *Salmonella typhimurium*; reverse mutations, differential toxicity, growth inhibition, and prophage induction in *Escherichia coli*; and DNA damage (*rec* assay) in *Bacillus subtilis*. Results from these studies are summarized in Appendix F, Table F-1.

ortho-Toluidine did not cause mutations in *S. typhimurium* or *E. coli* without metabolic activation. There were a few positive reverse mutation studies in *S. typhimurium* strains TA100, TA98, and TA1538 only with metabolic activation and modifications to the

standard protocol. These modifications included use of the fluctuation protocol (one study each with TA100 and TA1538), use of higher concentrations of S9 (30% rat or hamster, three studies with TA100 and one with TA98), and/or special preparations of S9 (phenobarbitol-induced rat S9, or phenobarbitone + β-naphthoflavone, one study each with TA98 and TA1538). Some negative findings were also found using the more sensitive fluctuation protocol in *Salmonella* strains TA98, 1535, and 1537. No clear differences were observed in studies using strains that detect base-pair mutations compared with strains detecting frameshift mutations. One forward mutation study in *S. typhimurium* strain BA13 was positive (arabinose resistance) with 30% rat S9 but negative with 10% rat S9. Two forward mutation studies (8-azaguanine resistance) in strain TM677 were negative. A host-mediated assay also reported that urine from *ortho*-toluidine–treated rats induced reverse mutations in TA98 but not in TA100.

The mutagenicity profile for *ortho*-toluidine in the Ames test is consistent with findings from studies on other arylamines. These studies suggest that the low mutagenic activity of arylamines in the Ames test might be explained by deficiencies in metabolizing enzymes (e.g., sulfotransferases and acetyltransferases) in *Salmonella*. One study found that the introduction of cDNA encoding hamster acetyltransferase in *S. typhimurium* TA1538 markedly enhanced the mutagenicity of arylamines in that test system (Kato and Yamazoe 1994). Similarly, Oda *et al.* (1999, 1995) reported increased sensitivity to aromatic amines in *Salmonella* tester strains over-expressing bacterial *O*-acetyltransferase (*O*-AT) or human *N*-acetyltransferases (NATs) compared with parent or *O*-AT deficient strains. This system is based on the induction of the *umuC* gene as part of the general SOS response to DNA damage. It is also possible that the type of damage induced by these carcinogens might include large-scale changes in genome structure (e.g., deletions, insertions, or translocations) that are not detected by the *Salmonella* tester strains. Other possibilities include a lack of sufficient quantities of the particular enzymes (with or without added S9 mix) required to activate certain carcinogens, or reactive intermediates might not be able to cross the cell wall. The special conditions required in most of the positive *Salmonella* assays with *ortho*-toluidine, and results for other genetic toxicity assays support these possibilities.

Reverse mutations were reported with metabolic activation in only one of five studies with *E. coli*, and growth inhibition was reported with metabolic activation in two of six DNA-repair-deficient *E. coli* strains. Differential toxicity was reported without metabolic activation in one study with *E. coli* strains with different capacities for recombinational repair (*pol* A^+ and *pol* A^-). The positive result was not confirmed in repeat studies in two different laboratories using the same protocol, or in another study that used the liquid suspension protocol. DNA damage was reported in one study with *rec* strains of *B. subtilis*, with and without metabolic activation.

Several studies investigated the co-mutagenic activity of norharman and *ortho*-toluidine (Appendix F, Table F-2). Norharman is found in cigarette smoke, coffee, alcoholic beverages, cooked meat and fish (formed as a pyrolysis product of tryptophan), and human urine (Gupta *et al.* 1989, Hada *et al.* 2001, Mori *et al.* 1996, Nishigaki *et al.* 2007, Oda *et al.* 2006). Norharman is non-mutagenic when administered alone, but is co-mutagenic when administered with non-mutagenic or weakly mutagenic aromatic amines

in the presence of S9. Norharman reacts with *ortho*-toluidine in the presence of S9 mix to form two mutagenic compounds (amino-3´-methylphenylnorharman and its hydroxyamino derivative). These compounds may be further activated by acetyltransferases (NATs). Oda *et al.* (2006) identified CYP1A1, CYP1A2, NAT1, and NAT2 as the activating enzymes.

5.1.2 Non-mammalian eukaryote systems

Studies in non-mammalian systems support the conclusion that *ortho*-toluidine is mutagenic under special assay conditions (Appendix F, Table F-3). In contrast to studies in bacteria and fungi, 5 of 6 somatic mutation studies in *Drosophila* were positive. Exposure to *ortho*-toluidine did not cause mutations in yeast or fungi; however, positive studies were observed for genetic crossing-over (based on only one study) and interchromosomal recombination (based on two studies), and for gene conversion in most but not all studies. Most of the positive studies used an optimized yeast P448/P450 assay that eliminated the need for exogenous metabolic activation. Only one study that used the optimized yeast system reported a negative result (gene conversion). Conflicting findings were found for differential toxicity (based on only 2 studies) and positive findings were found for the deletion assay in *Saccharomyces cerevisiae*.

5.1.3 Mammalian *in vitro* studies

Studies clearly show that *ortho*-toluidine induces a variety of genotoxic effects in human and rodent cells *in vitro* (Appendix F, Table F-4). Most of the *in vitro* genetic toxicology assays with *ortho*-toluidine were conducted as part of the second international collaborative study (Ashby *et al.* 1985) and were reviewed by Danford (1991) and IARC (2010a).

The available genotoxicity studies in human cells demonstrate that *ortho*-toluidine causes different types of genetic damage (including DNA and chromosomal damage) in various types of human cells. Genetic effects in human cells included DNA damage, unscheduled DNA synthesis (UDS), gene mutation, sister chromatid exchange (SCE), and micronucleus formation. Exogenous metabolic activation was required for UDS but not for SCE or micronucleus formation. All studies gave clear positive results with the exception of one inconclusive study for SCE. The inconclusive study showed a slight dose-related increase in SCE but did not reach a doubling of the control value and used a short incubation time (1 hour).

In general, similar types of genetic effects that were observed in human cells were also reported to occur in mammalian cells; however, for some types of damage, results were less consistent. The studies in non-human cells were conducted in a greater variety of cell types compared with the human cells. DNA damage was reported in rat hepatocytes, rat urinary-bladder mucosa cells, and Chinese hamster ovary cells (CHO). DNA damage in both human and rat urinary-bladder mucosal cells are of particular interest because the urinary bladder is a target site for carcinogenic effects in rats and humans (see Sections 3 and 4). The data also indicate that *ortho*-toluidine causes cytogenetic damage (SCE, chromosomal aberrations, micronuclei, or aneuploidy) in rodent cells; however, results were less consistent for SCE. There was no apparent requirement for S9 metabolic activation for cytogenetic effects, with the possible exception of chromosomal

aberrations. In some studies, metabolic activation appeared to reduce SCE levels. The negative results for SCE, micronucleus, and chromosomal aberrations occurred when short treatment times were used (1 hour). The positive studies used treatment times of at least 2 hours.

Gene mutation studies in rodent cells were positive in about one half of the studies reviewed; however, the required conditions were unclear. Chinese hamster V79 cells and mouse L5178Y cells were the most frequently used but there were no apparent patterns related to locus, S9 presence or concentration, dose, or treatment time. UDS was positive in only one of eight studies in rat or hamster hepatocytes. The one positive study used a relatively high dose compared with the negative studies. One study that investigated effects on the mitotic spindle in Chinese hamster lung cells was negative.

In addition, *ortho*-toluidine consistently induced cell transformation in rodent cells (Appendix F, Table F-5). Cell transformation assays measure morphological transformation as an early event in the *in vitro* neoplastic process and allow for a broader assessment of carcinogenic potential including both genotoxic and non-genotoxic events (Maire *et al.* 2012, Pant *et al.* 2012).

5.1.4 *In vivo* studies

The genotoxic effects of *ortho*-toluidine have been investigated in more than a dozen studies. Endpoints evaluated include DNA adducts, DNA damage, single-strand breaks, clastogenic effects, altered sperm morphology, and DNA synthesis inhibition.

Although results were mixed, the data show that *ortho*-toluidine is genotoxic to some tissues *in vivo*, including DNA damage in rat urinary bladder and mouse liver and micronuclei in rat blood. In general, the available DNA adduct data were not consistent with the observed carcinogenic effects in rats. Data for DNA adducts and other genotoxic effects from *in vivo* studies are reviewed below.

DNA adducts

DNA adducts of *ortho*-toluidine can be synthesized by reacting the *N*-acetoxyarylamine derivative of *ortho*-toluidine with nucleosides (2′-deoxyguanosine or 2′-deoxyadenosine) or with calf thymus DNA (Jones and Sabbioni 2003, Marques *et al.* 1997, Marques *et al.* 1996). The dG-C8 adduct, which has been associated with point mutations and activation of the c-H-*ras* oncogene, was the most common; however, dC, dA, and dT adducts also were detected when incubated with calf thymus DNA. Some studies indicate that *ortho*-toluidine forms DNA adducts *in vivo* (Appendix F, Table F-6); however, the DNA adduct levels for liver and nasal mucosa were not consistent with carcinogenicity data (Brock *et al.* 1990, Duan *et al.* 2008). For example, *ortho*-toluidine DNA adducts were detected in rat liver but not in the urinary bladder. The mechanistic implications of DNA adducts and DNA damage are discussed in Sections 5.2.1 and 5.2.2.

Böhm *et al.* (2011) detected *ortho*-toluidine-releasing DNA adducts in 11 urinary-bladder tumor samples (urothelial carcinomas) taken from 12 cancer patients and in 13 urinary-bladder epithelial samples and 10 bladder submucosal tissue samples taken from 46 sudden death victims at autopsy (Appendix F, Table F-7). This method allowed

measurement of the total adduct burden, but the identification or contribution of individual adducts were not determined. Adduct levels in bladder tumors were significantly higher than in non-cancerous bladder tissue. Adduct levels in smokers and non-smokers were not significantly different in this study.

Other genotoxic effects

Genotoxic effects were reported in two of the target organs where carcinogenic effects occurred (mouse liver and rat urinary bladder). *ortho*-Toluidine induced DNA strand breaks in mouse liver and kidney, DNA damage in rat urinary bladder but not in liver or kidney, and SCE in hamster and mouse bone marrow (Appendix F, Table F-8). Micronucleus (MN) formation was not reported in mouse bone marrow or rat liver, but was detected in peripheral blood of rats and erythrocytes of *Pleurodeles waltl*, an amphibian. No increase in chromosomal aberrations was observed in mice administered *ortho*-toluidine by intraperitoneal injection; this was the only study that evaluated chromosomal aberrations. One sperm morphology study was negative and a second study was inconclusive. The latter study showed a statistically significant increase in abnormal sperm but it did not meet all the criteria for a positive finding. DNA synthesis was inhibited in mouse testes but not mouse kidney.

5.1.5 Genotoxic effects of *ortho*-toluidine metabolites

N-Oxidized metabolites of *ortho*-toluidine were mutagenic in *Salmonella* while other metabolites were not mutagenic (Appendix F, Table F-9). Mutagenic activity of these metabolites is consistent with *N*-hydroxylation as a required step for metabolic activation (see Section 5.2.1). *S. typhimurium* tester strains TA98, TA100, TA1535, and TA1538 were used (Gupta *et al.* 1987, Hecht *et al.* 1979). No mutagenic activity was observed in TA1538. *N*-Hydroxy-*ortho*-toluidine and *ortho*-nitrosotoluene showed marked dose-related mutagenic activity toward TA100 and TA1535 with S9. When assayed without S9 metabolic activation, these metabolites were non-mutagenic when tested to toxicity. *N*-Acetyl-*N*-hydroxy-*ortho*-toluidine showed slight mutagenic activity in TA1535 without S9 at 10 μM/plate and a marginal mutagenic response in TA98 with S9 at 5 to 10 μM/plate. Other studies showed that anthranilic acid was not mutagenic in *S. typhimurium* TA98, TA100, TA1535, TA1537, or TA1538 with or without metabolic activation when tested by plate incorporation or preincubation methods at maximum nontoxic concentrations (1,000 to 5,000 μg/plate) (Chung *et al.* 1981) or in TA102 at concentrations up to 250 μg/plate with or without rat S9 (Gadupudi and Chung 2011).

N-Hydroxy-*ortho*-toluidine and *ortho*-nitrosotoluene were potent frameshift mutagens in *S. typhimurium* TA98 in the presence of the co-mutagen norharman and S9 (Gupta *et al.* 1989). Other *ortho*-toluidine metabolites tested (see list from Appendix F, Table F-9) were not mutagenic even in the presence of norharman and S9. The *meta*- and *para*-toluidines and their nitroso or hydroxylamino metabolites were not mutagenic with or without norharman or S9. These data provide further evidence that *N*-oxidation is required for metabolic activation and that the *ortho*-toluidine is more mutagenic than the *meta* or *para* isomers.

In addition to the reverse mutation assays in *Salmonella* discussed above, several other genotoxicity studies with the *ortho*-toluidine metabolite anthranilic acid also were negative. McFee *et al.* (1989) reported that anthranilic acid did not induce chromosomal aberrations or micronuclei in male $B6C3F_1$ mice but did have a positive effect on SCE in two of three trials. It did not induce DNA strand breaks in the pSP-72 plasmid at concentrations up to 400 μM (Gadupudi and Chung 2011), and it did not induce micronuclei in rodent V79, CHL, or CHO cells or in human peripheral blood lymphocytes, liver, or TK6 cells at doses up to 10 μM (Fowler *et al.* 2012). DNA strand breaks were not increased in mouse lymphoma cells (L5178Y/TK) with or without metabolic activation, but mutations at the TK locus were increased without metabolic activation (Garberg *et al.* 1988). Umeda *et al.* (1989) reported that anthranilic acid did not increase transformation frequency in X-ray-irradiated BALB/3T3 cells, but 3-hydroxyanthranilic acid (a metabolite of anthranilic acid) had a weak, though statistically significant, activity.

5.1.6 Synthesis of results

Overall, the large database of genetic and related effects indicates that *ortho*-toluidine can bind to DNA, cause DNA and chromosomal damage, and induce mutations. For some genetic endpoints, positive findings were only observed when special protocols were used or were limited to specific cell or tissue types. Genetic damage was observed in some tissues or cells that are target sites for carcinogenicity in experimental animals or humans.

Most of the data were reported in two international collaborative studies published in the early to mid 1980s. Only a few genetic toxicology studies were published since that time. A limitation of the database is there are no studies in humans with known exposure to *ortho*-toluidine; however, there are studies in human cells and human tissues. Studies in bacteria, mammalian cells, exposed animals, or cells from humans were considered to be the most informative. The overall assessment of the genetic effects of *ortho*-toluidine is summarized in Table 5-1. Findings were considered to be positive in the table if a consistent pattern was observed across studies; i.e., any conflicting findings across a specific endpoint could be explained by conditions of the assays, such as protocol, tissue or cell type, species, or metabolic activation.

Table 5-1. Genetic effects of *ortho*-toluidine

Effect	Bacteria	*In vitro*		*In vivo*	
		Rodents	Humans	Rodents	Humans
DNA adducts	NT	NT	NT	+[a]	+
Mutation	**(+)**[b]	**(-)**	+	NT	NT
DNA damage/strand breaks	NT	+	+	+[c]	NT
SCE	NT	+	±	+	NT
Chromosomal aberrations	NT	+	NT	–[d]	NT
Micronucleus	NT	±	+	+[e]	NT
Aneuploidy	NT	+[f]	NT	NT	NT
Inhibition of cellular	NT	+	NT	NT	NT

Effect	Bacteria	*In vitro*		*In vivo*	
		Rodents	Humans	Rodents	Humans
communication					
Differential toxicity	–	NT	NT	NT	NT
Cell transformation	NT	+	NT	NT	NT
Inhibition of DNA synthesis	NT	NT	NT	±[g]	NT
Unscheduled DNA synthesis	NT	-	+	NT	NT

– = negative, + = positive, (+) weakly positive, +/- = inconclusive, (-) mostly negative, NT = not tested.
[a]Positive in some tissues: male rat liver and nasal mucosa; negative in male rat urinary bladder and white blood cells and female rat liver.
[b]A few positive studies with modified protocols primarily using different metabolic activation systems, comutagenic activity with norharman, and some *N*-oxidized metabolites were mutagenic; overall assessment weakly mutagenic.
[c]Positive in some tissues: mouse liver and kidney and rat urinary bladder; negative in rat liver and kidney.
[d]Only one study reviewed.
[e]Positive in some tissues of some species: rat reticulocytes and newt erythrocytes; negative in mouse bone marrow and rat liver.
[f]Positive in some tissues/species: hamster lung V79 cells and liver fibroblasts, negative in rat liver epithelial cells.
[g]Positive in mouse testes, negative in mouse kidney.

Evidence that *ortho*-toluidine can bind DNA comes from findings of adducts in liver and nasal mucosa of rats exposed to *ortho*-toluidine, and from *ortho*-toluidine–releasing DNA adducts found in urinary-bladder tissue and tumors from humans. *ortho*-Toluidine is considered to be weakly mutagenic. Although *ortho*-toluidine was not mutagenic in most bacteria studies, a few reverse mutation studies in *Salmonella* were positive under modified conditions (fluctuation protocol, high concentrations of rat or hamster S9, and/or special preparations of induced S9), and one forward mutation study was positive with 30% hamster S9. This is consistent with findings observed for other aromatic amines. *ortho*-Toluidine was co-mutagenic with norharman and some oxidative metabolites of *ortho*-toluidine also were mutagenic in bacteria. It was also mutagenic in human lymphoblast cell lines (TK6 and AHH-1); however, findings were mixed in mammalian cells, which did not seem to be explained by exogenous metabolic activation. These conclusions are supported by the studies in non-mammalian eukaryotes; *ortho*-toluidine was clearly mutagenic in *Drosophila* and weakly mutagenic in yeast (see Appendix F, Table F-3).

DNA damage was reported in both *in vitro* and *in vivo* mammalian systems. Other cytogenetic effects (SCE, chromosomal aberrations, or micronuclei) were consistently induced in mammalian cells when incubation times of 2 hours or more were used. Clastogenic affects also were observed *in vivo* but not in all tissues examined. There is evidence that *ortho*-toluidine causes large-scale chromosome damage in yeast and mammalian cells (e.g., deletions, insertions, translocations, and/or aneuploidy) and oxidative damage to DNA. The only study that examined chromosomal aberrations (mouse bone marrow) was negative. Micronucleus formation was observed in rat reticulocytes but not in rat liver or mouse bone marrow. Aneuploidy also occurred in mammalian cells. Most cell transformation studies in several mammalian cell types were positive.

Genetic damage was observed in cells or tissue of some of the target sites (liver in mice and urinary bladder in rats) for carcinogenicity in experimental animals and humans (urinary bladder). *ortho*-Toluidine–releasing DNA adducts were isolated from human urinary-bladder tissues or tumors although the source of the exposure is unknown. However, DNA adducts were not observed in urinary-bladder tissue of rats exposed to *ortho*-toluidine. DNA damage was observed in both human and rat urinary mucosal cells, and in urinary-bladder tissues of rats and liver tissue of mice exposed to *ortho*-toluidine.

5.2 Mechanistic considerations

Aromatic amines include many chemicals that are carcinogenic, mutagenic, and/or are hemotoxicants (Benigni and Passerini 2002). In general, the same metabolic schemes, same kind of genotoxic lesions, and similar tissue specificity have been described for many aromatic amines and support a common mode of action for this chemical class (IARC 2010c). Recent investigations indicate that the biochemical mechanisms of action for the monocyclic compounds may be more complex than for the more extensively studied multi-ring aromatic amines (Skipper *et al.* 2010); however, data specific for *ortho*-toluidine are limited. Several aromatic amines are known human bladder carcinogens (benzidine, 4-aminobiphenyl, and 2-napthylamine) or are listed as *reasonably anticipated to be a human carcinogen* based in part on increased incidences of bladder tumors in animals (2-acetylaminofluorene and 4-chloro-*ortho*-toluidine). IARC (2010i) classified another bicyclic aromatic amine, 4,4´-methylenebis(2-chloroaniline) (MOCA or MBOCA), as a Group 1 carcinogen based on inadequate evidence in humans and sufficient evidence in experimental animals for its carcinogenicity supported by a common mode of action for monocyclic aromatic amines (which include *ortho*-toluidine) and evidence of genotoxicity and adducts in urothelial cells or lymphocytes from workers with known occupational exposure to MOCA.

No criteria have yet been identified that can separate genotoxic from non-genotoxic, or carcinogenic from non-carcinogenic monocyclic aromatic amines (IARC 2010c). However, quantitative structure-activity relationship (QSAR) models suggest that carcinogenic potency and carcinogenic activity of aromatic amines are described by different molecular properties (Benigni *et al.* 2000, Benigni and Passerini 2002, Franke *et al.* 2010, Franke *et al.* 2001). The QSARs for carcinogenicity were similar to those for mutagenicity in *Salmonella* and suggested that similar mechanisms were responsible for the mutagenic and carcinogenic activity of aromatic amines. Thus, results from the QSAR models are consistent with the importance of metabolic activation in aromatic amine carcinogenicity and mutagenicity. Electronic properties (measures of chemical reactivity or the ability to undergo metabolic transformation) and steric characteristics were the most important factors related to carcinogenic activity, while hydrophobicity (log P) was the most important factor for carcinogenic potency. Carcinogenic potency increased with increasing hydrophobicity (particularly for monocyclic amines) and increasing energy of the highest occupied molecular orbital (EHOMO). EHOMO is a parameter for oxidation reactions and indicates the propensity of the toxic amines to form *N*-hydroxylamines. Hydrophobicity is a primary determinant of absorption, distribution, and the interaction of xenobiotics with metabolizing enzymes.

The epidemiology data (see Section 3) identified the urinary bladder as a target for *ortho*-toluidine-induced cancer in humans. Carcinogenicity studies in experimental animals indicate that the urinary bladder, liver, mesenchymal tissue in the spleen and other visceral organs, the mesothelial lining of the testis and epididymis (*tunica vaginalis*), subcutaneous tissue, mammary gland, and blood vessels are target sites for *ortho*-toluidine (see Section 4). The data suggest the following: (1) multiple mechanisms are involved, (2) mechanisms may vary with target tissue, and (3) aromatic amines generally must be mutagenic and cytotoxic to induce a carcinogenic effect. Although the mechanisms of carcinogenicity in the various target tissues are not completely understood, the following sections discuss possible mechanisms of carcinogenicity for the target tissues.

5.2.1 Urinary-bladder tumors

Proposed mechanisms associated with urinary-bladder carcinogenesis include metabolic activation, direct and indirect genotoxic effects, and non-genotoxic mechanisms (e.g., cytotoxicity and sustained cell proliferation) (Skipper *et al.* 2010). Urinary bladder neoplasms were significantly increased in rats but not in mice (see Section 4); however, mice are less sensitive for developing urinary bladder cancer than rats (Frith *et al.* 1994). Although both male and female rats developed urinary-bladder tumors, the lower incidence in male rats compared with female rats might be related to sex-specific patterns of metabolic activation and detoxification (English *et al.* 2012). No metabolic studies have been conducted in female rats (see Section 2.2); however, English *et al.* reported that GSTM1 (a phase-II enzyme involved in arylamine detoxification) is more abundant in male mouse liver compared with females. If a similar pattern is true for rats, this would be consistent with a lower tumor incidence in male rats. There also is some evidence that women have a higher capacity for arylamine activation than men (Castelao *et al.* 2001). In addition, Richter *et al.* (2001) reported that levels of hemoglobin adducts of toluidine isomers tended to be lower in boys than in girls.

Data for other species are limited; however, polymorphic expression of some of the metabolizing enzymes have been linked to aromatic amine exposure and urinary-bladder cancer risk in humans. Genotoxic effects have been reported for *ortho*-toluidine and some of its metabolites (reviewed in Section 5.1) and cytotoxicity and cell proliferation are known to be important promoting factors in aromatic amine-induced carcinogenicity (Bitsch *et al.* 1999, IARC 2010c, Neumann 1986, 2007, Poirier *et al.* 1995, Woo and Lai 2004).

All the factors mentioned above were recently incorporated into a comprehensive model of the possible mode of carcinogenic action of *ortho*-toluidine in the human and rodent urinary bladder (English *et al.* 2012). The proposed key events based on data from *ortho*-toluidine and other aromatic amines are illustrated in Figure 5-1 and include the following: (1) initial bioactivation by hepatic P450 enzymes to *N*-hydroxy-*ortho*-toluidine, (2) further bioactivation in the urinary-bladder transitional epithelium via NAT1 yielding *N*-acetoxy-*ortho*-toluidine that hydrolyzes to nitrenium ions that can bind to DNA, (3) semiquinone/quinone redox cycling of unconjugated phenolic metabolites in the transitional epithelium producing reactive oxygen species (ROS), oxidative cellular damage and compensatory cell proliferation, (4) mutations from direct or indirect DNA

damage to urinary-bladder epithelial cells, and (5) development of urinary-bladder tumors. *N*-hydroxyarylamines also can be further metabolized to reactive *N*-sulfonyloxyarylamines or *N*-hydroxyarylamine *N*-glucuronides in the liver and these metabolites also may contribute to the genotoxicity and cytotoxicity of *ortho*-toluidine (English *et al.* 2012, Sabbioni and Sepai 1995). These key events, supporting data, and data weaknesses for the proposed mechanisms are discussed in the following sections.

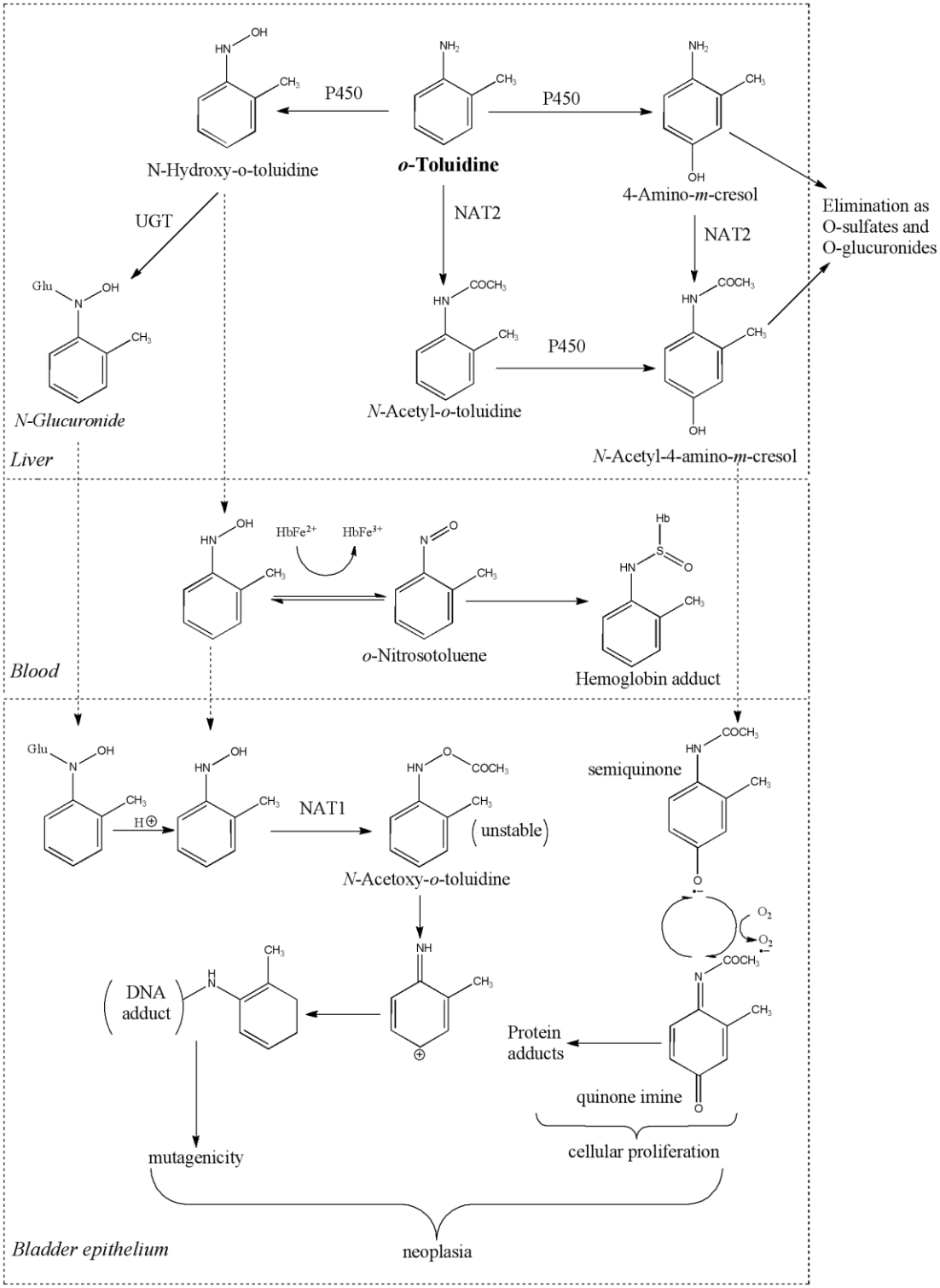

Figure 5-1. Proposed key events in the mode of action of *ortho*-toluidine-induced urinary-bladder cancer

Source: English *et al*. 2012, Kadlubar and Badawi 1995

Metabolic activation

It is known that aromatic amines require metabolic activation to exert toxic effects (IARC 2010c). Although not completely understood, activation steps include both phase-I oxidation and phase-II conjugation (primarily acetylation or sulfation) reactions (Skipper *et al.* 2010, Woo and Lai 2004). The first step involves *N*-hydroxylation (*N*-oxidation) or *N*-acetylation in the liver to form an aryl-*N*-hydroxylamine or an *N*-acetylated (arylamide) derivative. *N*-Acetylation is usually considered a detoxification pathway; however, arylamides can undergo further metabolic activation in the liver to form reactive and toxic metabolites (Delclos and Kadlubar 1997, Woo and Lai 2004). Studies in experimental animals indicate that *N*-acetylation of aromatic amines is a detoxification step for urinary-bladder carcinogenesis while *N*-hydroxylation is an obligatory step for carcinogenic activity (Freudenthal *et al.* 1999, Windmill *et al.* 1997).

Following *N*-oxidation or *N*-acetylation in the liver, further activation can occur through *N*,*O*-transacetylation, *O*-acetylation, or *O*-sulfation to form acyloxyarylamines or sulfonyloxyarylamines (English *et al.* 2012, Hein 1988a, 1988b, Windmill *et al.* 1997, Woo and Lai 2004). These reactions are catalyzed by cytosolic *N*-acetyltransferases (NAT1 and NAT2 in humans) and cytosolic sulfotransferases. Acyloxyarylamines and sulfonyloxyarylamines are highly reactive esters that can form electrophilic arylamidonium or arylnitrenium ions via heterolysis of the ester bond. Aryl-*N*-hydroxylamines may be further oxidized to nitroso derivatives in the blood. Nitroso metabolites form hemoglobin adducts and generate methemoglobin (see Appendix F, Table F-10) (English *et al.* 2012, Eyer 1983). However, the *N*-acetoxy derivative of *ortho*-toluidine so far has been identified only as a postulated metabolite based on studies with other aromatic amines. In addition, Hein *et al.* (1993) showed that the *N*-acetylation of *ortho*-toluidine by human NAT1 and NAT2 was consistently lower than for most other arylamines, including *para*-toluidine, 4-aminobiphenyl, 2-aminofluorene, 2-naphthylamine, and *para*-aminobenzoic acid. Zhang *et al.* (2006) also reported that *ortho*-toluidine binding to NAT1 was lower than that of 4-aminobiphenyl and para-aminobenzoic acid, which is because of steric hindrance by the methyl group. Both studies showed better activity for NAT2 than NAT1.

The phase-II activation steps are in competition with glucuronide or glutathione conjugation (Woo and Lai 2004). Glucuronide formation usually is a detoxification pathway, but these metabolites may be cleaved nonenzymatically in the mildly acidic pH of the urinary bladder (typically found in humans and dogs) or enzymatically by β-glucuronidase and further activated to arylnitrenium ions that can covalently bind to urothelial DNA (English *et al.* 2012, Freudenthal *et al.* 1999, Woo and Lai 2004, Yu *et al.* 2002). The *N*-hydroxy metabolites of aromatic amines also may enter the urinary-bladder lumen in the unconjugated form and, thus, would immediately be available for reabsorption into the bladder mucosa and binding to urothelial DNA (Kadlubar *et al.* 1991). There also is some evidence in dogs and humans that the *N*-glucuronide of the parent amine may reach the bladder. In this case, hydrolysis in the urine would release the free parent compound where it may be *N*-hydroxylated (activated) directly by the bladder epithelium (Freudenthal *et al.* 1999). Thus, *N*-hydroxy-*ortho*-toluidine and its conjugates are formed in the liver, enter the blood, and are transported to the bladder

where they form reactive nitrenium ions that can react with DNA in the transitional epithelium (English *et al.* 2012, Kadlubar and Badawi 1995, Riedel *et al.* 2006).

In general, glutathione conjugation is a detoxification reaction. Although glutathione conjugates have been described for other aromatic amines (Delclos and Kadlubar 1997, Skipper *et al.* 2010, Woo and Lai 2004), no glutathione conjugates were identified in metabolism studies with *ortho*-toluidine (see Section 2).

Further evidence of the importance of *N*-oxidation of *ortho*-toluidine as a metabolic activation step for bladder carcinogenicity was shown in a comparative carcinogenicity study of *ortho*-toluidine hydrochloride and *ortho*-nitrosotoluene in male F344 rats (Hecht *et al.* 1982). Test compounds were administered in feed for 72 weeks and all animals were killed at 93 weeks. Rats treated with the *N*-oxidized metabolite (*ortho*-nitrosotoluene) developed significantly more urinary-bladder tumors (16/30) than rats treated with *ortho*-toluidine (4/30).

Hemoglobin adducts

The finding of hemoglobin adducts in humans provides indirect evidence for the relevance of the *N*-oxidation metabolic pathway in humans. *ortho*-Toluidine–releasing hemoglobin or albumin adducts have been reported in *in vitro* studies (Stettler *et al.* 1992, see Appendix F, Table F-8), *in vivo* studies of exposed rats and mice (Birner and Neuman 1988, DeBord *et al.* 1992, Stettler *et al.* 1992, Cheever *et al.* 1992, see Appendix F, Table F-8), and in several studies in humans, including workers with a known excess of urinary-bladder cancer, non-occupationally exposed populations from various countries (see Table 1.4) and in patients treated with the local anesthetic prilocaine (which is metabolized to *ortho*-toluidine) (Gaber *et al.* 2007). (See Section 1 for additional information on *ortho*-toluidine hemoglobin adducts in human studies.) Hemoglobin adducts are formed from the reaction of hydroxy-*ortho*-toluidine metabolites with hemoglobin and most of the studies measured adducts released from the hemoglobin via base hydrolysis. Although the possibility that hydroxyl metabolites formed from ring oxidation cannot be ruled out, the hemoglobin adducts are believed to be formed from the *N*-hydroxy metabolites. An *in vitro* study of a related aromatic amine (3,4-dichloroaniline) reported that its *N*-hydroxy metabolite with hemoglobin was an order of magnitude greater that its ring-hydroxylated metabolite (Cheever *et al.* 1992). Studies of other aromatic amines that cause urinary-bladder cancer have shown that *N*-hydroxy-amines may be further oxidized to nitroso derivatives in the blood, generating methemoglobin and forming hemoglobin adducts (Skipper and Tannenbaum 1994). Birner and Neumann (1988) reported a positive correlation between hemoglobin–binding index and methemoglobin formation for six monocyclic amines that were studied (*ortho*-toluidine was not tested). Hemoglobin adducts are considered as biological markers of aromatic amine bioactivation to their ultimate carcinogenic metabolites and have been associated with bladder cancer risk in a population-based study (Gan *et al.* 2004). One study also reported a correlation between hemoglobin adducts and DNA adducts of 4-aminobiphenyl in exfoliated urothelial cells (Talaska *et al.* 1991).

Polymorphisms in metabolizing enzymes

Polymorphisms have been described for human NAT1 and NAT2 (Kadlubar and Badawi 1995, Talaska 2003, Yu *et al.* 2002). The human population can be divided into slow, intermediate, and fast acetylator phenotypes based on polymorphic expression of NAT2. Since *N*-acetylation in the liver is a detoxifying pathway for the urinary bladder, slow acetylators would be expected to detoxify aromatic amines less efficiently. Epidemiological data indicate that slow acetylators are more susceptible to aromatic amine-induced bladder cancer. In addition, the human urinary bladder has appreciable NAT1 activity and can catalyze *O*-acetylation of *N*-hydroxylamines to electrophilic *N*-acetoxy derivatives. There is some evidence that cigarette smokers that carry the high-activity NAT1 allele, especially when combined with the NAT2 slow acetylation genotype, are more likely to develop bladder cancer.

DNA damage

Genotoxic effects of *ortho*-toluidine that are potentially relevant to bladder cancer have been reported (see Section 5.1). Briefly, *ortho*-toluidine was mutagenic in human TK6 and AHH-1 lymphoblasts, induced DNA damage *in vitro* in several human cell types (urinary-bladder mucosa, MCL-5, and exfoliated milk cells), and induced DNA damage in rat urinary-bladder mucosa cells. *In vivo* studies also showed that *ortho*-toluidine could induce DNA damage in the rat urinary bladder and micronuclei in rat peripheral blood reticulocytes.

ortho-Toluidine formed DNA adducts *in vitro*, but an *in vivo* study in male rats did not detect adducts in the urinary-bladder epithelium (Duan *et al.* 2008) (see Section 5.1.4). *ortho*-toluidine–releasing DNA adducts have been detected in human urinary-bladder tissue and bladder tumors (see Appendix F, Table F-7), which supports the carcinogenicity of *ortho*-toluidine in the human urinary bladder (Böhm *et al.* 2011).

Some *N*-oxidized metabolites of *ortho*-toluidine are mutagenic with exogenous metabolic activation (see Section 5.1.5), and are carcinogenic (see Section 5.2.4). Thus, the *N*-oxidized derivatives of arylamines or arylamides are considered the proximate carcinogenic forms (Hein 1988a, Kato and Yamazoe 1994). A study in dogs reported that the extent and relative persistence of total DNA binding of several bicyclic and polycyclic aromatic amines (4-aminobiphenyl, 2-acetylaminofluorene, 1-naphthylamine, 2-naphthylamine, 4-nitrobiphenyl, benzidine, and *N*-acetylbenzidine) correlated with the compounds' carcinogenic potency in the urinary bladder (Beland *et al.* 1983). The adduct profiles were very similar to those obtained when the *N*-hydroxy metabolites of these compounds were reacted with DNA *in vitro*. Further studies in *S. typhimurium* showed that the C8-deoxyguanosine adduct was correlated with frameshift reversions and could be important for tumor initiation.

Although several studies have suggested that aromatic amines cause urinary-bladder cancer by forming DNA adducts and inducing mutations, there is evidence that gross chromosome alterations may be involved. Cytotoxic levels of 4-aminobiphenyl caused chromosomal instability (CIN, i.e., selective loss of chromosomes 4 and 6) in urinary bladder and liver cells; the specific chromosome lost varied according to cell type

(Saletta *et al.* 2007). CIN not only results in aneuploidy but also is associated with loss of heterozygosity, an important mechanism for inactivation of tumor suppressor genes. Thus, aromatic amines may affect tumorigenesis by inducing CIN. These data are consistent with previous studies of bladder cancer in humans that show complex patterns of aneuploidy (Höglund *et al.* 2001, Phillips and Richardson 2006, Sandberg 2002) and provide further evidence that exposure to specific carcinogens can select for tumor cells with distinct forms of genetic instability (Bardelli *et al.* 2001, Breivik and Gaudernack 1999). The genetic toxicology data for *ortho*-toluidine (see Section 5.1) are consistent with this hypothesis. Although *ortho*-toluidine is a weak mutagen, it induced aneuploidy, DNA strand breaks, and chromosomal damage in mammalian cells. It also caused DNA damage or strand breaks in the liver and kidney of exposed mice, SCE in bone marrow of exposed hamsters and mice, and micronuclei in peripheral blood cells of exposed rats.

Oxidative DNA damage

Oxidative DNA damage may be more important for the mutagenic and carcinogenic effects of monocyclic compounds compared with the bicyclic and polycyclic aromatic amines (Kawanishi *et al.* 2002, Ohkuma *et al.* 1999). DNA adducts can result in tumor initiation while oxidative products of DNA bases can be highly mutagenic and are involved in tumor initiation and promotion (Kawanishi *et al.* 2002). Many organic carcinogens, including aromatic nitro and amino compounds, induce oxidative DNA damage through generation of copper or iron-catalyzed reactive oxygen species (ROS) (Murata and Kawanishi 2011).

Two metabolites of *ortho*-toluidine (4-amino-3-methylphenol and *ortho*-nitrosotoluene) caused oxidative DNA damage in human c-Ha-*ras* and *p53* genes and induced 8-oxodG lesions in calf thymus DNA in the presence of NADH and Cu(II) (Ohkuma *et al.* 1999). Oxidative lesions (8-oxodG) in calf thymus DNA increased with dose for both metabolites (Figure 5-2). Two distinct mechanisms of Cu(II)-mediated DNA damage were proposed. 4-Amino-3-methylphenol is autooxidized to form the aminomethylphenoxyl radical while NADH reduces *ortho*-nitrosotoluene to the *ortho*-toluolhydronitroxide radical in the presence or absence of Cu(II). These radicals react with oxygen to form superoxide ion and hydrogen peroxide. Cu(II) is reduced by superoxide ion to Cu(I) and the interaction of Cu(I) and hydrogen peroxide generates ROS that are capable of damaging DNA. This is the same mechanism proposed by Watanabe *et al.* (2010) who also reported oxidative damage in calf thymus DNA, in DNA fragments from human *p53*, and in human leukemia (HL-60) cells treated with *ortho*-nitrosotoluene. *OGG1* expression levels also were increased in HL-60 cells and provided further evidence of oxidative damage. Oxidative DNA damage occurred only in the presence of Cu(II) and NADH, and the amount of 8-oxodG increased with *ortho*-nitrosotoluene concentrations. Superoxide dismutase (SOD), catalase, and the Cu(I) chelator, bathocuproine, reduced the amount of DNA damage. 8-OxodG is known to cause GC to TA transversions (Ohkuma *et al.* 1999, Shibutani *et al.* 1991). The mutation spectrum for the *p53* gene in human urinary-bladder carcinomas and bladder tumor cell lines has shown that GC to TA transversions are relatively common (Williamson *et al.* 1994).

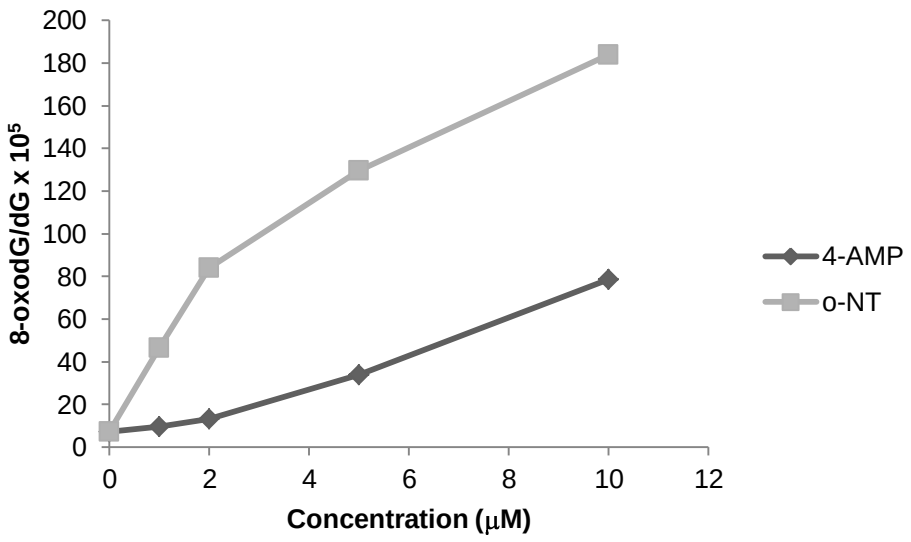

Figure 5-2. Formation of 8-oxodG lesions in calf thymus DNA treated with metabolites of *ortho*-toluidine in the presence of Cu(II).
Source: Ohkuma *et al.* 1999.
4-AMP = 4-amino-3-methylphenol, *o*-NT = *o*-nitrosotoluene.

Semiquinone/quinone redox cycling, cytotoxicity, and cellular proliferation

The cytochrome P450-mediated *N*-hydroxylation pathway is not the only phase-I oxidative metabolic pathway for aromatic amines. Direct ring oxidation of aromatic amines produces aminophenols that generally are regarded as detoxification products because they are usually conjugated with sulfate or glucuronic acid and excreted (English *et al.* 2012, Skipper *et al.* 2010). If the aminophenols are not conjugated, they can undergo peroxidase-catalyzed oxidation to form quinone imines (Figure 5-1). Although peroxidase activity in the liver is low compared with monooxygenase activity, other tissues, including the urinary bladder, contain high levels of peroxidase.

Concentrations of one of the phenolic metabolites of *ortho*-toluidine (*N*-acetyl-4-amino-*meta*-cresol) in rat urine were correlated with urinary-bladder–cell proliferation (UNEP 2004). These data support the assertion that toxicity to the urinary-bladder epithelium may be associated with reactive oxygen species generated by the redox cycling of *N*-acetyl-4-amino-*meta*-cresol and its quinone imine counterpart, or with direct damage mediated by the electrophilic quinone imine itself.

Several studies have reported cytotoxic and proliferative effects in the urinary bladder following subacute, subchronic, and chronic exposure of rats and mice to *ortho*-toluidine. Ekman and Strömbeck (1947, 1949) reported that the tumorigenic action of azo compounds was likely due to metabolism to toluidines because albino rats fed a diet containing *ortho*-toluidine or *meta*-toluidine developed epithelial changes in the bladder mucosa that were similar to those observed in rats fed tumorigenic azo compounds. These changes included keratosis, metaplasia, early epithelial proliferation, and a tendency to incipient papillomatosis. Both *meta*- and *ortho*-toluidine are metabolites of 2,3′-

azotoluene and urinary-bladder tumors occurred only when the metabolic products of 2,3′-azotoluene were in direct contact with the bladder mucosa (Strömbeck 1946).

The incidence of proliferative nonneoplastic lesions in the urinary bladder was significantly increased in rats or occurred only in dosed animals in two NTP carcinogenicity studies of *ortho*-toluidine (NCI 1979, NTP 1996). Neoplastic effects and preneoplastic effects (hyperplasia of transitional-cell epithelium) observed in the urinary bladder were reviewed in Section 4. A dose-related progression from hyperplasia of transitional-cell epithelium to transitional-cell carcinoma in the urinary bladder was observed, particularly in female rats. This lesion was reversible because complete regression occurred in the stop-exposure group (NTP 1996).

5.2.2 Other tumors

Very few mechanistic data for other tumor sites were identified. Reactive *N*-oxidized metabolites or *ortho*-toluidine reach the blood as evidenced by hemoglobin adducts detected in exposed humans and experimental animals, and at least one study reported micronucleus formation in peripheral blood of rats (see Sections 5.1.4, 5.2.1, 5.2.2). Limited information is available on mechanisms for liver tumors and splenic tumors (see below).

Liver tumors were significantly increased in female mice exposed to *ortho*-toluidine but not in male or female rats (see Section 4); however, placental glutathione *S*-transferase (PGST)-positive foci (a preneoplastic lesion) were significantly increased in male rats in a subchronic study (NTP 1996). Metabolic activation to reactive metabolites is a key step in aromatic amine-induced liver neoplasms, differences in metabolism may contribute to interspecies differences in susceptibility; *N*-acetylation is an activating reaction in the liver. Liver tumors in rodents exposed to aromatic amines likely result from *N*-hydroxy-*N*-acetylarylamine metabolites, which are formed from *N*-acetylation of *N*-hydroxy metabolites in the liver. The relative capability of NAT enzyme systems from liver cytosol of various mammalian species to acetylate the amine function of three carcinogenic aromatic amines (2-aminofluorene, 4-aminobiphenyl, and 2-aminonaphthalene) was highest in hamster followed by guinea pig, but enzyme activity in mouse liver cytosol was about an order of magnitude higher than rat liver cytosol (Lower and Bryan 1973). The comparatively greater acetylating activity in mouse liver could explain the greater susceptibility of mice to liver tumors with exposure to *ortho*-toluidine.

Exposure to *ortho*-toluidine caused DNA strand breaks in liver tissue from exposed mice, suggesting a role for genotoxicity. However, data on interactions of *ortho*-toluidine with DNA are limited. DNA binding alone does not necessarily explain the differences in carcinogenic potency observed among various aromatic amines or tissue-specific responses because biological events (e.g., promotion, DNA repair, DNA adduct persistence, cytotoxicity) in addition to macromolecular binding influence the expression of carcinogenic potential (Brock *et al.* 1990).

The spleen is a specific tumor target for *ortho*-toluidine based on evidence from studies in rats (see Section 4) (NCI 1979). Splenic fibrosarcomas are rare in rats, occurring in

about 0.4% (4/1003) of males and 0% (0/1000) of females in historical controls in dietary studies (http://www.ntp.niehs.nih.gov/ntp/research/database_searches/historical_controls/path/r_orlfd.txt). The morphologic similarity of splenic fibrosis and capsule hyperplasia to the sarcomas suggested that these lesions were preneoplastic and that the treatment-related splenic lesions appeared to be precursors to the neoplastic process (NCI 1979, Short *et al.* 1983). There is limited mechanistic data that is specific for *ortho*-toluidine–induced splenic tumors; however, data on aromatic amines suggest that the carcinogenic effects of *ortho*-toluidine in the spleen are associated with oxidative stress and erythrocyte toxicity (Khan *et al.* 1997, Ciccoli *et al.* 1999). Two metabolites of *ortho*-toluidine, 4-amino-3-methylphenol and *ortho*-nitrosotoluene, have been shown to cause oxidative damage in DNA (see Section 5.2.1), although no direct evidence of oxidative damage to the spleen was identified. Exposure to *ortho*-toluidine results in an increased incidence of several nonneoplastic effects in the spleen of rats that are consistent with a proposed mode-of-action involving toxic effects resulting from damaged red blood cells reaching the spleen. Histopathologic effects (fibrosis and mesothelial capsule hyperplasia) consistent with enhanced erythrocyte toxicity were reported by Short *et al.* (1983), and both NTP carcinogenicity studies (NCI 1979, NTP 1996) also reported nonneoplastic effects in the spleen of rats (congestion, hematopoietic cell proliferation, hemosiderin pigmentation, capsule fibrosis, capsule-lymphatic angiectasis).

5.3 Structural comparison studies

Several lines of evidence point to a role for the methyl group in the *ortho*-position in the carcinogenicity of *ortho*-toluidine. Rats administered single oral doses of *ortho*-, *meta*-, or *para*-toluidine excreted higher concentrations of unchanged *ortho*-toluidine (21% to 36%) compared with 2.5% for the *meta*- or *para*- isomers (Cheever *et al.* 1980). Thus, the higher concentration of unmetabolized *ortho*-toluidine in urine might partially explain why only the *ortho*-isomer caused urinary-bladder tumors in rats.

Hecht *et al.* (1979) investigated the structure-mutagenicity relationships among several monocyclic (including aniline and *ortho*-toluidine) and bicyclic aromatic amines and their *N*-oxidized derivatives and reported that the derivatives having a methyl group *ortho* to the amine group were generally more mutagenic in the Ames test. QSAR models suggest that substitution at the *ortho*-position also was an important factor that affected carcinogenic potency. Steric bulk at the *ortho*-position decreased potency by preventing enzymatic access to the nitrogen and formation of the reactive intermediate; however, substitution of chloro-, methyl- (e.g., *ortho*-toluidine), or methoxy- groups at this position enhanced potency (Benigni *et al.* 2000, Benigni and Passerini 2002, Franke *et al.* 2010, Franke *et al.* 2001).

The genotoxic effects of many aromatic amines are likely initiated by DNA adducts (Beyerbach *et al.* 1996). *N*-Hydroxyarylamines (*N*-oxidation products of aromatic amines form hemoglobin, albumin, and DNA adducts (Cheever *et al.* 1992, Sabbioni 1992, Sabbioni and Sepai 1995). The dG-C8 adduct, which has been associated with point mutations and activation of the c-H-*ras* proto-oncogene, is the most common (Beland and Kadlubar 1985, Beland *et al.* 1997, Marques *et al.* 1997, Marques *et al.* 1996). Other sites of DNA adducts include the N^2 and O^6 atoms of guanine and the C8 and N^6 atoms of

adenine (Branco *et al.* 1999, Delclos and Kadlubar 1997, Jones and Sabbioni 2003). Several studies reported that *ortho*-toluidine formed adducts with nucleosides, nucleotides, and DNA *in vitro* and that the three-dimensional conformation of various single-ring arylamine (methyl-, ethyl-, and dimethylaniline) adducts affected their ability to induce mutations (Beland *et al.* 1997, Beyerbach *et al.* 1996, Jones and Sabbioni 2003, Marques *et al.* 1997, Marques *et al.* 1996). Adducts that contained alkyl groups *ortho*- to the amine function (e.g., *ortho*-toluidine and 2,6-dimethylaniline) tended to be more mutagenic than their *meta*- or *para*-substituted analogues. Spectroscopic and theoretical data indicated that conformational differences among these adducts depended on the location of the alkyl group. The increased biological activity was attributed in part to the greater propensity of *ortho*-alkylated adducts to adopt a higher percentage of low-energy *syn* conformers that increased with the substitution pattern in the order *para* < *meta* < *ortho* < *ortho, para* < *ortho, meta* (Marques *et al.* 1996). The *syn* conformation enables an arylamine adduct to be inserted into the DNA helix.

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6 Overall Cancer Evaluation – Synthesis of Human, Animal, and Mechanistic Data

This section synthesizes the information from toxicological, mechanistic, and human epidemiologic studies, and applies the RoC listing criteria to that body of knowledge to reach a preliminary listing recommendation. The evidence for urinary-bladder cancer, which is the only tumor site that has been adequately studied in humans, is discussed in Section 6.1 and the available data for other tumor sites associated with exposure to *ortho*-toluidine are briefly discussed in Section 6.2.

6.1 Urinary-bladder cancer

Evidence that *ortho*-toluidine is a known human bladder carcinogen comes from human cancer studies finding increased risks of urinary-bladder cancer in humans, in concert with studies showing that it causes cancer at the same tissue site in rats and studies demonstrating the biological plausibility of mechanisms of its carcinogenicity in humans.

6.1.1 Human cancer studies

There is credible evidence of an association between increased urinary-bladder cancer risk and exposure to *ortho*-toluidine based on consistent findings across studies, the presence of exposure-duration response relationships in two studies (Carreón *et al.* 2010, Sorahan 2008), and large magnitudes of effect across studies. Potential confounding by occupational co-exposures can reasonably be ruled out in the studies of rubber chemical workers. Although there is limited information on cigarette smoking, potential confounding from smoking can reasonably be ruled out in the NIOSH cohort, and it is unlikely to explain the large risk estimates found in the smaller studies. Finally, the finding of increased urinary-bladder cancer risk in different cohorts with different exposure conditions and different co-exposures lends strong support to the conclusion that *ortho*-toluidine is the common causal risk factor (see Section 3).

6.1.2 Studies of cancer in experimental animals

There is site concordance for urinary-bladder cancer; *ortho*-toluidine causes urinary-bladder neoplasms in both female and male rats although the evidence is stronger in females. The urinary-bladder cancer findings in female rats are considered to be robust because of the relatively high tumor incidences, the rarity of the tumor in this species, and the shorter time to first observed tumor in the high-dose females than in the low-dose females (NCI 1979). Although the incidences of urinary-bladder cancer are lower in male rats, they were observed in three studies and are supported by the observation of a significantly increased incidence of transitional-cell hyperplasia of the urinary bladder in male rats after 13 or 26 weeks of exposure in subchronic exposure study (NTP 1996) (see Section 4).

6.1.3 Mechanistic evidence

Although the mechanisms of carcinogenicity of *ortho*-toluidine are not completely understood, the available evidence suggests that they are complex and involve several key modes of action, including metabolic activation that results in binding of reactive

metabolites to DNA and proteins, mutagenicity, oxidative DNA damage, chromosomal damage, and cytotoxicity. The key metabolic activation steps and genotoxic effects occur in both experimental animals and humans. *ortho*-Toluidine is an aromatic amine, and some chemicals in this class are known human bladder carcinogens – 4-aminobiphenyl, benzidine, and 2-naphthylamine. In addition, *ortho*-toluidine has a similar toxicological profile as another aromatic amine, 4,4′-methylenebis(2-chloroaniline), which is classified as carcinogenic to humans based on strong mechanistic data involving metabolic activation similar to that proposed for o*rtho*-toluidine.

Metabolic activation and formation of hemoglobin and DNA adducts

Metabolism of monocyclic aromatic amines, including *ortho*-toluidine, involves many competing activating and deactivating pathways including *N*-acetylation, *N*-oxidation and hydroxylation, and ring oxidation. Cytochrome P450-mediated *N*-hydroxylation to *N*-hydroxy derivative (*N*-hydroxy-*ortho*-toluidine), a proximate carcinogenic metabolite, occurs in the liver. *N*-hydroxy-*ortho*-toluidine is transported to the urinary bladder and can be bioactivated via conjugation by sulfation and/or acetylation by cytosolic NATs or SULTs. The postulated (based on comparison with other aromatic amines) conjugated form, *N*-acetoxy-*ortho*-toluidine, is a reactive ester that forms electrophilic arylnitrenium ions that can bind DNA. However, *ortho*-toluidine does not bind strongly to NAT1, which suggests that other modes of action may play a role in *ortho*-toluidine urinary-bladder carcinogenesis.

Studies of other aromatic amines that cause urinary-bladder cancer have shown that during the transport of the *N*-hydroxy-arylamines to the urinary bladder, bioreactive metabolites (nitroso form) can form and bind to hemoglobin in the blood (Skipper and Tannenbaum 1994). Thus, hemoglobin adducts may reflect the amount of amine that an individual takes up from the environment, converts to its proximate carcinogenic form, and exports into blood.

Evidence suggesting that this pathway is relevant to humans comes from numerous studies that detected hemoglobin adducts in *ortho*-toluidine–exposed humans (following both occupational and nonoccupational exposures), consistent with studies in experimental animals. Hemoglobin adducts are thought to be formed from the *ortho*-toluidine metabolite, *ortho*-nitrosotoluene, which also causes urinary-bladder cancer in rats (Hecht *et al.* 1982).

Metabolic activation, oxidative DNA damage, and genotoxicity

Other activation pathways for aromatic amines include peroxidase-catalyzed reactions that form quinone imines from non-conjugated phenolic metabolites. The urinary bladder, a primary target for carcinogenic aromatic amines, contains high peroxidase activity. Semiquinone/quinone redox cycling of unconjugated phenolic metabolites in the transitional epithelium can produce reactive oxygen species (ROS), oxidative cellular damage and compensatory cell proliferation. Support for this mechanism comes from studies of several *ortho*-toluidine metabolites that were shown to induce oxidative damage in human c-Ha-*ras* and *p53* genes and calf thymus DNA in the presence of Cu(II) and NADH. In addition, *ortho*-toluidine caused strand breaks in human and rat

urinary mucosa cells (*in vitro*) and in urinary-bladder tumors of rats exposed to *ortho*-toluidine.

Overall, the extensive data on genetic and related effects of *ortho*-toluidine indicate that it can cause DNA and chromosomal damage and induce mutations. Although *ortho*-toluidine is a weak mutagen in bacteria, it causes mutations in human lymphocytes, and two *ortho*-toluidine metabolites (*N*-hydroxy-*ortho*-toluidine and *ortho*-nitrosotoluene) are potent mutagens in bacteria with mammalian metabolic activation. DNA adducts have been detected in liver and nasal (but not urinary-bladder) tissue from exposed rats, and *ortho*-toluidine–releasing DNA adducts have been found in human urinary-bladder tumors and in normal human urinary-bladder tissue (presumably as a result of background environmental exposure) (see Section 5).

There is evidence that *ortho*-toluidine causes large-scale chromosome damage in yeast and mammalian cells (e.g., deletions, insertions, translocations, and/or aneuploidy) and oxidative damage to DNA. Exposure to aromatic amines has been shown to induce chromosomal instability in genetically stable urinary-bladder cancer cells. Chromosomal instability is associated with aneuploidy and loss of heterozygosity. Aneuploidy is a common feature of bladder cancer in humans and loss of heterozygosity is an important mechanism for inactivation of tumor-suppressor genes.

6.2 Other tumor sites

In addition to urinary-bladder neoplasms, exposure to *ortho*-toluidine also caused increases in the incidence of (malignant or combined malignant and benign) tumors in the blood vessels of male and female mice, liver of female mice, subcutaneous tissue in male and female rats, and connective tissue and mesothelium in male rats (see Section 4). Few mechanistic data are available for most of these tumor sites; and no compelling information was found to disregard the relevance to humans. In the liver, metabolic activation to reactive metabolites is a key step in aromatic amine-induced liver neoplasms; *N*-acetylation is an activating reaction in the liver. NAT enzyme activity for other aromatic amines in rat liver cytosol was about an order of magnitude lower than in mouse liver cytosol and may explain the greater susceptibility to liver cancer in mice (Lower and Bryan 1973). *ortho*-Toluidine caused single-strand breaks in exposed mice, suggesting that DNA damage might play a role in *ortho*-toluidine carcinogenicity. In addition, hemoglobin adducts have been reported in exposed mice, suggesting the role of reactive (hydroxylated) metabolites.

Several studies also examined the unique splenotoxic effects of *ortho*-toluidine and related compounds, and the evidence suggests that splenic tumors in rats result from a secondary response at cytotoxic doses associated with erythrocyte damage, vascular congestion, hemosiderin deposition, iron overload, hemorrhage, hyperplasia, and fibrosis. No mechanistic data were found for tumors at other sites.

6.3 Preliminary listing recommendation

ortho-Toluidine is known to be a human carcinogen based on sufficient evidence from studies in humans in concert with (1) cancer studies showing site concordance for cancer in female and male rats and (2) mechanistic data demonstrating biological plausibility in humans.

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7 References

1. Ahmadzai AA, Trevisan J, Pang W, Patel, II, Fullwood NJ, Bruce SW, Pant K, Carmichael PL, Scott AD, Martin FL. 2012. Classification of test agent-specific effects in the Syrian hamster embryo assay (pH 6.7) using infrared spectroscopy with computational analysis. *Mutagenesis* 27(3): 375-382. (Supported by Unilever. Authors affiliated with Lancaster University, UK; BioReliance Corporation, MD; Unilever Colworth Science Park, UK.)

2. Akron. 2012a. *The Chemical Database. o-Toluidine*. The Department of Chemistry at the University of Akron. http://ull.chemistry.uakron.edu/erd and search on CAS number. Accessed on 5/31/12.

3. Akron. 2012b. *The Chemical Database. 2-Methylaniline Hydrochloride*. The Department of Chemistry at the University of Akron. http://ull.chemistry.uakron.edu/erd and search on CAS number. Accessed on 10/26/12.

4. Akyüz M, Ata S. 2008. Determination of aromatic amines in hair dye and henna samples by ion-pair extraction and gas chromatography-mass spectrometry. J Pharm Biomed Anal 47(1): 68-80. (Supported by the State Planning Organization, Turkey, and the Zonguldak Karaelmas University. Authors affiliated with Zonguldak Karaelmas University, Turkey.)

5. Al-Hadithi NA. 1974. The role of some tryptophan metabolites in certain diseases of the genito-urinary system. *Br J Urol* 46(3): 337-342. (Support not reported. Author affiliated with Baghdad University, Iraq.)

6. Alibaba. 2013. *Alibaba.com Product Database*. Alibaba.com. http://www.alibaba.com and search on "hair dye," then narrow search by country, Turkey. Accessed on 6/4/13.

7. Allbiz. 2013. *Allbiz Product Database*. Allbiz. http://www.tr.all.biz/en/hair-dye-bgg1059300. Accessed on 5/31/13.

8. Amlacher E, Ziebarth D. 1979. Effectiveness in the carcinogenicity prescreening. A partial comparison of the bacterial mutagenicity test (Ames), the thymidine incorporation inhibiting screening system (Amlacher) and the promoting activity test (Danz). Arch Geschwulstforsch 49(6): 490-494. (Support not reported. Authors affiliated with Friedrich-Schiller University, Germany; Academy of Sciences at GDR, Germany.)

9. An T, Sun L, Li G, Wan S. 2010. Gas-phase photocatalytic degradation and detoxification of *o*-toluidine: Degradation mechanism and Salmonella mutagenicity assessment of mixed gaseous intermediates. *J Mol Catal A-Chem* 333(1-2): 128-135. (Supported by the National Natural Science Foundation of

China and the Science and Technology Project of Guangdong Province, China. Authors affiliated with Chinese Academy of Sciences, China.)

10. Anders A, Zechel C, Schlatterer B, Groger H, Schmidt D, Smith A, Anders F. 1991. Genetic and molecular approach for breeding and use of laboratory fish for the detection of agents with carcinogenic and/or promoting activity. *Bull Cancer* 78(5): 415-433. (Support not reported. Authors affiliated with Genetisches Institut der Justus Liebig Universitat Giessen, Germany; Unweltbundesamt, Germany; University College and Middlesex School of Medicine, UK.)

11. Ashby J, de Serres FJ, Draper M, Ishidate M, Jr., Margolin BH, Matter BE, Shelby MD, eds. 1985. *Evaluation of Short-Term Tests for Carcinogens. Report of the International Program on Chemical Safety Collaborative Study on In Vitro Assays*. vol. 5. New York, NY: Elsevier Science Publishers.

12. Axelson O, Steenland K. 1988. Indirect methods of assessing the effects of tobacco use in occupational studies. Am J Ind Med 13(1): 105-118. (Support not reported. Authors affiliated with NIOSH, OH; Department of Occupational Medicine, Sweden.)

13. Bakke OM, Scheline RR. 1970. Hydroxylation of aromatic hydrocarbons in the rat. *Toxicol Appl Pharmacol* 16(3): 691-700. (Supported by L. Meltzers Høyskolefond, Norsk Medisinaldepot and Norges Almenvitenskapelige Forskningsråd. Authors affiliated with University of Bergen, Norway.)

14. Baptista RJ. 2012. *The Faded Rainbow: The Rise and Fall of the Western Dye Industry 1856-2000*. 19 pp. (Support and author affiliations not reported.)

15. Bardelli A, Cahill DP, Lederer G, Speicher MR, Kinzler KW, Vogelstein B, Lengauer C. 2001. Carcinogen-specific induction of genetic instability. *Proc Natl Acad Sci U S A* 98(10): 5770-5775. (Supported by the Concern Foundation, the Clayton Fund, and National Institutes of Health. Authors affiliated with Johns Hopkins Oncology Center, MD; Howard Hughes Medical Institute, MD; Graduate Program in Human Genetics and Molecular Biology, MD; University of Munich, Germany.)

16. Barrett JC, Lamb PW. 1985. Tests with the Syrian hamster embryo cell transformatin assay. *Prog Mutat Res* 5: 623-628. (Support not reported. Authors affiliated with NIEHS, NC.)

17. Beland FA, Beranek DT, Dooley KL, Heflich RH, Kadlubar FF. 1983. Arylamine-DNA adducts *in vitro* and *in vivo*: their role in bacterial mutagenesis and urinary bladder carcinogenesis. *Environ Health Perspect* 49: 125-134. (Supported by the Veteran's Administration. Authors affiliated with National Center for Toxicological Research, AR.)

18. Beland FA, Kadlubar FF. 1985. Formation and persistence of arylamine DNA adducts *in vivo*. *Environ Health Perspect* 62: 19-30. (Support not reported. Authors affiliated with National Center for Toxicological Research, AR.)

19. Beland FA, Melchior WB, Jr., Mourato LL, Santos MA, Marques MM. 1997. Arylamine-DNA adduct conformation in relation to mutagenesis. *Mutat Res* 376(1-2): 13-19. (Supported by NATO, Junta Nacional de Investigação Científica e Tecnológica, Portugal, and Oak Ridge Institute. Authors affiliated with National Center for Toxicological Research, AR; Centro de Química Estrutural, Portugal.)

20. Benigni R, Giuliani A, Franke R, Gruska A. 2000. Quantitative structure-activity relationships of mutagenic and carcinogenic aromatic amines. *Chem Rev* 100(10): 3697-3714. (Support not reported. Authors affiliated with Istituto Superiore di Sanitá, Italy; Consulting in Drug Design GbR, Germany.)

21. Benigni R, Passerini L. 2002. Carcinogenicity of the aromatic amines: from structure-activity relationships to mechanisms of action and risk assessment. *Mutat Res* 511(3): 191-206. (Support not reported. Authors affiliated with stituto Superiore di Sanitá, Italy.)

22. Bernard S. 2012. Stanley Bernard, Drexel Chemical Company, letter to the U.S. House of Representatives, June 19, 2012.

23. Beyerbach A, Farmer PB, Sabbioni G. 1996. Synthesis and analysis of DNA adducts of arylamines. *Biomarkers* 1(1): 9-20. (Supported by the European Community. Authors affiliated with Universität Würzburg, Germany; University of Leicester, UK.)

24. Birner G, Neumann HG. 1988. Biomonitoring of aromatic amines II: Hemoglobin binding of some monocyclic aromatic amines. *Arch Toxicol* 62(2-3): 110-115. (Supported by the Deutsche Forschungsgemeinschaft. Authors affiliated with University of Würzburg, Germany.)

25. Bitsch A, Klöhn PC, Hadjiolov N, Bergmann O, Neumann HG. 1999. New insights into carcinogenesis of the classical model arylamine 2-acetylaminofluorene. *Cancer Lett* 143(2): 223-227. (Supported by the Deutsche Forschungsgemeinschaft. Authors affiliated with University of Würzburg, Germany.)

26. Böhm F, Schmid D, Denzinger S, Wieland WF, Richter E. 2011. DNA adducts of *ortho*-toluidine in human bladder. *Biomarkers* 16(2): 120-128. (Support not reported. Authors affiliated with Ludwig-Maximilians-University, Germany; University of Regensburg, Germany.)

27. Bowers JS. 2011. Toluidines. In *Ullman's Encyclopedia of Industrial Chemistry*. vol. 37. Weinheim: Wiley-VCH Velrag GmbH & Co KGaA. p. 119-126.

28. Boyland E, Watson G. 1956. 3-Hydroxyanthranilic acid, a carcinogen produced by endogenous metabolism. *Nature* 177(4514): 837-838. (Supported by the Chester Beatty Research Institute, British Empire Cancer Campaign, the Jane Coffin Childs Memorial Fund for Medical Research, the Anna Fuller Fund, and the National Cancer Institute of the National Institutes of Health, U.S. Public Health Service. Authors affiliated with Royal Cancer Hospital, UK.)

29. Branco PS, Antunes AM, Marques MM, Chiarelli MP, Lobo AM, Prabhakar S. 1999. New syntheses of DNA adducts from methylated anilines present in tobacco smoke. *Chem Res Toxicol* 12(12): 1223-1233. (Supported by Fundação para a Ciência e Tecnologia (Lisbon) and NIH.)

30. Branner B, Kutzer C, Zwickenpflug W, Scherer G, Heller W-D, Richter E. 1998. Haemoglobin adducts from aromatic amines and tobacco-specific nitrosamines in pregnant smoking and non-smoking women. Biomarkers 3(1): 35-47. (Supported by VERUM, Stiftung für Verhalten und Umwelt. Authors affiliated with Walther-Straub-Institut für Pharmakologie und Toxikologie, Germany; Analytisch-Biologisches Forschungslabor, Germany.)

31. Brauers A, Manegold E, Buettner R, Baron JM, Merk HF, Jakse G. 2000. Cytochrome P450 isoenzyme mRNA expression pattern in human urinary bladder malignancies and normal urothelium. Cancer Detect Prev 24(4): 356-363. (Supported by the START-Program by the medical faculty of the Technical University, Aachen. Authors affiliated with Technical University, Aachen, Germany.)

32. Breivik J, Gaudernack G. 1999. Genomic instability, DNA methylation, and natural selection in colorectal carcinogenesis. *Semin Cancer Biol* 9(4): 245-254. (Supported by the Norwegian Research Council for Science and the Humanities. Authors affiliated with Norwegian Radium Hospital, Norway.)

33. Brock WJ, Hundley SG, Lieder PH. 1990. Hepatic macromolecular binding and tissue distribution of ortho- and para-toluidine in rats. *Toxicol Lett* 54(2-3): 317-325. (Support not reported. Authors affiliated with E.I. Du Pont de Nemours, DE.)

34. Brown KK, Teass AW, Simon S, Ward EM. 1995. A biological monitoring method for *o*-toluidine and aniline in urine using high performance liquid chromatography with electrochemical detection. *Appl Occup Environ Hyg* 10(6): 557-565. (Support not reported. Authors affiliated with National Institute for Occupational Safety and Health, OH.)

35. Bryan GT, Brown RR, Price JM. 1964a. Mouse bladder carcinogenicity of certain tryptophan metabolites and other aromatic nitrogen compounds suspended in cholesterol. *Cancer Res* 24: 596-602. (Supported by the American Cancer Society, the National Institutes of Arthritis and Metabolic Diseases, the

National Cancer Institute and the Elsa U. Pardee Foundation. Authors affiliated with University of Wisconsin, WI.)

36. Bryan GT, Brown RR, Price JM. 1964b. Incidence of mouse bladder tumors following implantation of paraffin pellets containing certain tryptophan metabolites. *Cancer Res* 24: 582-585. (Supported by the American Cancer Society, the National Institutes of Arthritis and Metabolic Diseases, the National Cancer Institute and the the Elsa U. Pardee Foundation. Authors affiliated with University of Wisconsin, WI.)

37. Bryan GT. 1969. Role of tryptophan metabolites in urinary bladder cancer. *Am Ind Hyg Assoc J* 30(1): 27-34. (Supported by the National Cancer Institute and the American Cancer Society. Author affiliated with University of Wisconsin, WI.)

38. Bryan GT. 1971. The role of urinary tryptophan metabolites in the etiology of bladder cancer. *Am J Clin Nutr* 24(7): 841-847. (Supported by the National Cancer Institute and the American Cancer Society. Author affiliated with University of Wisconsin Medical School, WI.)

39. Bryant MS, Vineis P, Skipper PL, Tannenbaum SR. 1988. Hemoglobin adducts of aromatic amines: associations with smoking status and type of tobacco. *Proc Natl Acad Sci U S A* 85(24): 9788-9791. (Supported by the National Cancer Institute, the International Union Against Cancer, the American Cancer Society, the National Institute of Environmental Health Sciences, the National Institutes of Health, the Associazione Italiana per la Ricerca sul Cancro and the Italian National Research Council. Authors affiliated with Massachusetts Institute of Technology, MA; Dipartimento di Scienze Biomediche e Oncologie Umana, Italy.)

40. Bus JS, Popp JA. 1987. Perspectives on the mechanism of action of the splenic toxicity of aniline and structurally-related compounds. *Food Chem Toxicol* 25(8): 619-626. (Support not reported. Authors affiliated with Chemical Industry Institute of Toxicology, NC; Upjohn Company, MI.)

41. Cain JC, Thorpe JF. 1905. The Synthetic Dyestuffs and the Intermediate Products from Which They are Derived, London, UK: Charles Griffin and Company, Ltd. 405 pp.

42. Carreón T, Hein MJ, Viet SM, Hanley KW, Ruder AM, Ward EM. 2010. Increased bladder cancer risk among workers exposed to *o*-toluidine and aniline: a reanalysis. *Occup Environ Med* 67(5): 348-350. (Supported by CDC/NIOSH. Authors affiliated with NIOSH, OH; Westat, Inc., MD; American Cancer Society, GA.)

43. Case RA, Hosker ME, Mc DD, Pearson JT. 1954. Tumours of the urinary bladder in workmen engaged in the manufacture and use of certain dyestuff intermediates in the British chemical industry. I. The role of aniline, benzidine,

alpha-naphthylamine, and beta-naphthylamine. *Br J Ind Med* 11(2): 75-104. (Support not reported. Authors affiliated with University of London, UK; Royal Cancer Hospital.)

44. Case RA, Pearson JT. 1954. Tumours of the urinary bladder in workmen engaged in the manufacture and use of certain dyestuff intermediates in the British chemical industry. II. Further consideration of the role of aniline and of the manufacture of auramine and magenta (fuchsine) as possible causative agents. Br J Ind Med 11(3): 213-216. (Supported by the Association of British Chemical Manufacturers and the Chester Beatty Research Institute. Authors affiliated with University of London, UK.)

45. Castelao JE, Yuan JM, Skipper PL, Tannenbaum SR, Gago-Dominguez M, Crowder JS, Ross RK, Yu MC. 2001. Gender- and smoking-related bladder cancer risk. J Natl Cancer Inst 93(7): 538-545. (Supported by NIH and NIEHS. Authors affiliated with University of Southern California, CA; Massachusetts Institute of Technology, MA.)

46. Castro-Jiménez MA, Orozco-Vargas LC. 2011. Parental exposure to carcinogens and risk for childhood acute lymphoblastic leukemia, Colombia, 2000-2005. *Prev Chronic Dis* 8(5): A106. (Supported by COLCIENCIAS, the National Cancer Institute of Colombia and Universidad Industrial de Santander. Authors affiliated with Universidad Industrial de Santander, Colombia; Grupo Colombiano de Estudios Alfa en Epidemiología, Colombia.)

47. CDC. 2012. *Fast Facts: Smoking and Tobacco Use*. Centers for Disease Control and Prevention. http://www.cdc.gov/tobacco/data_statistics/fact_sheets/fast_facts/. Accessed on 2/21/13.

48. Cesarone CF, Bolognesi C, Santi L. 1982. Evaluation of damage to DNA after in vivo exposure to different classes of chemicals. *Arch Toxicol* 49(Suppl. 5): 355-359. (Support not reported. Authors affiliated with University of Genoa, Italy; Istituto Scientifico per lo Studio e la Cura dei Tumori, Italy.)

49. Cheever KL, Richards DE, Plotnick HB. 1980. Metabolism of *ortho*-, *meta*-, and *para*-toluidine in the adult male rat. *Toxicol Appl Pharmacol* 56(3): 361-369. (Support not reported. Authors affiliated with the National Institute for Occupational Safety and Health, OH.)

50. Cheever KL, DeBord DG, Swearengin TF, Booth-Jones AD. 1992. *ortho*-Toluidine blood protein adducts: HPLC analysis with fluorescence detection after a single dose in the adult male rat. *Fundam Appl Toxicol* 18(4): 522-531. (Support not reported. Authors affiliated with National Institute for Occupational Safety and Health, OH.)

51. ChemIDplus. 2012. *ChemIDplus Advanced*. National Library of Medicine. http://chem.sis.nlm.nih.gov/chemidplus/chemidheavy.jsp and select Registry Number and search on CAS number. Accessed on 5/31/12.

52. Chung KT, Fulk GE, Andrews AW. 1981. Mutagenicity testing of some commonly used dyes. *Appl Environ Microbiol* 42(4): 641-648. (Supported by the National Cancer Institute. Authors affiliated with Frederick Cancer Research Center, MD; Soochow University, Taiwan.)

53. Chung KT, Gadupudi GS. 2011. Possible roles of excess tryptophan metabolites in cancer. *Environ Mol Mutagen* 52(2): 81-104. (Support not reported. Authors affiliated with University of Memphis, TN.)

54. Ciccoli L, Ferrali M, Rossi V, Signorini C, Alessandrini C, Comporti M. 1999. Hemolytic drugs aniline and dapsone induce iron release in erythrocytes and increase the free iron pool in spleen and liver. *Toxicol Lett* 110(1-2): 57-66. (Supported by the Italian Ministry of University and Scientific Research. Authors affiliated with Università di Siena, Italy.)

55. Collins JJ, Strauss ME, Riordan SG. 1999. Mortalities of workers at the Nitro plant with exposure to 2-mercaptobenzothialzole. *Occup Environ Med* 56(10): 667-671. (Supported by Solutia, MO. Authors affiliated with Solutia, MO; Monsanto, MO.)

56. Conso F, Pontal P. 1982. [Amino-tumeurs de la vessie. Rôle possible de l'exposition industrielle à i'o. toluidine et à l'o. aminoazotoluène. *Arch Mal Prof* 43(4): 307-310. (Support unknown due to foreign language. Authors affiliated with Hôpital Raymond-Poincaré; Hôpital Fernand-Widal, France.)

57. Danford N. 1991. The genetic toxicology of *ortho*-toluidine. *Mutat Res* 258(3): 207-236. (Support not reported. Authors affiliated with Microptic Ltd., UK.)

58. Daniel MR, Dehnel JM. 1981. Cell transformation test with baby hamster kidney cells. In *Evaluation of Short-term tests for Carcinogens*. vol. 1. de Serres FJ, Ashby J, eds. New York, NY: Elsevier North Holland, Inc. p. 626-637. (Support not reported. Authors affiliated with Huntington Research Center, UK.)

59. de Serres FJ, Ashby J, eds. 1981. *Evaluation of Short-Term Tests for Carcinogens*. Progress in Mutation Research, vol. 1. New York, NY: Elsevier North Holland, Inc. 813 pp.

60. DeBord DG, Swearengin TF, Cheever KL, Booth-Jones AD, Wissinger LA. 1992. Binding characteristics of ortho-toluidine to rat hemoglobin and albumin. *Arch Toxicol* 66(4): 231-236. (Support not reported. Authors affiliated with NIOSH, OH.)

61. DeBruin LS, Pawliszyn JB, Josephy PD. 1999. Detection of monocyclic aromatic amines, possible mammary carcinogens, in human milk. *Chem Res*

Toxicol 12(1): 78-82. (Supported by the Canadian Breast Cancer Foundation, the Natural Sciences and Engineering Research Council of Canada, Varian, and Supelco, Inc. Authors affiliated with University of Guelph, Canada; University of Waterloo, Canada.)

62. Decarli A, Peto J, Piolatto G, La Vecchia C. 1985. Bladder cancer mortality of workers exposed to aromatic amines: analysis of models of carcinogenesis. *Br J Cancer* 51(5): 707-712. (Supported by the Italian National Research Council and the Italian Association for Cancer Research. Authors affiliated with University of Milan, Italy; Institute of Cancer Research, UK; University of Turin, Italy; "Mario Negri" Institute, Italy.)

63. Delclos KB, Kadlubar FF. 1997. Carcinogenic aromatic amines and amides. In *Comprehensive Toxicology*. vol. 12, Chemical Carcinogens and Anticarcinogens. Bowden GT, Fischer SM, eds. New York, NY: Elsevier Science. pp. 141-170. (Support not reported. Authors affiliated with National Center for Toxicological Research, AR.)

64. Diaz Gómez MI, Fanelli SL, Delgado de Layño AM, Castro JA, Castro GD. 2006. Liver nuclear and microsomal CYP2E1-mediated metabolism of xenobiotics in rats chronically drinking an alcohol-containing liquid diet. *Toxicol Ind Health* 22(9): 367-374. (Supported by the University of San Martín. Authors affiliated with Centro de Investigaciones Toxicológicas (CEITOX), CITEFA/CONICET, Argentina.)

65. DrugsArea. 2007. *Prilocaine*. DrugsArea.com. http://drugsarea.com/Dets-Drugs/Prilocainepd.html. Accessed on 2/22/13.

66. Duan JD, Jeffrey AM, Williams GM. 2008. Assessment of the medicines lidocaine, prilocaine, and their metabolites, 2,6-dimethylaniline and 2-methylaniline, for DNA adduct formation in rat tissues. *Drug Metab Dispos* 36(8): 1470-1475. (Support not reported. Authors affiliated with New York Medical College, NY.)

67. EJView. 2012a. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 1 mile radius around feature of interest. Goodyear Chemical Plant. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

68. EJView. 2012b. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 0.5 mile radius around feature of interest. Goodyear Chemical Plant. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

69. EJView. 2012c. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 1 mile radius around feature of interest.

Albemarle Corp., Pasadena. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

70. EJView. 2012d. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 0.5 mile radius around feature of interest. Albemarle Corp., Pasadena. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

71. EJView. 2012e. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 1 mile radius around feature of interest. BASF Corporation. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

72. EJView. 2012f. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 0.5 mile radius around feature of interest. BASF Corporation. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

73. EJView. 2012g. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 1 mile radius around feature of interest. First Chemical Corporation. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

74. EJView. 2012h. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 0.5 mile radius around feature of interest. First Chemical Corporation. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

75. EJView. 2012i. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 1 mile radius around feature of interest. Tennessee Eastman Division. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

76. EJView. 2012j. Environmental Justice. EJView - Residential population, by Census 2000 Block Group, within a 0.5 mile radius around feature of interest. Tennessee Eastman Division. U.S. Environmental Protection Agency. http://epamap14.epa.gov/ejmap/entry.html. Accessed on 10/4/12.

77. Ekman B, Strömbeck JP. 1947. Demonstration of tumorigenic decomposition products of 2, 3-azotoluene. *Acta Phys Scand* 14(1-2): 43-50. (Support not reported. Authors affiliated with University of Lund, Sweden.)

78. Ekman B, Strömbeck JP. 1949. The effect of some splitproducts of 2,3-azotoluene on the urinary bladder in th erat and their excretion on various diets. *Acta Path Micro Scand* 26(3): 447-471. (Supported by the State Medical Research Council. Authors affiliated with University of Lund, Sweden.)

79. el-Bayoumy K, Donahue JM, Hecht SS, Hoffmann D. 1986. Identification and quantitative determination of aniline and toluidines in human urine. *Cancer Res* 46(12 Pt 1): 6064-6067. (Supported by the National Cancer Institute. Authors affiliated with American Health Foundation, NY.)

80. English JC, Bhat VS, Ball GL, McLellan CJ. 2012. Establishing a total allowable concentration of o-toluidine in drinking water incorporating early lifestage exposure and susceptibility. Regul Toxicol Pharmacol 64(2): 269-284. (Support not reported. Authors affiliated with NSF International, MI.)

81. EPA. 1984. *Chemical Hazard Information Profile (CHIP): ortho-Toluidine; ortho-Toluidine Hydrochloride*. Washington, D.C.: Office of Pesticide Programs and Toxic Substances (as cited in IARC 2012)

82. EPA. 1994. *Integrated Risk Information System. Aniline*. U.S. Environmental Protection Agency. Updated on 2/1/94. http://www.epa.gov/iris/subst/0350.htm. Accessed on 6/26/12.

83. EPA. 2012. *Inventory Update Reporting (IUR)*. U.S. Environmental Protection Agency. http://www.epa.gov/oppt/iur/ and search by CAS no.

84. Eyer P. 1983. The red cell as a sensitive target for activated toxic arylamines. *Arch Toxicol Suppl* 6: 3-12. (Support not reported. Author affiliated with Ludwig-Maximilians-Universität München, Germany.)

85. FDA. 1971. Food and Drug Administration Advisory Committee on protocols for safety evaluation: panel on carcinogenesis report on cancer testing in the safety evaluation of food additives and pesticides. *Toxicol Appl Pharmacol* 20(3): 419-438. (Support not reported. Authors affiliated with FDA Advisory Committee on Protocols for Safety Evaluation.)

86. FDA. 2006. *U.S. Food and Drug Administration - Total Diet Study Market Baskets 1991-3 through 2003-4*. College park, MD: U.S. Food and Drug Aministration. 127 pp.

87. Fernandez M, Gauthier L, Jaylet A. 1989. Use of newt larvae for *in vivo* genotoxicity testing of water: results on 19 compounds evaluated by the micronucleus test. *Mutagenesis* 4(1): 17-26. (Supported by the Ministère de l'Environnement, France. Authors affiliated with CNRS, France.)

88. Fowler P, Smith K, Young J, Jeffrey L, Kirkland D, Pfuhler S, Carmichael P. 2012. Reduction of misleading ("false") positive results in mammalian cell genotoxicity assays. I. Choice of cell type. *Mutat Res* 742(1-2): 11-25. (Supported by the European Cosmetic Industry Association (COLIPA) and the UK National Centre for the 3Rs (NC3Rs). Authors affiliated with Unilever, UK; Covance Laboratories Limited, UK; Kirkland Consulting, UK; Procter & Gamble, OH.)

89. Franke R, Gruska A, Giuliani A, Benigni R. 2001. Prediction of rodent carcinogenicity of aromatic amines: a quantitative structure-activity relationships model. *Carcinogenesis* 22(9): 1561-1571. (Support not reported. Authors affiliated with Consulting in Drug Design GbR, Germany; Istituto Superiore di Sanita, Italy.)

90. Franke R, Gruska A, Bossa C, Benigni R. 2010. QSARs of aromatic amines: identification of potent carcinogens. *Mutat Res* 691(1-2): 27-40. (Supported by the European Union. Authors affiliated with Consulting in Drug Design GbR, Germany; Istituto Superiore di Sanità, Italy.)

91. Frederick CB, Mays JB, Ziegler DM, Guengerich FP, Kadlubar FF. 1982. Cytochrome P-450- and flavin-containing monooxygenase-catalyzed formation of the carcinogen N-hydroxy-2-aminofluorene and its covalent binding to nuclear DNA. *Cancer Res* 42(7): 2671-2677. (Supported by the U.S. FDA. Authors affiliated with U.S. EPA, AR; University of Texas at Austin, TX; Vanderbilt University School of Medicine, TN.)

92. Freeman HS. 2012. *Use of o-Toluidine in the Manufacture of Dyes and on the Potential for Exposure to Other Chemicals in the Processes Involving o-Toluidine*. Durham, NC: Integrated Laboratory Systems, Inc. 15 pp.

93. Freudenthal RI, Stephens E, Anderson DP. 1999. Determining the potential of aromatic animes to induce cancer of the urinary bladder. *Int J Toxicol* 18: 353-359. (Support not reported. Authors affiliated with ChemFirst Inc., MS.)

94. Frith CH, Greenman DL, Cohen SM. 1994. Urinary bladder carcinogenesis in the rodent. In Carcinogenesis. Waalkes MP, Ward JM, eds. New York, NY: Raven Press, Ltd. pp. 161-197. (Support not reported. Authors affiliated with Toxicology Pathology Associates, AR; National Center for Toxicology, AR; University of Nebraska Medical Center, NE.)

95. Fujii K. 1991. Evaluation of the newborn mouse model for chemical tumorigenesis. *Carcinogenesis* 12(8): 1409-1415. (Supported by the Ministry of Education, from the Ministry of Health and Welfare and for the Research Project at the University of Tsukuba, Japan. Author affiliated with University of Tsukuba, Japan.)

96. Gaber K, Harreus UA, Matthias C, Kleinsasser NH, Richter E. 2007. Hemoglobin adducts of the human bladder carcinogen *o*-toluidine after treatment with the local anesthetic prilocaine. *Toxicology* 229(1-2): 157-164. (Support not reported. Authors affiliated with Ludwig-Maximilians University of Munich, Germany; Julius-Maximilians-University of Wuerzburg, Germany.)

97. Gadupudi GS, Chung KT. 2011. Comparative genotoxicity of 3-hydroxyanthranilic acid and anthranilic acid in the presence of a metal cofactor Cu (II) *in vitro*. *Mutat Res* 726(2): 200-208. (Supported by the University of Memphis. Authors affiliated with University of Memphis, TN.)

98. Gan J, Skipper PL, Tannenbaum SR. 2001. Oxidation of 2,6-dimethylaniline by recombinant human cytochrome P450s and human liver microsomes. *Chem Res Toxicol* 14(6): 672-677. (Supported by NIH and a DuPont educational grant. Authors affiliated with Massachusetts Institute of Technology, MA.)

99. Gan J, Skipper PL, Gago-Dominguez M, Arakawa K, Ross RK, Yu MC, Tannenbaum SR. 2004. Alkylaniline-hemoglobin adducts and risk of non-smoking-related bladder cancer. *J Natl Cancer Inst* 96(19): 1425-1431. (Supported by the U.S. Public Health Service and NIEHS. Authors affiliated with Massachusetts Institute of Technology, MA; University of Southern California, CA.)

100. Garberg P, Åkerblom EL, Bolcsfoldi G. 1988. Evaluation of a genotoxicity test measuring DNA-strand breaks in mouse lymphoma cells by alkaline unwinding and hydroxyapatite elution. *Mutat Res* 203(3): 155-176. (Support not reported. Authors affiliated with AB Astra, Sweden.)

101. Garisto GA, Gaffen AS, Lawrence HP, Tenenbaum HC, Haas DA. 2010. Occurrence of paresthesia after dental local anesthetic administration in the United States. J Am Dent Assoc 141(7): 836-844. (Support not reported. Authors affiliated with University of Toronto, Canada.)

102. Genin VA, Pliss GB, Pylev LN, Shabad LM. 1978. [Prevention of occupational urinary bladder tumours in the manufacture of toluidines]. *Gigiena Truda i Professional'nye Zabolevaniya* 7: 10-15. (Support and author affiliations unknown due to foreign language.)

103. Goodman DG, Ward JM, Reichardt WD. 1984. Splenic fibrosis and sarcomas in F344 rats fed diets containing aniline hydrochloride, *p*-chloroaniline, azobenzene, *o*-toluidine hydrochloride, 4,4'-sulfonyldianiline, or D & C red No. 9. *J Natl Cancer Inst* 73(1): 265-273. (Supported by the National Toxicology Program and the National Cancer Institute. Authors affiliated with Clement Associates, Inc., VA; NIH, MD.)

104. Gupta RL, Gupta AK, Pathak DP, Juneja TR. 1987. Mutagenic studies of ortho-toluidine and its potential metabolites. *Indian J Exp Biol* 25(9): 618-622. (Support not reported. Authors affiliated with Panjab University, India.)

105. Gupta RL, Kaur IP, Gupta AK, Pathak DP, Juneja TR. 1989. Effect of norharman on the mutagenicity of toluidine metabolites. *Toxicol Lett* 48(1): 75-81. (Support not reported. Authors affiliated with Panjab University, India.)

106. Hada N, Totsuka Y, Enya T, Tsurumaki K, Nakazawa M, Kawahara N, Murakami Y, Yokoyama Y, Sugimura T, Wakabayashi K. 2001. Structures of mutagens produced by the co-mutagen norharman with *o*- and *m*-toluidine isomers. *Mutat Res* 493(1-2): 115-126. (Supported by the Ministry of Health and Welfare of Japan, Organization for Pharmaceutical Safety and Research (OPSR) of Japan, the Smoking Research Foundation and the Foundation of Cancer

Research. Authors affiliated with National Cancer Center Research Institute, Japan; National Institute of Health Sciences, Japan; Toho University, Japan.)

107. Hanley KW, Viet SM, Hein MJ, Carreón T, Ruder AM. 2012. Exposure to *o*-toluidine, aniline, and nitrobenzene in a rubber chemical manufacturing plant: A retrospective exposure assessment update. *J Occup Environ Hyg* 9(8): 478-490. (Support not reported. Authors affiliated with NIOSH, OH; WESTAT, MD.)

108. Hatch GG, Anderson TM. 1985. Assays for enhanced DNA viral transformation of primary Syrian hamster embryo (SHE) cells. *Prog Mutat Res* 5: 629-638. (Supported by the US EPA and NIEHS. Authors affiliated with Northrop Services Inc., NC.)

109. Hecht SS, El-Bayoumy K, Tulley L, LaVoie E. 1979. Structure-mutagenicity relationships of N-oxidized derivatives of aniline, *o*-toluidine, 2'-methyl-4-aminobiphenyl, and 3,2'-dimethyl-4-aminobiphenyl. *J Med Chem* 22(8): 981-987. (Supported by NCI and NIOSH. Authors affiliated with American Health Foundation, NY.)

110. Hecht SS, El-Bayoumy K, Rivenson A, Fiala E. 1982. Comparative carcinogenicity of *o*-toluidine hydrochloride and *o*-nitrosotoluene in F-344 rats. *Cancer Lett* 16(1): 103-108. (Supported by the National Cancer Institute. Authors affiliated with American Health Foundation, NY.)

111. Hecht SS, El-Bayoumy K, Rivenson A, Fiala ES. 1983. Bioassay for carcinogenicity of 3,2'-dimethyl-4-nitrosobiphenyl, *o*-nitrosotoluene, nitrosobenzene and the corresponding amines in Syrian golden hamsters. *Cancer Lett* 20(3): 349-354. (Supported by NIOSH and NCI. Authors affiliated with American Health Foundation, NY.)

112. Hein DW. 1988a. Acetylator genotype and arylamine-induced carcinogenesis. *Biochim Biophys Acta* 948(1): 37-66. (Supported by USPHS and NCI. Authors affiliated with Morehouse School of Medicine, GA.)

113. Hein DW. 1988b. Genetic polymorphism and cancer susceptibility: evidence concerning acetyltransferases and cancer of the urinary bladder. *Bioessays* 9(6): 200-204. (Supported by the National Cancer Institute. Authors affiliated with Morehouse School of Medicine, GA.)

114. Hein DW, Doll MA, Rustan TD, Gray K, Feng Y, Ferguson RJ, Grant DM. 1993. Metabolic activation and deactivation of arylamine carcinogens by recombinant human NAT1 and polymorphic NAT2 acetyltransferases. *Carcinogenesis* 14(8): 1633-1638. (Supported by the USPHS, the National Cancer Institute and the Medical Research Council of Canada. Authors affiliated with University of North Dakota School of Medicine, ND; Hospital for Sick Children, Canada.)

115. Hein DW. 2009. N-acetyltransferase SNPs: emerging concepts serve as a paradigm for understanding complexities of personalized medicine. *Expert Opin Drug Metab Toxicol* 5(4): 353-366. (Supported by NCI, NIEHS and the National Institute of Child Health and Development. Author affiliated with University of Louisville School of Medicine, KY.)

116. Henne KR, Fisher MB, Iyer KR, Lang DH, Trager WF, Rettie AE. 2001. Active site characteristics of CYP4B1 probed with aromatic ligands. *Biochemistry* 40(29): 8597-8605. (Supported by the National Institutes of Health. Authors affiliated with University of Washington, WA; Pfizer Inc., CT; Bayer AG, Germany.)

117. Hill AB. 1965. The environment and disease: association or causation? *Proc R Soc Med* 58: 295-300.

118. Hjelm M. 1965. Age dependency and cause of prilocaine-induced methaemoglobaemiae. *Acta Anaesth Scandinav* 9(Suppl 16): 171-174. (Support not reported. Author affiliated with University Hospital, Sweden.)

119. Höglund M, Säll T, Heim S, Mitelman F, Mandahl N, Fadl-Elmula I. 2001. Identification of cytogenetic subgroups and karyotypic pathways in transitional cell carcinoma. *Cancer Res* 61(22): 8241-8246. (Supported by the Swedish Cancer Society, the Norwegian Cancer Society, Swedish Match AB, the Crafoord Foundations, the Erik-Philip So¨rensen Foundation, and the Nilsson Family Foundation. Authors affiliated with University Hospital, Sweden; Lund University, Sweden; Norwegian Radium Hospital, Norway.)

120. Howden LM, Meyer JA. 2011. *Age and Sex Composition: 2010*. Washington, D.C.: U.S. Census Bureau. 16 pp.

121. Howe JR. 1977. Is there a cancer risk in the laboratory use of magenta and related dyes? Lab Prac 26: 87-91. (Support not reported. Author affiliated with The Veteri nary Laboratory, UK.)

122. HSDB. 2005. Hazardous Substances Data B*ank. 2-Methylaniline Hydrochloride*. National Library of Medicine. http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB and search on CAS number or compound name. . Accessed on 1/19/11.

123. HSDB. 2011. *Hazardous Substances Data Bank. 2-Aminotoluene*. National Library of Medicine. http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB and search on CAS number or compound name. Accessed on 1/19/11.

124. Huncharek M, Kupelnick B. 2005. Personal use of hair dyes and the risk of bladder cancer: results of a meta-analysis. Public Health Rep 120(1): 31-38. (Supported by the Marshfield Medical Research Foundation, Marshfield, WI. Authors affiliated with Marshfield Clinic Cancer Center, WI; Meta-Analysis Research Group, WI.)

125. IARC. 1987. *ortho*-Toluidine. In *Overall Evaluations of Carcinogenicity*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, suppl. 7. Lyon, France: International Agency for Research on Cancer. p. 362.

126. IARC. 1999. *Species Differences in Thyroid, Kidney and Urinary Bladder Carcinogenesis*, IARC Scientific Publications no. 147. Lyon, France: International Agency for Research on Cancer. pp. 1-14.

127. IARC. 2000. *ortho*-Toluidine. In *Some Industrial Chemicals*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 77. Lyon, France: International Agency for Research on Cancer. pp. 267-322.

128. IARC. 2010a. *ortho*-Toluidine. In *Some Aromatic Amines, Organic Dyes, and Related Exposures*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 99. Lyon, France: International Agency for Research on Cancer. pp. 395-439.

129. IARC. 2010b. 4-Chloro-*ortho*-toluidine. In *Some Aromatic Amines, Organic Dyes, and Related Exposures*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 99. Lyon, France: International Agency for Research on Cancer. pp. 471-498.

130. IARC. 2010c. General discussion of common mechanisms for aromatic amines. In *Some Aromatic Amines, Organic Dyes, and Related Exposures*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 99. Lyon, France: International Agency for Research on Cancer. pp. 41-54.

131. IARC. 2010d. 4-4-Methylenebis (2-chloroaniline). In *Some Aromatic Amines, Organic Dyes, and Related Exposures*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 99. Lyon, France: International Agency for Research on Cancer. pp. 325-367.

132. IARC. 2012. *ortho*-Toluidine. In *A Review of Human Carcinogens: Chemical Agents and Related Occupations*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 100F. Lyon, France: International Agency for Research on Cancer. 8 pp.

133. IPCS. 1998. *Concise International Chemical Assessment Document 7: o-Toluidine*. Geneva, Switzerland: World Health Organization. 22 pp.

134. Ishida T, Matsumoto T. 1992. Enantioselective metabolism of cumene. *Xenobiotica* 22(11): 1291-1298. (Supported by the Ministry of Education. Authors affiliated with Hiroshima Institute of Technology, Japan; University of Tokushima, Japan.)

135. Jodynis-Liebert J, Matuszewska A. 1999. Effect of toluidines and dinitrotoluenes on caffeine metabolic ratio in rat. *Toxicol Lett* 104(1-2): 159-

165. (Support not reported. Authors affiliated with Karol Marcinkowski University of Medical Sciences, Poland.)

136. Jones CR, Sabbioni G. 2003. Identification of DNA adducts using HPLC/MS/MS following *in vitro* and *in vivo* experiments with arylamines and nitroarenes. *Chem Res Toxicol* 16(10): 1251-1263. (Supported by the European Commission. Authors affiliated with University of Newcastle upon Tyne, UK; Ludwig-Maximilians-Universität München, Germany; Institute of Environmental and Occupational Toxicology, Switzerland.)

137. Kadlubar FF, Dooley KL, Teitel CH, Roberts DW, Benson RW, Butler MA, Bailey JR, Young JF, Skipper PW, Tannenbaum SR. 1991. Frequency of urination and its effects on metabolism, pharmacokinetics, blood hemoglobin adduct formation, and liver and urinary bladder DNA adduct levels in beagle dogs given the carcinogen 4-aminobiphenyl. *Cancer Res* 51(16): 4371-4377. (Supported by NIH. Authors affiliated with National Center for Toxicological Research, AK; Massachusetts Institute of Technology, MA.)

138. Kadlubar FF, Badawi AF. 1995. Genetic susceptibility and carcinogen-DNA adduct formation in human urinary bladder carcinogenesis. Toxicol Lett 82-83: 627-632. (Support not reported. Authors affiliated with Natronal Center for Toxrcologrcal Research, AR.)

139. Kato R, Yamazoe Y. 1994. Metabolic activation of *N*-hydroxylated metabolites of carcinogenic and mutagenic arylamines and arylamides by esterification. *Drug Metab Rev* 26(1-2): 413-429. (Support not reported. Authors affiliated with Keio University, Japan.)

140. Kauppinen T, Pukkala E, Saalo A, Sasco AJ. 2003. Exposure to chemical carcinogens and risk of cancer among Finnish laboratory workers. Am J Ind Med 44(4): 343-350. (Supported by the Commission of European Communities, Europe against Cancer Programme, the Direction Générale de la Santé, Paris, the Ligue Nationale contre le Cancer, Paris, the Fondation Weisbrem-Benenson de la Fondation de France, Paris and IARC. Authors affiliated with Finnish Institute of Occupational Health, Finland; Finnish Cancer Registry, Finland; IARC, France.)

141. Kawanishi S, Hiraku Y, Murata M, Oikawa S. 2002. The role of metals in site-specific DNA damage with reference to carcinogenesis. *Free Radic Biol Med* 32(9): 822-832. (Support not reported. Authors affiliated with Mie University School of Medicine, Japan.)

142. Kerckaert GA, LeBoeuf RA, Isfort RJ. 1998. Assessing the predictiveness of the Syrian hamster embryo cell transformation assay for determining the rodent carcinogenic potential of single ring aromatic/nitroaromatic amine compounds. *Toxicol Sci* 41(2): 189-197. (Support not reported. Authors affiliated with Procter & Gamble Company, OH.)

143. Khalafallah AS, Abul-Fadl MA. 1964. Studies on the urinary excretion of certain tryptophan metabolites before and after tryptophan loading dose in bilharziasis, bilharzial bladder cancer and certain other types of malignancies in Egypt. *Br J Cancer* 13: 592-604. (Support not reported. Authors affiliated with Cairo University, Egypt.)

144. Khan MF, Boor PJ, Gu Y, Alcock NW, Ansari GA. 1997. Oxidative stress in the splenotoxicity of aniline. *Fundam Appl Toxicol* 35(1): 22-30. (Supported by NIEHS and the National Heart, Lung and Blood Institute, NIH. Authors affiliated with University of Texas Medical Branch, TX.)

145. Khlebnikova MI, Gladkova EV, Kurenko LT, Pshenitsyn AV, Shalin BM. 1970. [Problems of industrial hygiene and health status of workers engaged in the production of o-toluidine]. *Gigiena Truda i Professional'nye Zabolevaniya* 14: 7-10. (Support and author affiiations unknown due to foreign language.)

146. Korinth G, Weiss T, Angerer J, Drexler H. 2006. Dermal absorption of aromatic amines in workers with different skin lesions: a report on 4 cases. *J Occup Med Toxicol* 1: 17. (Supported by the institution for statutory accident insurance of the German chemical industry (Berufsgenossenschaft der chemischen Industrie). Authors affiliated with University of Erlangen-Nuremberg, Germany; Ruhr University of Bochum, Germany.)

147. Korinth G, Weiss T, Penkert S, Schaller KH, Angerer J, Drexler H. 2007. Percutaneous absorption of aromatic amines in rubber industry workers: impact of impaired skin and skin barrier creams. *Occup Environ Med* 64(6): 366-372. (Supported by the institution for statutory accident insurance of the German chemical industry (Berufsgenossenschaft der chemischen Industrie). Authors affiliated with University of Erlangen-Nuremberg, Germany.)

148. Korinth G, Luersen L, Schaller KH, Angerer J, Drexler H. 2008. Enhancement of percutaneous penetration of aniline and *o*-toluidine *in vitro* using skin barrier creams. *Toxicol In Vitro* 22(3): 812-818. (Supported by the institution for statutory accident insurance of the German chemical industry (German: Berufsgenossenschaft der Chemischen Industrie). Authors affiliated with University Erlangen-Nuremberg, Germany.)

149. Kubota Y. 1979. Experience with the chemical substances control law in Japan. Ecotoxicol Environ Saf 3(3): 256-268. (Support not reported. Author affiliated with Ministry of International Trade and Industry, Japan; National Chemical Laboratory for Industry, Japan.)

150. Kulkarni B, Fiala ES, Weisburger JH. 1983. Estimation of N-hydroxy-o-toluidine, a urinary metabolite of o-toluidine and o-nitrosotoluene, by high performance liquid chromatography with electrochemical detection. *Carcinogenesis* 4(10): 1275-1279. (Supported by the National Cancer Institute. Authors affiliated with the American Health Foundation, NY.)

151. Kütting B, Göen T, Schwegler U, Fromme H, Uter W, Angerer J, Drexler H. 2009. Monoarylamines in the general population--a cross-sectional population-based study including 1004 Bavarian subjects. *Int J Hyg Environ Health* 212(3): 298-309. (Supported by the Bavarian State Ministry of the Environment, Public Health and Consumer Protection. Authors affiliated with Friedrich-Alexander-University of Erlangen-Nuremberg, Germany; Bavarian Health and Food Safety Authority, Germany.)

152. Lawrence N, McGregor DB. 1985. Assays for the induction of morphological transformation in C3H/10T 1/2 cells in culture with and without S9-mediated metabolic activation. *Prog Mutat Res* 5: 651-658. (Support not reported. Authors affiliated with Inveresk Research International Limited, Scotland.)

153. Lewalter J, Korallus U. 1985. Blood protein conjugates and acetylation of aromatic amines. New findings on biological monitoring. *Int Arch Occup Environ Health* 56(3): 179-196. (Support not reported. Authors affiliated with Bayer AG, Germany.)

154. Lindner D, Smith S, Leroy CM, Tricker AR. 2011. Comparison of exposure to selected cigarette smoke constituents in adult smokers and nonsmokers in a European, multicenter, observational study. *Cancer Epidemiol Biomarkers Prev* 20(7): 1524-1536. (Supported in part by Philip Morris USA, Inc., prior to the spin-off of Philip Morris International, Inc., by Altria Group, Inc., on March 28, 2008. Authors affiliated with Philip Morris Products S.A., Neuchâtel; Clinopsis S.A., Switzerland; Celerion, North Ireland.)

155. Lower GM, Jr., Bryan GT. 1973. Enzymatic *N*-acetylation of carcinogenic aromatic amines by liver cytosol of species displaying different organ susceptibilities. *Biochem Pharmacol* 22(13): 1581-1588. (Supported by NCI. Authors affiliated with University of Wisconsin Medical School, WI.)

156. Lüersen L, Wellner T, Koch HM, Angerer J, Drexler H, Korinth G. 2006. Penetration of β-naphthylamine and *o*-toluidine through human skin *in vitro*. *Arch Toxicol* 80(10): 644-646. (Supported by the institution for statutory accident insurance of the German chemical industry (German: Berufsgenossenschaft der Chemischen Industrie). Authors affiliated with University Erlangen–Nuremberg, Germany.)

157. Lutz W, Krajewska B. 1991. [Aromatic amines, oncogenes and cancer of the bladder]. *Med Pr* 42(6): 477-484. (Support unknown due to foreign language. Authors afiliated with Zakladu Diagnostyki Laboratoryjnej Inystytutu Medycyny Pracy w Lodzi.)

158. Maeshima H, Ohno K, Nakano S, Yamada T. 2010. Validation of an i*n vitro* screening test for predicting the tumor promoting potential of chemicals based on gene expression. *Toxicol In Vitro* 24(3): 995-1001. (Support not reported. Authors affiliated with Nissin Foods Holdings Co., Ltd., Japan.)

159. Maire MA, Pant K, Poth A, Schwind KR, Rast C, Bruce SW, Sly JE, Kunz-Bohnenberger S, Kunkelmann T, Engelhardt G, Schulz M, Vasseur P. 2012. Prevalidation study of the Syrian hamster embryo (SHE) cell transformation assay at pH 7.0 for assessment of carcinogenic potential of chemicals. *Mutat Res* 744(1): 64-75. (Support not reported. Authors affiliated with Université Paul Verlaine de Metz, France; BioReliance, MD; Harlan Cytotest Cell Research GmbH, Germany; BASF SE, Germany.)

160. Markowitz SB, Levin K. 2004. Continued epidemic of bladder cancer in workers exposed to ortho-toluidine in a chemical factory. *J Occup Environ Med* 46(2): 154-160. (Support not reported. Authors affiliated with City University of New York, NY.)

161. Markowitz SB, Levin K. 2005. Corrections to: Continued epidemic of bladder cancer in workers exposed to ortho-toluidine in a chemical factory. (vol 46, pg 154, 2004). J Occup Environ Med 47(9): 875-877. (Support not reported. Authors affiliated with Queens College–CBNS, NY.)

162. Markowitz SB. 2005. Corrections to: Markowitz SB, Levin K. Continued epidemic of bladder cancer in workers exposed to ortho-toluidine in a chemical factory. J Occup Environ Med. 2004;46:154-160. *J Occup Environ Med* 47(9): 875-877. (Support not reported. Author affiliated with Queens College, NY.)

163. Marques MM, Mourato LL, Santos MA, Beland FA. 1996. Synthesis, characterization, and conformational analysis of DNA adducts from methylated anilines present in tobacco smoke. *Chem Res Toxicol* 9(1): 99-108. (Supported by NATO and Junta Nacional de Investigação Científica e Tecnológica, Portugal. Authors affiliated with Instituto Superior Técnico, Portugal; National Center for Toxicological Research, AR.)

164. Marques MM, Mourato LL, Amorim MT, Santos MA, Melchior WB, Jr., Beland FA. 1997. Effect of substitution site upon the oxidation potentials of alkylanilines, the mutagenicities of *N*-hydroxyalkylanilines, and the conformations of alkylaniline-DNA adducts. *Chem Res Toxicol* 10(11): 1266-1274. (Supported by NATO, Junta Nacional de Investigação Científica e Tecnológica, Portugal and Oak Ridge Institute for Science and Education. Authors affiliated with Instituto Superior Técnico, Portugal; National Center for Toxicological Research, AR.)

165. Martin FL, Cole KJ, Harvey D, Weaver G, Williams JA, Millar BC, Phillips DH, Grover PL. 2000a. DNA damage in human breast milk cells and its induction by 'early' and 'late' milk extracts. *Carcinogenesis* 21(4): 799-804. (Supported by the Association for International Cancer Research, the Cancer Research Campaign and the Departmenr of Health. Authors affiliated with Haddow Laboratories, UK; Queen Charlotte's and Chelsea Hospital, UK.)

166. Martin FL, Cole KJ, Williams JA, Millar BC, Harvey D, Weaver G, Grover PL, Phillips DH. 2000b. Activation of genotoxins to DNA-damaging species in exfoliated breast milk cells. *Mutat Res* 470(2): 115-124. (Supported by the Association for International Cancer Research, the Cancer Research Campaign, and the Department of Health. Authors affiliated with Haddow Laboratories, UK; Queen Charlotte's and Chelsea Hospital, UK.)

167. Matsushima M, Takano S, Ertürk E, Bryan GT. 1982. Induction of ornithine decarboxylase activity in mouse urinary bladder by l-tryptophan and some of its metabolites. *Cancer Res* 42(9): 3587-3591. (Supported by the National Bladder Cancer Project and the National Cancer Institute. Authors affiliated with Wisconsin Clinical Cancer Center, WI; Toho University School of Medicine, Japan.)

168. Matthews EJ, DelBalzo T, Rundell JO. 1985. Assays for morphological transformation and mutation to ouabain resistance of Balb / c-3T3 cells in culture. *Prog Mutat Res* 5: 639-650. (Support not reported. Authors affiliated with Litton Bionetics Inc., MD.)

169. McFee AF, Jauhar PP, Lowe KW, MacGregor JT, Wehr CM. 1989. Assays of three carcinogen/non-carcinogen chemical pairs for *in vivo* induction of chromosome aberrations, sister chromatid exchanges and micronuclei. *Environ Mol Mutagen* 14(4): 207-220. (Supported by NIEHS. Authors affiliated with Oak Ridge Associated Universities, TN; USDA Western Regional Research Center, CA; Toxicology Consulting Services, Inc., CA; Utah State University, UT.)

170. Meijers AP, vanderleer RC. 1976. The occurrence of organic micropollutants in the River Rhine and the River Maas in 1974. Water Res 10: 597-604 (as cited in HSDB 2011.)

171. Michaels D. 1988. Waiting for the body count: Corporate decision making and bladder cancer in the U. S. dye industry. *Med Anthropol Q* 2(3): 215-232. (Support not reported. Authors affiliated with Montefiore Medical Center and Albert Einstein College of Medicine.)

172. Mori M, Totsuka Y, Fukutome K, Yoshida T, Sugimura T, Wakabayashi K. 1996. Formation of DNA adducts by the co-mutagen norharman with aromatic amines. *Carcinogenesis* 17(7): 1499-1503. (Supported by the Ministry of Health and Welfare of Japan, the Ministry of Education, Science, Sports and Culture of Japan, the Smoking Research Foundation and the Bristol-Myers Squibb Foundation. Authors affiliated with National Cancer Center Research Institute, Japan; Showa University School of Pharmaceutical Sciences, Japan.)

173. Morris PJT, Travis AS. 1992. A History of the International Dyestuff Industry. *Am Dyestuff Rep* 81(11): 49 pp. (Support not reported. Authors affiliated with

Science Museum of London, UK; Hebrew University of Jerusalem, Israel; Leo Baeck Institute, UK.)

174. Murata M, Kawanishi S. 2011. Mechanisms of oxidative DNA damage induced by carcinogenic arylamines. *Front Biosci* 16: 1132-1143. (Support not reported. Authors affiliated with Mie University School of Medicine, Japan; Suzuka University of Medical Science, Japan.)

175. Nagao M, Yahagi T, Sugimura T. 1978. Differences in effects of norharman with various classes of chemical mutagens and amounts of S-9. *Biochem Biophys Res Commun* 83(2): 373-378 (as cited in Danford 1991)

176. Nagao M, Takahashi Y. 1981. Mutagenic activity of 42 coded compounds in the Salmonella/microsome assay. In *Evaluation of Short-Term Tests for Carcinogens*. Progress in Mutation Research, Vol. 1. de Serres FJ, Ashby J, eds. New York: Elsevier. pp. 302-313 (as cited in Danford 1991)

177. NCI. 1979. *Bioassay of o-Toluidine Hydrochloride for Possible Carcinogenicity (CAS No. 636-21-5)*. Technical Report Series No. 153. DHEW Publication No. (NIH) 79-1709. Bethesda, MD: National Cancer Institute. 145 pp.

178. NCR. 2012. *National Response Center*. http://www.nrc.uscg.mil/nrchp.html. Accessed on 5/31/12.

179. Neal SB, Probst GS. 1983. Chemically-induced sister-chromatid exchange in vivo in bone marrow of Chinese hamsters. An evaluation of 24 compounds. *Mutat Res* 113(1): 33-43. (Support not reported. Authors affiliated with Eli Lilly and Company, IL.)

180. Nesnow S, Curtis G, Garland H. 1985. Tests with the C3H/10T 1/2 clone 8 morphological transformation bioassay. *Prog Mutat Res* 5: 659-664. (Support not reported. Authors affiliated with U.S. EPA, NC; Northrop Services, Inc., NC.)

181. Neumann HG. 1986. The role of DNA damage in chemical carcinogenesis of aromatic amines. *J Cancer Res Clin Oncol* 112(2): 100-106. (Supported by Deutsche Forschungsgemeinschaft. Author affiliated with University of Würzburg, Germany.)

182. Neumann HG. 2007. Aromatic amines in experimental cancer research: tissue-specific effects, an old problem and new solutions. *Crit Rev Toxicol* 37(3): 211-236. (Supported by the Deutsche Forschungsgemeinschaft. Author affiliated with University of Würzburg, Germany.)

183. Neumann HG. 2010. Aromatic amines: mechanisms of carcinogenesis and implications for risk assessment. *Front Biosci* 15: 1119-1130. (Supported by the Deutsche Forschungsgemeinschaft. Author affiliated with University of Wuerzburg, Germany.)

184. Neurath GB, Dünger M, Pein FG, Ambrosius D, Schreiber O. 1977. Primary and secondary amines in the human environment. Food Cosmet Toxicol 15(4): 275-282. (Supported by the Deutsche Forschungsgemeinschaft, Bonn-Bad Godesberg, Bundesrepublik Deutschland. Authors affiliated with Microanalytical Laboratory, Germany.)

185. NIOSH. 1990a. *National Occupational and Hazard Survey (1981-1983)*. National Institute for Occupational Safety and Health. Last updated 7/1/90. http://www.cdc.gov/noes/noes4/73470sco.html, http://www.cdc.gov/noes/noes4/x8305sco.html.

186. NIOSH. 1990b. *NIOSH Alert: Preventing Bladder Cancer from Exposure to o-Toluidine and Aniline*. DHHS (NIOSH) Publication Number 90-116. Atlanta, GA: Centers for Disease Control and Prevention. http://www.cdc.gov/niosh/docs/90-116/.

187. NIOSH. 1991. Preventing bladder cancer from exposure to o-toluidine and aniline. Am Ind Hyg Assoc J 52(5): A260, A262.

188. Nishigaki R, Totsuka Y, Kataoka H, Ushiyama H, Goto S, Akasu T, Watanabe T, Sugimura T, Wakabayashi K. 2007. Detection of aminophenylnorharman, a possible endogenous mutagenic and carcinogenic compound, in human urine samples. Cancer Epidemiol Biomarkers Prev 16(1): 151-156. (Supported by the Ministry of Health, Labour and Welfare of Japan. Authors affiliated with National Cancer Center Research Institute, Japan; National Cancer Center Hospital, Japan; Shujitsu University, Japan; Tokyo Metropolitan Institute of Public Health, Japan; National Institute for Environmental Studies, Japan; Kyoto Pharmaceutical University, Japan.)

189. NTP. 1996. *NTP Technical Report on Comparative Toxicity and Carcinogenicity Studies of o-Nitrotoluene and o-Toluidine Hydrochloride (CAS Nos. 88-72-2 and 636-21-5) Administered in Feed to Male F344/N Rats*. Toxicity Report Series No. 44. NIH Publication No. 96-3936. Research Triangle Park, NC: National Toxicology Program. 99 pp.

190. NTP. 2000. Local Anesthetics That Metabolize to 2,6-Xylidine or o-Toluidine. Final Review of Toxicological Literature. Research Triangle Park, NC: National Toxicology Program, National Institute of Environmental Health Sciences. 329 pp.

191. NTP. 2009. *Toxicology and Carcinogenesis Studies of Cumene (CAS No. 98-82-8) in F344/N Rats and B6C3F$_1$ Mice (Inhalation Studies)*. NTP TR 542, NIH Publication No. 09-5885. Research Triangle Park, NC: National Toxicology Program. 206 pp.

192. NTP. 2011a. *o*-Nitrotoluene. In *Report on Carcinogens*. 12th edition. Research Triangle Park, NC: National Toxicology Program. ppp. 331-333.

193. NTP. 2011b. 4,4′□Methylenedianiline and Its Dihydrochloride. In *Report on Carcinogens*. 12th edition. Research Triangle Park, NC: National Toxicology Program. pp. 265-266.

194. Oda Y, Yamazaki H, Watanabe M, Nohmi T, Shimada T. 1995. Development of high sensitive *umu* test system: rapid detection of genotoxicity of promutagenic aromatic amines by *Salmonella typhimurium* strain NM2009 possessing high *O*-acetyltransferase activity. *Mutat Res* 334(2): 145-156. (Supported by the Japan Health Sciences Foundation. Authors affiliated with Osaka Prefectural Institute of Public Health, Japan; National Institute of Health Sciences, Japan.)

195. Oda Y, Yamazaki H, Shimada T. 1999. Role of human *N*-acetyltransferases, NAT1 or NAT2, in genotoxicity of nitroarenes and aromatic amines in *Salmonella typhimurium* NM6001 and NM6002. *Carcinogenesis* 20(6): 1079-1083. (Supported by the Japan Health Sciences Foundation. Authors affiliated with Osaka Prefectural Institute of Public Health, Japan.)

196. Oda Y, Totsuka Y, Wakabayashi K, Guengerich FP, Shimada T. 2006. Activation of aminophenylnorharman, aminomethylphenylnorharman and aminophenylharman to genotoxic metabolites by human *N*-acetyltransferases and cytochrome P450 enzymes expressed in *Salmonella typhimurium umu* tester strains. *Mutagenesis* 21(6): 411-416. (Supported by the Ministry of Health, Labor and Welfare of Japan and United States Public Health Service. Authors affiliated with Osaka Prefectural Institute of Public Health, Japan; National Cancer Center Research Institute, Japan; Vanderbilt University School of Medicine, TN; Osaka City University Medical School, Japan.)

197. Oettel H, Thiess AM, Uhl C. 1968. [Contribution to the problem of occupational lung cancers. Long-term observations from the BASF. First report]. *Zentralbl Arbeitsmed* 18(10): 291-303. (Support and author affiliations unknown due to foreign language.)

198. Ohkuma Y, Hiraku Y, Oikawa S, Yamashita N, Murata M, Kawanishi S. 1999. Distinct mechanisms of oxidative DNA damage by two metabolites of carcinogenic *o*-toluidine. *Arch Biochem Biophys* 372(1): 97-106. (Supported by the Ministry of Education, Science, Sports, and Culture of Japan. Authors affiliated with Mie University School of Medicine, Japan.)

199. OSHA. 2011. Chemical Exposure Health Data. United States Department of Labor. Accessed on 6/11/13. Go to https://www.osha.gov/opengov/healthsamples.html and enter the chemical's IMIS number; click "Submit." (IMIS numbers are available at https://www.osha.gov/dts/chemicalsampling/toc/chmn_A.html; enter chemical name in Search box, click enter, and select "Chemical Sampling Information" link.)

200. Ott MG, Langner RR. 1983. A mortality survey of men engaged in the manufacture of organic dyes. *J Occup Med* 25(10): 763-768. (Support not reported. Authors affiliated with Dow Chemical Company, MI.)

201. Pant K, Bruce SW, Sly JE, Kunkelmann T, Kunz-Bohnenberger S, Poth A, Engelhardt G, Schulz M, Schwind KR. 2012. Prevalidation study of the Syrian hamster embryo (SHE) cell transformation assay at pH 6.7 for assessment of carcinogenic potential of chemicals. *Mutat Res* 744(1): 54-63. (Support not reported. Authors affiliated with BioReliance, MD; Harlan Cytotest Cell Research GmbH (Harlan CCR), Germany; BASF SE, Germany.)

202. Phillips JL, Richardson IC. 2006. Aneuploidy in bladder cancers: the utility of fluorescent *in situ* hybridization in clinical practice. *BJU Int* 98(1): 33-37. (Support not reported. Authors affiliated with Beth Israel Medical Center, NY.)

203. Piolatto G, Negri E, La Vecchia C, Pira E, Decarli A, Peto J. 1991. Bladder cancer mortality of workers exposed to aromatic amines: an updated analysis. *Br J Cancer* 63(3): 457-459. (Supported by the CNR (Italian National Research Council) Applied Projects 'Oncology' and Risk Factors for Disease. Authors affiliated with Universitá di Torino, Italy; Istituto di Ricerche Farmacologiche 'Mario Negri.' Italy; University of Lausanne, Switzerland; Università di Milano, Italy; Università di Trento, Italy; Institute of Cancer Research, UK.)

204. Pira E, Piolatto G, Negri E, Romano C, Boffetta P, Lipworth L, McLaughlin JK, La Vecchia C. 2010. Bladder cancer mortality of workers exposed to aromatic amines: a 58-year follow-up. *J Natl Cancer Inst* 102(14): 1096-1099. (Supported by the Italian Association for Cancer Research. Authors affiliated with University of Turin, Italy; "Mario Negri" Institute, Italy; International Agency for Research on Cancer, France; International Epidemiology Institute, MD; University of Milan, Italy.)

205. Pliss GB. 2004. [Experimental study of ortho-toluidine carcinogenicity]. *Vopr Onkol* 50(5): 567-571. (Support not reported. Author affiliated with N.N. Petrov Research Institute of Oncology, Russia.)

206. Poirier MC, Fullerton NF, Smith BA, Beland FA. 1995. DNA adduct formation and tumorigenesis in mice during the chronic administration of 4-aminobiphenyl at multiple dose levels. *Carcinogenesis* 16(12): 2917-2921. (Support not reported. Authors affiliated with NCI, MD; National Center for Toxicological Research, AR.)

207. Prince MM, Ward EM, Ruder AM, Salvan A, Roberts DR. 2000. Mortality among rubber chemical manufacturing workers. *Am J Ind Med* 37(6): 590-598. (Support not reported. Authors affiliated with NIOSH, OH; LADSEB-CNR, Italy.)

208. Richardson K, Band PR, Astrakianakis G, Le ND. 2007. Male bladder cancer risk and occupational exposure according to a job-exposure matrix-a case-

control study in British Columbia, Canada. *Scand J Work Environ Health* 33(6): 454-464. (Supported by the Workers' Compensation Board of British Columbia, the National Health Research and Development Program, Health Canada, and the Michael Foundation for Health Research. Authors affiliated with BC Cancer Research Centre, Canada; University of British Columbia, Canada; Health Canada; Occupational Health and Safety Agency for Health Care in BC, Canada.)

209. Richter E, Rosler S, Scherer G, Gostomzyk JG, Grubl A, Kramer U, Behrendt H. 2001. Haemoglobin adducts from aromatic amines in children in relation to area of residence and exposure to environmental tobacco smoke. *Int Arch Occup Environ Health* 74(6): 421-428. (Supported by VERUM, Stiftung für Verhalten und Umwelt. Authors affiliated with Ludwig-Maximilians-Universität München, Germany; Analytisch-biologisches Forschungslabor, Germany; Gesundheitsamt der Stadt Augsburg, Germany; Technischen Universität München, Germany; Medizinisches Institut für Umwelthygiene, Germany.)

210. Richter E, Branner B. 2002. Biomonitoring of exposure to aromatic amines: haemoglobin adducts in humans. *J Chromatogr B Analyt Technol Biomed Life Sci* 778(1-2): 49-62. (Support not reported. Authors affiliated with Ludwig-Maximilians-Universität München, Germany.)

211. Riedel K, Scherer G, Engl J, Hagedorn HW, Tricker AR. 2006. Determination of three carcinogenic aromatic amines in urine of smokers and nonsmokers. *J Anal Toxicol* 30(3): 187-195. (Support not reported. Authors affiliated with Analytisch-Biologisches Forschungslabor GmbH, Germany; Phillip Morris Products S.A., Switzerland.)

212. Riffelmann M, Muller G, Schmieding W, Popp W, Norpoth K. 1995. Biomonitoring of urinary aromatic amines and arylamine hemoglobin adducts in exposed workers and nonexposed control persons. *Int Arch Occup Environ Health* 68(1): 36-43. (Support not reported. Authors affiliated with Institut für Hygiene und Arbeitsmedizin der Universitätsklinik (GHS) Essen, Germany.)

213. Robbiano L, Carrozzino R, Bacigalupo M, Corbu C, Brambilla G. 2002. Correlation between induction of DNA fragmentation in urinary bladder cells from rats and humans and tissue-specific carcinogenic activity. *Toxicology* 179(1-2): 115-128. (Supported by Genoa University. Authors affiliated with University of Genoa, Italy.)

214. Robinson D, Smith JN, Williams RT. 1955. Studies in detoxication. 60. The metabolism of alkylbenzenes: isopropylbenzene (cumene) and derivatives of hydratropic acid. *Biochem J* 59(1): 153-159. (Supported by the Medical Research Council. Authors affiliated with St Mary's Hospital Medical School, UK.)

215. Rubino GF, Scansetti G, Piolatto G, Pira E. 1982. The carcinogenic effect of aromatic amines: an epidemiological study on the role of *o*-toluidine and 4,4'-methylene bis (2-methylaniline) in inducing bladder cancer in man. *Environ Res* 27(2): 241-254. (Support not reported. Authors affiliated with Turin University, Italy.)

216. Ruder AM, Ward EM, Roberts DR, Teass AW, Brown KK, Fingerhut MA, Stettler LE. 1992. Response of the National Institute for Occupational Safety and Health to an occupational health risk from exposure to ortho-toluidine and aniline. *Scand J Work Environ Health* 18 Suppl 2: 82-84. (Support not reported. Authors affiliated with National Institute for Occupational Safety and Health, OH.)

217. Sabbioni G. 1992. Hemoglobin binding of monocyclic aromatic amines: molecular dosimetry and quantitative structure activity relationships for the *N*-oxidation. *Chem Biol Interact* 81(1-2): 91-117. (Supported by the Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung, the Deutsche Forschungsgemeinschaft and the European Community. Authors affiliated with Universität Würzburg, Germany.)

218. Sabbioni G, Sepai O. 1995. Comparison of hemoglobin binding, mutagenicity, and carcinogenicity of arylamines and nitroarenes. *Chimia* 49(10): 374-380. (Supported by the Schweizerischer Nationalfonds zur Förderung der wissenschaftlichen Forschung and the European Community. Authors affiliated with Universität Würzburg, Germany.)

219. Sakai A, Sasaki K, Muramatsu D, Arai S, Endou N, Kuroda S, Hayashi K, Lim YM, Yamazaki S, Umeda M, Tanaka N. 2010. A Bhas 42 cell transformation assay on 98 chemicals: The characteristics and performance for the prediction of chemical carcinogenicity. *Mutat Res* 702(1): 100-122. (Support not reported. Authors affiliated with Hatano Research Institute, Japan.)

220. Salamone MF, Heddle JA, Katz M. 1981. Chapter 66: Mutagenic Activity of 41 Compounds in the *In Vivo* Micronucleus Assay. In *Evaluation of Short-Term Tests for Carcinogens*. Progress in Mutation Research, vol. 1. de Serres FJ, Ashby J, eds. New York, NY: Elsevier North Holland, Inc. p. 686-697. (Supported by the Ontario Ministry of the Environment, Provincial Lottery Trust Fund. Authors affiliated with York University, Canada.)

221. Saletta F, Matullo G, Manuguerra M, Arena S, Bardelli A, Vineis P. 2007. Exposure to the tobacco smoke constituent 4-aminobiphenyl induces chromosomal instability in human cancer cells. *Cancer Res* 67(15): 7088-7094. (Supported by the Compagnia di San Paolo (Torino), the Italian Association for Cancer Research, the Italian Technology and Research Ministry, the Regione Piemonte and partly by Environmental Cancer Risk, Nutrition, and Individual Susceptibility, a network of excellence operating within the European Union 6th Framework Program, Priority 5: ‘‘Food Quality and Safety.’’ Authors affiliated

with University of Torino Medical School, Italy; FIRC Institute of Molecular Oncology, Italy; Imperial College London, UK.)

222. Sandberg AA. 2002. Cytogenetics and molecular genetics of bladder cancer: a personal view. *Am J Med Genet* 115(3): 173-182. (Support not reported. Author affiliated with St. Joseph's Hospital and Medical Center, AZ; University of Arizona, AZ.)

223. Sanner T, Rivedal E. 1985. Tests with the Syrian hamster embryo (SHE) cell transformation assay. *Prog Mutat Res* 5: 665-671. (Support not reported. Authors affiliated with The Nonvegian Radium Hospital, Norway.)

224. Seiler JP. 1977. Inhibition of testicular DNA synthesis by chemical mutagens and carcinogens. Preliminary results in the validation of a novel short term test. Mutat Res 46(4): 305-310. (Support not reported. Author affiliated with Swiss Federal Research Station, Switzerland.)

225. Seyler TH, Reyes LR, Bernert JT. 2010. Analysis of 4-aminobiphenyl hemoglobin adducts in smokers and nonsmokers by pseudo capillary on-column gas chromatography- tandem mass spectrometry. J Anal Toxicol 34(6): 304-311. (Support not reported. Authors affiliated with Centers for Disease Control and Prevention, GA.)

226. Shibutani S, Takeshita M, Grollman AP. 1991. Insertion of specific bases during DNA synthesis past the oxidation-damaged base 8-oxodG. Nature 349(6308): 431-434. (Supported by the National Cancer Institute and the National Institute of Environmental Health Sciences. Authors affiliated with State University of New York at Stony Brook, NY.)

227. Short CR, King C, Sistrunk PW, Kerr KM. 1983. Subacute toxicity of several ring-substituted dialkylanilines in the rat. *Fundam Appl Toxicol* 3(4): 285-292. (Supported by the Ethyl Corporation. Authors affiliated with Louisiana State University, LA; Ethyl Corporation, LA.)

228. Sinks T, Lushniak B, Haussler BJ, Sniezek J, Deng JF, Roper P, Dill P, Coates R. 1992. Renal cell cancer among paperboard printing workers. *Epidemiology* 3(6): 483-489. (Support not reported. Authors affiliated with NIOSH, OH; Emory University Schol of Public Health, GA.)

229. Skipper PL, Kim MY, Sun HL, Wogan GN, Tannenbaum SR. 2010. Monocyclic aromatic amines as potential human carcinogens: old is new again. *Carcinogenesis* 31(1): 50-58. (Supported by NIEHS. Authors affiliated with Massachusetts Institute of Technology, MA.)

230. Skipper PL, Tannenbaum SR. 1994. Molecular dosimetry of aromatic amines in human populations. *Environ Health Perspect* 102(Suppl 6): 17-21. (Support not reported. Authors affiliated with Massachusetts Institute of Technology, MA.)

231. SMARTe.org. 2008. *Understanding Units of Measurement*. http://www.smarte.org/smarte/resource/sn-units-of-measure.xml.

232. Son OS, Everett DW, Fiala ES. 1980. Metabolism of *o*-[*methyl*-^{14}C]toluidine in the F344 rat. *Xenobiotica* 10(7-8): 457-468. (Supported by the National Cancer Institute. Authors affiliated with American Health Foundation, NY.)

233. Sorahan T, Pope D. 1993. Mortality study of workers employed at a plant manufacturing chemicals for the rubber industry: 1955-86. *Br J Ind Med* 50(11): 998-1002. (Support not reported. Authors affiliated with University of Birmingham, UK.)

234. Sorahan T, Hamilton L, Jackson JR. 2000. A further cohort study of workers employed at a factory manufacturing chemicals for the rubber industry, with special reference to the chemicals 2-mercaptobenzothiazole (MBT), aniline, phenyl-β-naphthylamine and *o*-toluidine. *Occup Environ Med* 57(2): 106-115. (Support not reported. Authors affiliated with University of birmingham, UK.)

235. Sorahan T. 2008. Bladder cancer risks in workers manufacturing chemicals for the rubber industry. *Occup Med (Lond)* 58(7): 496-501. (Support not reported. Author affiliated with University of Birmingham, UK.)

236. SRI. 2012. *Directory of Chemical Producers*. Menlo Park, CA: SRI Consulting. Database edition. http://www.ihs.com/products/chemical/companies/producers.aspx Accessed on 1/9/12.

237. Stabbert R, Schäfer KH, Biefel C, Rustemeier K. 2003. Analysis of aromatic amines in cigarette smoke. Rapid Commun Mass Spectrom 17(18): 2125-2132. (Support not reported. Authors affiliated with Philip Morris Research Laboratories GmbH, Germany.)

238. Stasik MJ, Lange H-L, Schuckmann F. 1985. A retrospective mortality study of 4-chloro-2-methylaniline workers. Paper presented at the MEDICHEM symposium, Bahia, Brasil. pp. 61, 437.

239. Stasik MJ. 1988. Carcinomas of the urinary bladder in a 4-chloro-o-toluidine cohort. *Int Arch Occup Environ Health* 60(1): 21-24. (Support not reported. Author affiliated with Department of Occupational Medicine of Hoechst, Germany.)

240. Stettler LE, Savage RE, Brown KK, Cheever KL, Weigel WW, DeBord DG, Teass AW, Dankovic D, Ward EM. 1992. Biological monitoring for occupational exposures to *ortho*-toluidine and aniline. *Scand J Work Environ Health* 18(Suppl 2): 78-81. (Support not reported. Authors affiliated with NIOSH, OH.)

241. Stiborová M, Mikšanová M, Šulc M, Rýdlová H, Schmeiser HH, Frei E. 2005. Identification of a genotoxic mechanism for the carcinogenicity of the environmental pollutant and suspected human carcinogen *o*-anisidine. *Int J Cancer* 116(5): 667-678. (Supported by the Grant Agency of the Czech Republic and the Ministry of Industry and Trade of the Czech Republic. Authors affiliated with Charles University, Czech Republic; German Cancer Research Center, Germany.)

242. Stillwell WG, Bryant MS, Wishnok JS. 1987. GC/MS analysis of biologically important aromatic amines. Application to human dosimetry. *Biomed Environ Mass Spectrom* 14(5): 221-227. (Supported by the American Cancer Society, the National Institutes of Health, the National Institute of Environmental Health Sciences and the DHHS. Authors affiliated with Massachusetts Institute of Technology, MA.)

243. Strömbeck JP. 1946. Azotoluene bladder tumours in rats. *J Pathol Bacteriol* 58: 275-278. (Supported by Konung Gustaf V : s Jubileumsfond and Stiftelsen Therese och Johan Anderssons Minne. Author affiliated with Surgical Clinic, Sweden.)

244. Stuermer DH, Ng DJ, Morris CJ. 1982. Organic contaminants in groundwater near an underground coal gasification site in northeastern Wyoming. Environ Sci Technol 16(9): 582-587. (Supported by the U.S. Department of Energy. Authors affiliated with University of California - Livermore, CA.)

245. Styles JA. 1981. Activity of 42 coded compounds in the BHK-21 cell transformation test. *Prog Mutat Res* 1: 638-646. (Support not reported. Authors affiliated with Imperial Chemical Industries Limited, UK.)

246. Sugimura T, Nagao M, Wakabayashi K. 1982. Metabolic aspects of the comutagenic action of norharman. *Adv Exp Med Biol* 136B: 1011-1025 (as cited in Danford 1991)

247. Suk WA, Humphreys JE. 1985. Assay for the carcinogenicity of chemical agents using enhancement of anchorage-independent survival of retrovirus-infected Fischer rat embryo cells. *Prog Mutat Res* 5: 673-683. (Supported by NIEHS. Authors affiliated with Northrop Services, Inc., NC.)

248. Suzuki H, Ikeda N, Kobayashi K, Terashima Y, Shimada Y, Suzuki T, Hagiwara T, Hatakeyama S, Nagaoka K, Yoshida J, Saito Y, Tanaka J, Hayashi M. 2005. Evaluation of liver and peripheral blood micronucleus assays with 9 chemicals using young rats. A study by the Collaborative Study Group for the Micronucleus Test (CSGMT)/Japanese Environmental Mutagen Society (JEMS)-Mammalian Mutagenicity Study Group (MMS). *Mutat Res* 583(2): 133-145. (Support not reported. Authors affiliated with Ina Research Inc., Japan; Kao Corporation, Japan; R&D Kissei Pharmaceutical Co. Ltd., Japan; Hokko Chemical IndustryCo. Ltd., Japan; National Institute of Health Sciences, Japan;

Sankyo Co. Ltd., Japan; Nisshin Kyorin Pharmaceutical Co. Ltd., Japan; Toa Eiyo Ltd., Japan; Kaken Pharmaceutical Co. Ltd., Japan; Mitsubishi Chemical SafetyInstitute Ltd., Japan; BiosafetyResear ch Center, Foods, Drugs and Pesticides, Japan.)

249. Takayama S, Hasegawa H, Ohgaki H. 1989. Combination effects of forty carcinogens administered at low doses to male rats. *Jpn J Cancer Res* 80(8): 732-736. (Supported by the Ministry of Health and Welfare and the Ministry of Health and Welfare for the Comprehensive lO-Year Strategy for Cancer Control, Japan. Authors affiliated with Nippon Medical College, Japan; INational Cancer Center Research Institute, Japan.)

250. Talaska G, Schamer M, Skipper P, Tannenbaum S, Caporaso N, Unruh L, Kadlubar FF, Bartsch H, Malaveille C, Vineis P. 1991. Detection of carcinogen-DNA adducts in exfoliated urothelial cells of cigarette smokers: association with smoking, hemoglobin adducts, and urinary mutagenicity. Cancer Epidemiol Biomarkers Prev 1(1): 61-66. (Supported by NIH and NIEHS. Authors affiliated with University of Cincinnati, OH; Massachusetts Institute of Technology, MA; NCI, MD; National Center for Toxicological Research, AR; IARC, France; Dipartimento di Scienze Biomediche e Oncologia Umana, Italy.)

251. Talaska G. 2003. Aromatic amines and human urinary bladder cancer: exposure sources and epidemiology. *J Environ Sci Health C Environ Carcinog Ecotoxicol Rev* 21(1): 29-43. (Support not reported. Author affiliated with University of Cincinnati School of Medicine, OH.)

252. Tanaka N, Bohnenberger S, Kunkelmann T, Munaro B, Ponti J, Poth A, Sabbioni E, Sakai A, Salovaara S, Sasaki K, Thomas BC, Umeda M. 2012. Prevalidation study of the BALB/c 3T3 cell transformation assay for assessment of carcinogenic potential of chemicals. *Mutat Res* 744(1): 20-29. (Support not reported. Authors affiliated with Hatano Research Institute, Japan; Harlan Cytotest Cell Research GmbH (Harlan CCR), Germany; Joint Research Centre of the European Commission, Italy.)

253. Teass AW, DeBord DG, Brown KK, Cheever KL, Stettler LE, Savage RE, Weigel WW, Dankovic D, Ward E. 1993. Biological monitoring for occupational exposures to o-toluidine and aniline. *Int Arch Occup Environ Health* 65(1 Suppl): S115-S118. (Support not reported. Authors affiliated with NIOSH, OH.)

254. Topham JC. 1980. Do induced sperm-head abnormalities in mice specifically identify mammalian mutagens rather than carcinogens? Mutat Res 74(5): 379-387. (Support not reported. Authors affiliated with Imperial Chemical Industries, UK.)

255. Topham JC. 1981. Chapter 70: Evaluation of Some Chemicals by the Sperm Morphology Assay. In *Evaluation of Short-Term Tests for Carcinogens*.

Progress in Mutation Research, vol. 1. de Serres FJ, Ashby J, eds. New York, NY: Elsevier North Holland, Inc. p. 718-720. (Support not reported. Authors affiliated with lCI Pharmaceuticals Division, UK.)

256. TOXMAP. 2012. *TOXMAP: Environmental Health e-Maps*. U.S. National Library of Medicine. http://toxmap.nlm.nih.gov/toxmap/main/index.jsp and search o-toluidine. Accessed on 5/31/12.

257. TRI. 2012. *TRI Explorer Chemical Report*. U.S. Environmental Protection Agency. http://www.epa.gov/triexplorer and select *o*-Toluidine and *o*-Toluidine Hydrochloride. Last accessed on 11/28/12.

258. Tsuchimoto T, Matter BE. 1981. Chapter 68: Activity of Coded Compounds in the Micronucleus Test In *Evaluation of Short-Term Tests for Carcinogens*. Progress in Mutation Research, vol. 1. de Serres FJ, Ashby J, eds. New York, NY: Elsevier North Holland, Inc. p. 705-711. (Support not reported. Authors affiliated with Sandoz Ltd., Switzerland.)

259. Uebelin VF, Pletscher A. 1954. [Ätiologie und prophylaxe gewerblicher tumoren in der fabstoffindustrie]. Schweiz Med Wochenschr 84(32): 917-920. (Support and author affiliations unknown due to foreign language.)

260. Umeda M, Tanaka K, Ono T. 1989. Promotional effect of lithocholic acid and 3-hydroxyanthranilic acid on transformation of X-ray-initiated BALB/3T3 cells. *Carcinogenesis* 10(9): 1665-1668. (Supported by the Science and Technology Agency. Authors affiliated with Yokohama City University, Japan; Kanagawa Cancer Center, Japan.)

261. UNEP. 2004. *Screening Information Dataset: o-Toluidine (CAS No. 95-53-4)*. UNEP Chemicals. 297 pp. http://www.chem.unep.ch/irptc/sids/OECDSIDS/sidspub.html and search by chemical name.

262. USITC. 2012. *USITC Interactive Tariff and Trade Dataweb*. United States International Trade Commission. http://dataweb.usitc.gov/scripts/user_set.asp and search on HTS no. 292143. Accessed on 11/28/12.

263. Vardanyan R, Hruby V. 2006. Synthesis of Essential Drugs, San Diego, CA: Elsevier, Inc. p. 17.

264. Veys CA. 1996. Bladder cancer in rubber workers: A phenyl beta-naphthylamine (PBNA) exposed workforce. *Prog Rubber Plastics Tech* 12(4): 258-273. (Support not reported. Author affiliated with University of Keele, UK.)

265. Viet SM, Hanley KW, Carreón-Valencia T, *et al.* 2009. *Assessment of Exposure to o-Toluidine and Other Aromatic Amines in a Rubber Chemical*

Manufacturing Plant. NIOSH 2009 Feb IWSB Report #73.08. (Support not reported. Authors affiliated with WESTAT, MD; NIOSH.)

266. Vitzthum OG, Werkhoff P, Hubert P. 1975. New volatile constituents of black tea aroma. *J Agric Food Chem* 23: 999-1003 (as cited in IARC 2012)

267. Ward E, Carpenter A, Markowitz S, Roberts D, Halperin W. 1991. Excess number of bladder cancers in workers exposed to ortho-toluidine and aniline. *J Natl Cancer Inst* 83(7): 501-506. (Support not reported. Authors affiliated with NIOSH, OH; Mt. Sinai School of Medicine, NY.)

268. Ward E, Roberts D, Dankovic D, Flesch J, Reed L, Fajen J. 1994. Response to "A re-examination of the cause of excess bladder cancers in chemical plant workers". *J Natl Cancer Inst* 86(1): 60-62. (Support not reported. Authors affiliated with NIOSH, OH.)

269. Ward EM, Sabbioni G, DeBord DG, Teass AW, Brown KK, Talaska GG, Roberts DR, Ruder AM, Streicher RP. 1996. Monitoring of aromatic amine exposures in workers at a chemical plant with a known bladder cancer excess. *J Natl Cancer Inst* 88(15): 1046-1052. (Support not reported. Authors affiliated with NIOSH, OH; University of Wurzburg, Germany; University of Cincinnati, OH.)

270. Ward EM. 1997. Monitoring of aromatic amine exposures in workers at a chemical plant with a known bladder cancer excess - response. *J Natl Cancer Inst* 89(10): 735. (Support not reported. Auhor affiliated with NIOSH, OH.)

271. Watanabe C, Egami T, Midorikawa K, Hiraku Y, Oikawa S, Kawanishi S, Murata M. 2010. DNA damage and estrogenic activity induced by the environmental pollutant 2-nitrotoluene and its metabolite. *Environ Health Prev Med* 15(5): 319-326. (Supported by the Ministry of Education, Culture, Sports, Science and Technology of Japan. Authors affiliated with Mie University School of Medicine, Japan; Suzuka University of Medical Science, Japan.)

272. Wegman RCC, De Korte GAL. 1981. Aromatic amines in surface waters of the Netherlands. Water Res 15: 391-394. (Support not reported. Authors affiliated with National Institute of Public Health, Netherlands.)

273. Weisburger EK, Russfield AB, Homburger F, Weisburger JH, Boger E, Van Dongen CG, Chu KC. 1978. Testing of twenty-one environmental aromatic amines or derivatives for long-term toxicity or carcinogenicity. *J Environ Pathol Toxicol* 2(2): 325-356. (Supported by the National Cancer Institute, Public Health Service, Bethesda, MD. Authors affiliated with NCI, MD; Bio-Research Consultants, Inc., MA; American Health Foundation, NY.)

274. Wellner T, Luersen L, Schaller KH, Angerer J, Drexler H, Korinth G. 2008. Percutaneous absorption of aromatic amines - a contribution for human health risk assessment. *Food Chem Toxicol* 46(6): 1960-1968. (Supported by the

institution for statutory accident insurance of the German chemical industry (German: Berufsgenossenschaft der Chemischen Industrie). Authors affiliated with University Erlangen-Nuremberg, Germany.)

275. Williamson MP, Elder PA, Knowles MA. 1994. The spectrum of TP53 mutations in bladder carcinoma. Genes Chromosomes Cancer 9(2): 108-118. (Support not reported. Authors affiliated with Marie Curie Research Institute, UK.)

276. Windmill KF, McKinnon RA, Zhu X, Gaedigk A, Grant DM, McManus ME. 1997. The role of xenobiotic metabolizing enzymes in arylamine toxicity and carcinogenesis: functional and localization studies. *Mutat Res* 376(1-2): 153-160. (Support not reported. Authors affiliated with University of Queensland, Australia; University of South Australia, Australia; Hospital for Sick Children, Canada.)

277. Woo Y-T, Lai DY. 2004. Aromatic Amino and Nitro–Amino Compounds and their Halogenated Derivatives. In *Patty's Toxicology*. http://onlinelibrary.wiley.com/book/10.1002/0471125474.

278. Yu MC, Skipper PL, Tannenbaum SR, Chan KK, Ross RK. 2002. Arylamine exposures and bladder cancer risk. *Mutat Res* 506-507: 21-28. (Supported by the United States Public Health Service. Authors affiliated with University of Southern California, CA; Massachusetts Institute of Technology, MA; Ohio State University College of Pharmacy, OH.)

279. Zdzienicka MZ, de Kok AJ, Simons JWIM. 1985. Assays for the induction of cell transformation in Chinese hamster ovary (CHO) cells and in Syrian hamster embryo (SHE) cells. *Prog Mutat Res* 5: 685-688. (Support not reported. Authors affiliated with State University of Leiden, Netherlands.)

280. Zhang N, Liu L, Liu F, Wagner CR, Hanna PE, Walters KJ. 2006. NMR-based model reveals the structural determinants of mammalian arylamine N-acetyltransferase substrate specificity. *J Mol Biol* 363(1): 188-200. (Supported by the National Institutes of Health, a UMN Grant-in-Aid of Research, Artistry, and Scholarship, the Minnesota Medical Foundation, the Academic Health Center Faculty Research Development Grant and NSF BIR-961477. Authors affiliated with University of Minnesota, MN.)

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Abbreviations

^{1}H NMR:	proton nuclear magnetic resonance
4-AMP:	4-amino-3-methylphenol
4-COT:	4-chloro-*ortho*-toluidine
8-OH-dG:	8-hydroxydeoxyguanosine
AAF:	2-acetylaminofluorene
ACGIH:	American Conference of Governmental Industrial Hygienists
ADME:	absorption, distribution, metabolism, and excretion
ALL:	acute lymphoblastic leukemia
CA:	chromosomal aberration
CASRN:	Chemical Abstracts Service registry number
CDR:	Chemical Data Reporting Rule
CHO:	Chinese hamster ovary
CIN:	chromosomal instability
dA:	deoxyadenosine
DEN:	diethylnitrosamine
dG:	deoxyguanosine
DNA:	deoxyribonucleic acid
EG:	ethylguanine
EHOMO:	energy of the highest occupied molecular orbital
Endo III:	endonuclease III
EPA:	Environmental Protection Agency
FDA:	Food and Drug Administration
FU:	follow-up
G:	guanine

GC/MS:	gas chromatography/mass spectroscopy
GI:	gastrointestinal
GIS:	Geographic Information System
GM:	geometric mean
Hb:	hemoglobin
HDAC:	histone deacetylase
HEG:	(2-hydroxyethyl) guanine
HGPRT:	hypoxanthine-guanine phosphoribosyl transferase
HHE:	Health Hazard Evaluation
HIC:	highest ineffective concentration
HID:	highest ineffective dose
HPLC:	high-performance liquid chromatography
hr:	hour
HWE:	healthy worker (hire or survival) effect
I:	inconclusive
i.p.:	intraperitoneal
i.v.:	intravenous
IARC:	International Agency for Research on Cancer
ICD-9:	International Classification of Diseases, Ninth Revision
IDLH:	immediately dangerous to life and health
IUR:	Inventory Update Rule
JEM:	job-exposure matrix
kg:	kilogram
L:	liter
LEC:	lowest effective concentration

LED:	lowest effective dose
Log K_{ow}:	logarithm of octanol/water partition coefficient
LOH:	loss of heterozygosity
m^3:	cubic meter
MBT:	2-mercaptobenzothiazole
MG:	methylguanine
mg:	milligram
mL:	milliliter
MN:	micronucleus
MS:	mass spectrometry
N.D.:	not detected; not determined
NA:	not applicable
NAT1:	*N*-acetyltransferase 1
NAT2:	*N*-acetyltransferase 2
NCE:	normochromatic erythrocyte
NDMA:	*N*-nitrosodimethylamine
NHANES:	National Health and Nutrition Examination Survey
NIOSH:	National Institute for Occupational Safety and Health
NLM:	National Library of Medicine
NOES:	National Occupational Exposure Survey
NPL:	National Priorities List
NR:	not reported; none reported
NS:	not significant
nt:	nucleotides
NT:	not tested

o-NT:	*o*-nitrosotoluene
OR:	odds ratio
OSHA:	Occupational Safety and Health Administration
OTM:	olive tail moment
PBN:	phenyl-β-naphthylamine
PCE:	polychromatic erythrocyte
PCNA:	proliferating cell nuclear antigen
PEL:	permissible exposure limit
PGST:	placental glutathione *S*-transferase
p.o.:	per os (oral administration)
ppm:	parts per million
QSAR:	quantitative structure-activity relationship
RBC:	red blood cell
RLV:	Rauscher-leukemia virus
ROS:	reactive oxygen species
RQ:	reportable quantity
RR:	relative risk
SA7:	Simian Agent 7 adenovirus
SAFE:	significance analysis of function and expression
SCE:	sister-chromatid exchange
SIC:	Standard Industrial Classification
SIR:	standardized incidence ratio
SMR:	standardized mortality ratio
SOCMI:	synthetic organic chemical manufacturing industry
SOD:	superoxide dismutase

SPA:	solid phosphoric acid
SRR:	standardized rate ratio
SSB:	single strand break
TDS:	Total Diet Study
TL:	tail length
TLC:	thin-layer chromatography
TLV-TWA:	threshold limit value – time-weighted average
TRI:	Toxics Release Inventory
TSCA:	Toxic Substances and Recovery Act
TSFE:	time since first employment
UDS:	unscheduled DNA synthesis
UK:	United Kingdom
WBC:	white blood cell
wt%:	weight percent
µg:	microgram

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Glossary

Accelerant: A substance the increases the speed of curing of rubber.

Ames assay: The Ames *Salmonella*/microsome mutagenicity assay is a short-term bacterial reverse mutation assay specifically designed to detect a wide range of chemical substances that can produce genetic damage that leads to gene mutations.

Aneuploidy: An abnormality involving a chromosome number that is not an exact multiple of the haploid number (one chromosome set is incomplete).

Arabinose resistance: The L-arabinose resistance test with *Salmonella typhimurium* (Ara test) is a forward mutation assay that selects a single phenotypic change (from L-arabinose sensitivity to L-arabinose resistance) in a unique tester strain (an araD mutant).

Ascertainment bias: Systematic failure to represent equally all classes of cases or persons supposed to be represented in a sample.

Attrition bias: Systematic differences between **comparison groups** in withdrawals or exclusions of **participants** from the results of a study.

Biexponential process: A process of drug (or xenobiotic) clearance with two phases with different rates. The first phase often involves rapid distribution of a drug to peripheral tissues, while the second phase represents clearance mechanisms that eliminate the drug from the body. (See "Two-compartment pharmacokinetic model.")

Biodegradation: Biotransformation; the conversion within an organism of molecules from one form to another. A change often associated with change in pharmacologic activity.

Boiling point: The boiling point of the anhydrous substance at atmospheric pressure (101.3 kPa) unless a different pressure is stated. If the substance decomposes below or at the boiling point, this is noted (dec). The temperature is rounded off to the nearest °C.

Colour index: A compendium of dyes and pigments prepared in the United Kingdom by the Society of Dyers and Colourists and in the United States by the American Association of Textile Chemists and Colorists. The index serves as a common reference database of information on generic names, chemical structures, companies offering dyes and pigments, and technical application details of many colorants.

Comet assay: single cell gel electrophoresis for assessment of DNA damage in presumptive target tissues.

Critical temperature: The temperature at and above which a gas cannot be liquefied, no matter how much pressure is applied.

Differential selection: Selective pressure for self renewal. Gene mutations that confer a growth or survival advantage on the cells that express them will be selectively enriched in the genome of tumors.

Disposition: The description of absorption, distribution, metabolism, and excretion of a chemical in the body.

Double acid conjugate: a compound formed by the joining of two acids.

Epigenetic mechanisms: Changes in gene function that do not involve a change in DNA sequence but are nevertheless mitotically and/or meiotically heritable. Examples include DNA methylation, alternative splicing of gene transcripts, and assembly of immunoglobulin genes in cells of the immune system.

Genomic instability: An increased propensity for genomic alterations that often occurs in cancer cells. During the process of cell division (mitosis) the inaccurate duplication of the genome in parent cells or the improper distribution of genomic material between daughter cells can result from genomic instability.

Healthy worker hire effect: Initial selection of healthy individuals at time of hire so that their disease risks differ from the disease risks in the source (general) population.

Healthy worker survival effect: A continuing selection process such that those who remain employed tend to be healthier than those who leave employment.

Henry's Law constant: The ratio of the aqueous-phase concentration of a chemical to its equilibrium partial pressure in the gas phase. The larger the Henry's law constant the less soluble it is (i.e., greater tendency for vapor phase). The relationship is defined for a constant temperature, e.g., 25°C.

Host-mediated assay: This assay evaluates the genotoxicity of a substance to microbial cells introduced (e.g., by intravenous injection) into a host animal. The host animal receives the test compound orally, and therefore acts as a source of chemical metabolism, distribution and excretion of the test compound.

Keratosis: A localized horny overgrowth of the skin, such as a wart or callus.

Loss of heterozygosity: If there is one normal and one abnormal allele at a particular locus, as might be seen in an inherited autosomal dominant cancer susceptibility disorder, loss of the normal allele produces a locus with no normal function. When the loss of heterozygosity involves the normal allele, it creates a cell that is more likely to show malignant growth if the altered gene is a tumor suppressor gene.

Melting point: The melting point of the substance at atmospheric pressure (101.3 kPa). When there is a significant difference between the melting point and the freezing point, a range is given. In case of hydrated substances (i.e., those with crystal water), the apparent melting point is given. If the substance decomposes at or below its melting point, this is noted (dec). The temperature is rounded off to the nearest °C.

Metabolic activation: The chemical alteration of an exogenous substance by or in a biological system. The alteration may inactivate the compound or it may result in the production of an active metabolite of an inactive parent compound.

Metaplasia: A change of cells to a form that does not normally occur in the tissue in which it is found.

Methemoglobin: A form of hemoglobin found in the blood in small amounts. Unlike normal hemoglobin, methemoglobin cannot carry oxygen. Injury or certain drugs, chemicals, or foods may cause a higher-than-normal amount of methemoglobin to be made. This causes a condition called methemoglobinemia.

Micronuclei: Small nuclei separate from, and additional to, the main nucleus of a cell, produced during the telophase of mitosis or meiosis by lagging chromosomes or chromosome fragments derived from spontaneous or experimentally induced chromosomal structural changes.

Miscible: A physical characteristic of a liquid that forms one liquid phase with another liquid (e.g., water) when they are mixed in any proportion.

Molecular weight: The molecular weight of a substance is the weight in atomic mass units of all the atoms in a given formula. The value is rounded to the nearest tenth.

Mutations: A change in the structure of a gene, resulting from the alteration of single base units in DNA, or the deletion, insertion, or rearrangement of larger sections of genes or chromosomes. The genetic variant can be transmitted to subsequent generations.

National Priorities List: The list of national priorities among the known releases or threatened releases of hazardous substances, pollutants, or contaminants throughout the United States and its territories. The NPL is intended primarily to guide the EPA in determining which sites warrant further investigation.

Non-differential misclassification: The probability of erroneous classification of an individual, a value, or an attribute into a category other than that to which it should be assigned is the same in all study groups.

Norharman: A beta-carboline widely distributed in the environment.

Normochromatic erythrocyte: A mature erythrocyte that lacks ribosomes and can be distinguished from immature, polychromatic erythrocytes by stains selective for RNA.

Osmotic mini pump: A miniature implantable infusion pump that is used to continuously infuse laboratory animals with a drug or other material. Absorption of water from surrounding tissues by osmosis through an outer rigid shell provides the means by which the material is forced out of a collapsible internal chamber at a constant rate.

Personal protective equipment: Specialized clothing or equipment, worn by an employee to minimize exposure to a variety of hazards. Examples of PPE include such

items as gloves, foot and eye protection, protective hearing devices (earplugs, muffs) hard hats, respirators and full body suits.

Plate incorporation: A commonly used procedure for performing a bacterial reverse mutation test. Suspensions of bacterial cells are exposed to the test substance in the presence and in the absence of an exogenous metabolic activation system. In the plate-incorporation method, these suspensions are mixed with an overlay agar and plated immediately onto minimal medium. After two or three days of incubation, revertant colonies are counted and compared with the number of spontaneous revertant colonies on solvent control plates.

Poly-3 trend test: A survival-adjusted statistical test that takes survival differences into account by modifying the denominator in the numerical (quantal) estimate of lesion incidence to reflect more closely the total number of animal years at risk.

Polychromatic erythrocyte: A newly formed erythrocyte (reticulocyte) containing RNA.

Proto-oncogene: A gene involved in normal cell growth. Mutations (changes) in a proto-oncogene may cause it to become an oncogene, which can cause the growth of cancer cells.

$\boldsymbol{P_{trend}}$**:** Level of statistical significance of a change over time in a group selected to represent a larger population.

S9 metabolic activation: The chemical alteration of an exogenous substance by or in a biological system. The alteration may inactivate the compound or it may result in the production of an active metabolite of an inactive parent compound.

Selection bias: An error in choosing the individuals or groups to take part in a study. Ideally, the subjects in a study should be very similar to one another and to the larger population from which they are drawn (for example, all individuals with the same disease or condition). If there are important differences, the results of the study may not be valid.

Sister-chromatid exchange: The exchange during mitosis of homologous genetic material between sister chromatids; increased as a result of inordinate chromosomal fragility due to genetic or environmental factors.

Solubility: The ability of a substance to dissolve in another substance and form a solution. The Report on Carcinogens uses the following definitions (and concentration ranges) for degrees of solubility: (1) *miscible* (see definition), (2) *freely soluble*- capable of being dissolved in a specified solvent to a high degree (> 1,000 g/L), (3) *soluble*- capable of being dissolved in a specified solvent (10–1,000 g/L), (4) *slightly soluble*- capable of being dissolved in a specified solvent to a limited degree (1-10 g/L), and (5) practically insoluble- incapable of dissolving to any significant extent in a specified solvent (< 1 g/L).

Specific gravity: The ratio of the density of a material to the density of a standard material, such as water at a specific temperature; when two temperatures are specified, the first is the temperature of the material and the second is the temperature of water.

Spot test: Qualitative assay in which a small amount of test chemical is added directly to a selective agar medium plate seeded with the test organism, e.g., *Salmonella*. As the chemical diffuses into the agar, a concentration gradient is formed. A mutagenic chemical will give rise to a ring of revertant colonies surrounding the area where the chemical was applied; if the chemical is toxic, a zone of growth inhibition will also be observed.

Steric bulk: An indicator of the stability of the spatial arrangement of atoms in a molecule.

Toxicokinetics: The mathematical description (toxicokinetic models) of the time course of disposition of a chemical in the body.

TOXMAP: A Geographic Information System from the National Library of Medicine that uses maps of the United States to help users visually explore data from EPA's TRI and Superfund programs.

Transitions: DNA nucleotide substitution mutation in which a purine base is substituted for another purine base (adenine → guanine or guanine → adenine) or a pyrimidine base for another pyrimidine base (cytosine → thymine or thymine → cytosine).

Transversions: DNA nucleotide substitution mutation in which a purine base (adenine or guanine) is substituted for a pyrimidine base (cytosine or thymine) or vice versa.

***Tunica vaginalis*:** The serous membranous covering of the testis.

Two-compartment pharmacokinetic model: A two-compartment pharmacokinetic model resolves the body into a central compartment and a peripheral compartment. The central compartment generally comprises tissues that are highly perfused such as heart, lungs, kidneys, liver and brain. The peripheral compartment comprises less well-perfused tissues such as muscle, fat and skin. A two-compartment model assumes that, following drug administration into the central compartment, the drug distributes between that compartment and the peripheral compartment. However, the drug does not achieve instantaneous distribution (i.e., equilibrium), between the two compartments. After a time interval (t), distribution equilibrium is achieved between the central and peripheral compartments, and elimination of the drug is assumed to occur from the central compartment.

Type-I error: The error of rejecting a true null hypothesis, i.e., declaring that a difference exists when it does not.

Type-II error: The error of failing to reject a false null hypothesis, i.e., declaring that a difference does not exist when in fact it does.

Vapor density, relative: A value that indicates how many times a gas (or vapor) is heavier than air at the same temperature. If the substance is a liquid or solid, the value applies only to the vapor formed from the boiling liquid.

Vapor pressure: The pressure of the vapor over a liquid (and some solids) at equilibrium, usually expressed as mm Hg at a specific temperature (°C).

Appendix A: Literature Search Strategy

This document identifies the data sources, search terms, and search strategies that were used to identify literature for the draft monograph on *ortho*-toluidine (CASRN 95-53-4). The literature search strategy used for *ortho*-toluidine involved several approaches designed to identify potentially useful information for the broad range of topics covered by a Report on Carcinogens (RoC) monograph, as listed below.

- Properties and Human Exposure (focusing on the U.S. population)
- Disposition (ADME) and Toxicokinetics
- Human Cancer Studies
- Studies of Cancer in Experimental Animals
- Mechanistic Data and Other Relevant Effects
  - Genetic and Related Effects
  - Mechanistic Considerations

The methods for identifying the relevant literature for the draft *ortho*-toluidine monograph including (1) the search strategy, (2) updating the literature search, and (3) review of citations using web-based systematic review software are illustrated in Figure 1 and discussed below. The detailed literature search strategy, including all database sources, and exclusion/inclusion criteria, are available at http://ntp.niehs.nih.gov/go/37898

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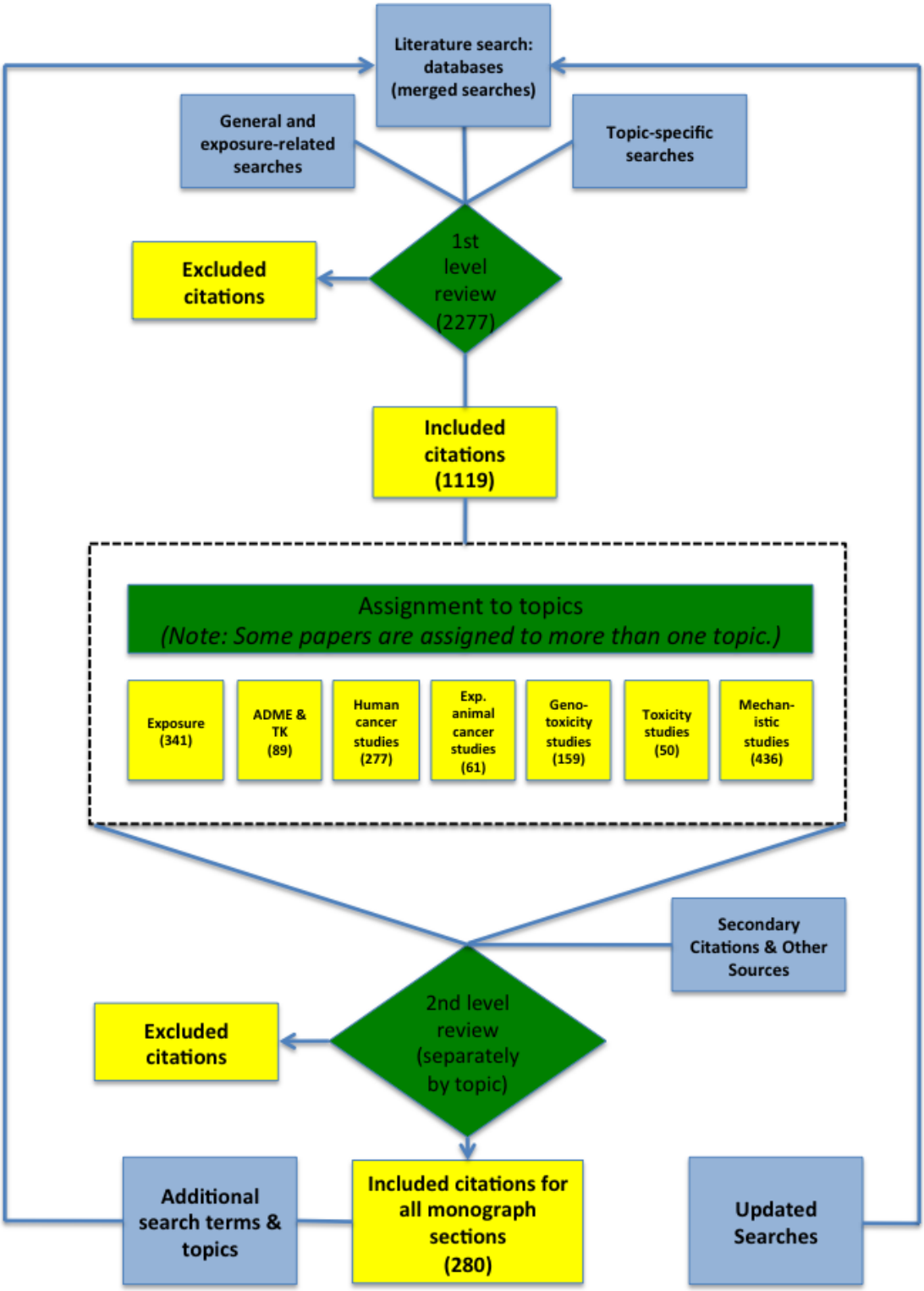
Figure A-1. Literature search strategy and review



Search strategies

Relevant literature is identified using search terms, data sources, and strategies as discussed below.

1. **General data search:** This search covers a broad range of general data sources (see *ortho*-Toluidine Literature Search Strategy, available at http://ntp.niehs.nih.gov/go/37898) for information relevant to many or all of the wide range of monograph topics pertaining to *ortho*-toluidine.
2. **Exposure-related data search:** This search covers a broad range of potential sources (see *ortho*-Toluidine Literature Search Strategy, available at http://ntp.niehs.nih.gov/go/37898) for exposure-related information and physical-chemical properties.
3. **Database searches in PubMed, Scopus, and Web of Science:** The majority of the primary literature used to draft the *ortho*-toluidine monograph was identified from searches of these three extensive databases available through the NIEHS Library. Synonyms, metabolites, and the chemical class for *ortho*-toluidine were identified from the sources listed in Table A-1 and the search terms are listed in Table A-2. The substance search terms were combined with the search terms for each of the monograph topics listed above to create the specific literature searches. See Table A-2 for details on this approach and Table A-3 for topic-specific search terms.

   Searches for human cancer studies are somewhat unique because they involve the identification of search terms for exposure scenarios that might result in exposure of people to *ortho*-toluidine. For *ortho*-toluidine, these exposure-related search terms were based on its use in the manufacture of dyes, rubber chemicals, and a herbicide intermediate, and those search terms were combined with search terms specific for human cancer (see Tables A2 and A3).
4. **QUOSA library of occupational case-control studies** search of the QUOSA-based library of approximately 6,000 occupational case-control studies, approximately 60% of which are currently available as searchable full-text pdfs, was conducted using the synonyms “o-toluidine”, “ortho-toluidine”, “95-53-4”, “2-toluidine”, “1-amino-2-methylbenzene”, “2-amino-1-methylbenzene”, “2-aminotoluene”, “o-aminotoluene”, “ortho-aminotoluene”, “2-methyl-1-aminobenzene”, “2-methylaniline”, “o-methylaniline”, “ortho-methylaniline”, “o-methylbenzenamine”, “ortho-methylbenzenamine”, “2-methylphenylamine”, “2-tolylamine”, “o-tolylamine”, “ortho-tolylamine.”
5. **Special topic-focused searches:** No special topic-focused searches were conducted for *ortho*-toluidine, but searches for general information on potential confounders were conducted.
6. **Secondary sources:** Citations identified from authoritative reviews or from primary references located by literature search, together with publications citing

key papers identified using the Web of Science "Cited Reference Search," were also added.

Because *ortho*-toluidine has been listed in the Report on Carcinogens as *reasonably anticipated to be a human carcinogen* since 1983, searches for studies of cancer in experimental animals were limited to studies published since 1982. The monograph relies primarily on authoritative reviews for information on exposure, toxicokinetics, and genotoxicity, but literature searches were conducted to update that information from the date of the most recent comprehensive review by IARC (Working group met in 2008, literature searches were conducted from 2007).

Updating the literature search

The literature searches will be updated prior to submitting the draft monograph for peer review and prior to finalizing the monograph. Monthly search alerts for *ortho*-toluidine synonyms, metabolites, chemical class, exposure scenarios (human cancer), and topic-focused searches were created in PubMed, Scopus, and Web of Science, and the results of these searches from the closing date of the initial search will be downloaded for review.

Review of citations using web-based systematic review software

Citations retrieved from literature searches were uploaded to web-based systematic review software and screened using inclusion and exclusion criteria. Multi-level reviews of the literature were conducted, with initial reviews (Level 1) based on titles and abstracts only to identify citations that could be excluded and to assign the included literature to one or more monograph topics; subsequent reviews (Level 2) for literature assigned to the various monograph topics (Exposure, ADME & TK, Human cancer studies, etc.) were based on full-text (i.e., PDFs) of the papers and were carried out by the writer and scientific reviewer for each monograph section. Two reviewers, at least one of whom is a member of the ORoC at NIEHS, participated at each level of review. The inclusion/exclusion criteria are available in the *ortho*-Toluidine Literature Search Strategy document, available at http://ntp.niehs.nih.gov/go/37898

Table A-1. Data sources for *ortho*-toluidine searches

Information type	Data sources
Synonyms	National Library of Medicine databases (e.g., ChemIDplus, Hazardous Substances Data Base)
Metabolites	Son *et al*. (1980)

Table A-2. Literature search approach for *ortho*-toluidine

Substance	Search terms	Topics (combined with)[a]
ortho-Toluidine synonyms	o-toluidine, ortho-toluidine, 95-53-4, 2-toluidine, 1-amino-2-methylbenzene, 2-amino-1-methylbenzene, 2-aminotoluene, o-aminotoluene, ortho-aminotoluene, 2-methyl-1-aminobenzene, 2-methylaniline, o-methylaniline, ortho-methylaniline, o-methylbenzenamine, ortho-methylbenzenamine, 2-methylphenylamine, 2-tolylamine, o-tolylamine, ortho-tolylamine	Human exposure Toxicokinetics Human cancer studies Cancer studies in experimental animals Genotoxicity Toxicity Mechanism
ortho-Toluidine metabolites and their synonyms	Anthranilic acid, *N*-acetyl-anthranilic acid, *N*-acetyl-*o*-toluidine, *N*-acetyl-*o*-aminobenzyl alcohol, o-azoxytoluene, *o*-nitrosotoluene, *N*-hydroxy-*o*-toluidine, 4-amino-cresyl sulfate, *N*-acetyl-4-amino-*m*-cresyl sulfate, 2-amino-*m*-cresyl sulfate, 4-amino-*m*-cresyl glucuronide, 4-acetyl-4-amino-*m*-cresyl-glucuronide, *N*-acetyl-*o*-aminobenzyl glucuronide	Human cancer studies Cancer studies in experimental animals (for the mechanistic section) Genotoxicity Toxicity Mechanism
Chemical class synonyms	Monocyclic aromatic amines, arylamines, alkylanilines	Cancer studies in experimental animals (for the mechanistic section) Genotoxicity Toxicity Mechanism
Exposure scenarios (Dye industry, rubber chemical manufacturing, and herbicide manufacturing)	(dyestuff OR (dye AND (manufacturing OR manufacture)) OR rubber chemicals OR ortho toluidine OR o-toluidine OR chloro-o-toluidine OR chloro-*ortho* toluidine OR aniline OR ((manufacture OR manufacturing OR production) AND magenta) OR metolachlor OR acetochlor)	Human cancer studies

[a] Search terms for each of these topics were developed in consultation with an informational specialist.

Table A-3. Search terms for monograph topics for *ortho*-toluidine

Monograph Topic	Search terms used in PubMed, Scopus, and Web of Science	MeSH terms used in Pubmed
Exposure	exposure OR occurrence OR oral OR dermal OR air OR water OR food OR soil OR environmental pollut* OR environmental exposure* OR occupational exposure*	(“Environmental Pollutants” [MeSH] OR “Environmental Pollution” [MeSH])
ADME/ Toxicokinetics	*Toxicokinetic search terms*- administration OR absorption OR distribution OR tissue distribution OR bioavailab* OR biological availability OR metaboli* OR biotransform* OR activat* OR bioactivat* OR detoxif* OR excret* OR clearance OR eliminat* OR kinetic* OR pharmacokinetic* OR toxicokinetic* OR cytochrome P450 *Combine with AND* *Animal study search terms*- in vivo OR animal* OR mouse OR mice OR rat OR hamster OR guinea pig OR rabbit OR monkey OR dog	*Toxicokinetic search terms*- "Pharmacokinetics"[Mesh]) OR "Metabolism"[Mesh]) OR "Cytochrome P450 Enzyme System"[Mesh]
Human Cancer	*Cancer search terms*- cancer OR mortality OR follow-up OR incidence) *Combine with AND* *Epidemiology search terms* - epidemiogic* OR workers OR case-control OR cohort OR case-report OR case-series	None
Animal Tumors	*Cancer search terms*- cancer OR neoplasm* OR carcinogen* OR malignan* OR oncogene* OR tumor* OR tumour* *Combine with AND* *Animal study search terms*- animal* OR mouse OR mice OR rat OR hamster OR "guinea pig" OR rabbit OR monkey OR dog	*Cancer search terms*- "Neoplasms"[Mesh]) OR "Carcinogens"[Mesh]
Genotoxicity	genetic toxicology" OR clastogen* OR "DNA strand break*" OR "unscheduled DNA synthesis" OR "UDS" OR aneuploid OR aneuploid* OR polyploid OR polyploid* OR "neoplastic cell transformation" OR "chromosom* aberration*" OR cytogenetic OR cytogenetic* OR "DNA adduct*" OR "DNA damage" OR "DNA repair" OR crosslink* OR "germ-line mutation" OR micronucle* OR mutagen OR mutagen* OR mutation OR mutation* OR oncogen* OR "sister chromatid exchange" OR "SCE" OR "SOS response*" OR "Ames test" OR "gene expression" OR "cell proliferation" OR cytotoxic OR cytotoxic* OR "comet assay"	"DNA Damage"[Mesh] OR "DNA Repair"[Mesh] OR "Mutagens"[Mesh] OR "Mutation"[Mesh] OR "Cytogenetic Analysis"[Mesh] OR "Oncogenes"[Mesh] OR "Mutagenicity Tests"[Mesh]
Toxicity	toxic* OR toxin*OR cytotoxic* OR (nephrotoxic* OR hepatotoxic* OR pneumotoxic* OR thyrotoxic*	"Toxic Actions"[Mesh]) OR "Toxicity Tests"[Mesh]) OR "adverse effects" [Subheading]

Monograph Topic	Search terms used in PubMed, Scopus, and Web of Science	MeSH terms used in Pubmed
Mechanisms of Carcinogenicity	((mode OR mechanism*) AND action) OR (carcinogen OR genetic OR epigenetic OR inhibit* OR promot* OR interact* OR activate* OR detoxific* OR "oxidative damage" OR alkylat* OR adduct)) AND ((animal OR animals OR mouse OR mice OR rat OR hamster OR "guinea pig" OR rabbit OR monkey OR dog OR pig) OR (person* OR people OR individual* OR subject* OR participant*))	

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Appendix B: Regulations and Guidelines

Regulations and guidelines

Regulations

U.S. Environmental Protection Agency (EPA)

Clean Air Act

National Emission Standards for Hazardous Air Pollutants:

Requires major and area sources to sharply reduce routine emissions of toxic air pollutants in accordance with specific performance-based standards for all air emission sources that emit one or more of the listed pollutants. *ortho*-Toluidine is listed as a hazardous air pollutant.

Comprehensive Environmental Response, Compensation, and Liability Act

Reportable quantity (RQ) = 100 lb

Resource Conservation and Recovery Act

When *ortho*-toluidine becomes a waste, it must be managed according to Federal and/or State hazardous waste regulations. Listed hazardous waste codes = U222, U328, K112, K113, K114.

Occupational Safety and Health Administration (OSHA)

Permissible exposure limit (PEL) = 5 ppm

Guidelines

American Conference of Governmental Industrial Hygienists (ACGIH)

Threshold limit value – time-weighted average (TLV-TWA) = 2 ppm

National Institute for Occupational Safety and Health (NIOSH)

Immediately dangerous to life and health (IDLH) limit = 50

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Appendix C: Background exposure information on epidemiologic studies

The available epidemiologic studies evaluating potential exposure to *ortho*-toluidine and cancer include workers in industries manufacturing either (1) dyestuffs, (2) synthesis of 4-chloro-*ortho*-toluidine, or (3) certain rubber chemicals (see Section 1.4). These occupational settings also involve potential exposure to other substances. Many of the studies do not have detailed information on exposure to *ortho*-toluidine or other co-exposures; however, some of this information can be inferred from knowledge of the manufacturing process, or dye chemistry. In order to provide background information for interpreting these epidemiologic studies, the nature of the potential for exposure to *ortho*-toluidine and to other intermediates or end products in these manufacturing processes is discussed below.

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To return to text citing Appendix C in Section 3, click here.

C.1 Manufacture of dyestuffs

The review of epidemiologic studies of dyestuffs manufacture (see Section 3) with potential exposure to *ortho*-toluidine includes four different cohorts ([1] Case *et al.* (1954) and Case and Pearson (1954), [2] Rubino *et al.* (1982), [3] Stasik (1988), and [4] Ott and Langner (1983)) that examined the incidence of urinary bladder cancer in relation to manufacturing processes that potentially involved exposure to *ortho*-toluidine. Occupational exposure to *ortho*-toluidine can be inferred from knowledge of dye production processes in dye worker cohort studies where very few or no quantitative data are available on exposure to *ortho*-toluidine (Freeman 2012). In general, exposure to *ortho*-toluidine was more likely to have occurred in manufacturing facilities prior to the adoption of formal regulations regarding building ventilation and personal protective equipment (e.g., adoption of OSHA regulations in the mid-1970s).

C.1.1 Aniline production in Great Britain: Case et al. *(1954) and Case and Pearson (1954)*

Case *et al.* and Case and Pearson reported findings of urinary bladder cancer among dyestuff workers, employed from 1910 to 1952 at 21 firms in Great Britain Although the authors do not mention exposure to *ortho*-toluidine in their study, potential exposure might have occurred among both aniline and magenta manufacturing workers (see below) based on the production processes of the first half of the 20th century. The benzene preparations used in the early part of the 20th century varied in purity and often contained toluene. Crude benzene was marketed in preparations identified based on the percentage that distills before 100°C is reached as 90s (75% benzene, 24% toluene, 1% xylene), 50s (50% benzene, 40% toluene, 10% xylene), and 30s (10% benzene, 60% toluene, 30% xylene) (Cain and Thorpe 1905). When the crude benzene preparations were subjected to the processes of nitration and reduction, a mixture of aniline and toluidines (*ortho*-, *meta*-, and *para*- in the approximate proportions 15:9:1) resulted. The probability of exposure

to *ortho*-toluidine among aniline manufacturing workers must be considered as low because of the uncertainty about the degree of purity of the benzene, especially as it might have changed over the 42 years of exposure covered by these studies.

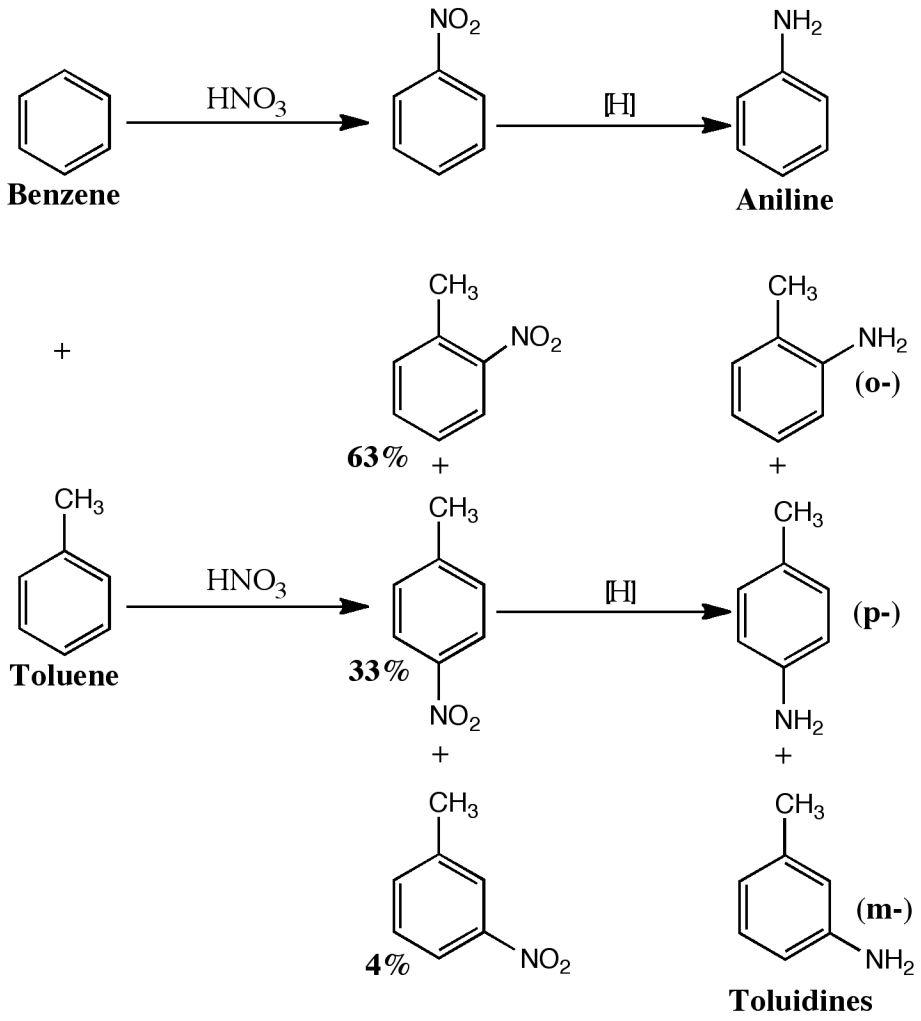
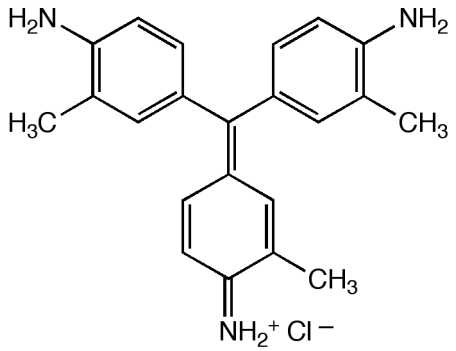


Figure C-1. Synthesis of aniline from benzene and mixed isomers of toluidine from toluene by successive nitration and reduction reactions

C.1.2 Magenta manufacturing in Great Britain: Case et al. *(1954) Pira* et al. *(2010)*

The studies of dyestuff manufacture and use workers by Case *et al.* (1954) and Case and Pearson (1954) covered the period of 1910 to 1952 and included manufacture of magenta and other dyes. (Magenta III, also called "New Fuchsin" or new magenta, III is the product generally produced in the United Kingdom (Figure C-2).



Magenta III

Figure C-2. Structure of Magenta III

In the United Kingdom, the process for manufacturing magenta, resulting mainly in the production of magenta III, involved condensation of *ortho*-toluidine and formaldehyde in the presence of *ortho*-nitrotoluene (Howe 1977). One can reasonably infer that workers in the study by Case *et al.* and Case and Pearson were exposed to *ortho*-toluidine (see Section 3).

A sub-cohort of dyestuff workers engaged in manufacture of fuchsin or *ortho*-toluidine was included in the bladder cancer mortality study reported by Pira *et al.* (2010) (see Section 3.X). Earlier studies of dyestuff workers from the same plant were published by Rubino *et al.* (1982) and Piolatto *et al.* (1991); the latter publication reported findings for magenta and Safranine T manufacturing workers combined. Safranine T workers had potential co-exposures to 2,5-diaminotoluene and aminoazotoluene; Pira *et al.* reported estimates that appear to be specific for *ortho*-toluidine and magenta manufacturing workers. The process for making *ortho*-toluidine and 4,4'-methylene bis(2-methylaniline) as precursors for fuchsin (identified as New Fuchsin by Rubino *et al.*) are shown in Figure B-3. *ortho*-Toluidine was used as a precursor for the production of New Fuchsin (Figure B-4). Rubino *et al.* reported that the *ortho*-toluidine production department was housed in a different building within the factory area from the building in which New Fuchsin was produced. The process for producing the fuchsin dye was described as involving heating a mixture of *ortho*-toluidine, 4,4'-methylene bis(2-methylaniline), and aniline with a step at the end of the process for the recovery of excess *ortho*-toluidine.

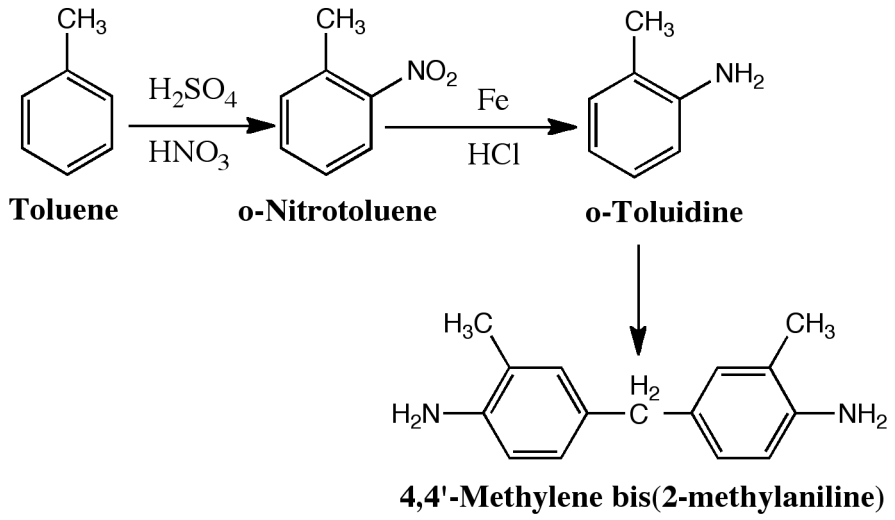
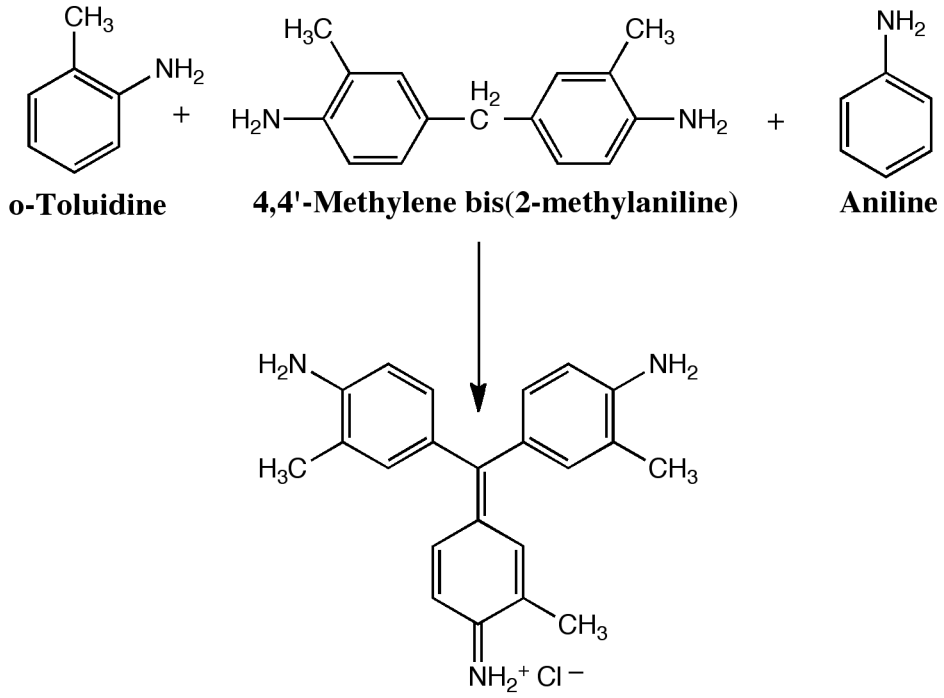


Figure C-3. Synthesis of ortho-toluidine and 4,4'-methylene bis(2-methylaniline) for production of fuchsin (New Fuchsin)



New Fuchsin (Magenta III)

Figure C-4. Synthesis of New Fuchsin from *ortho*-toluidine, 4,4'-methylene bis(2-methylaniline, and aniline

C.1.3 Manufacture of dyes and dye intermediates in the United States: Ott and Langner (1983)

Ott and Langner reported that U.S. dye production workers employed in the bromindigo and thioindigo production area of a manufacturing facility between 1914 and 1958 were potentially exposed to *ortho*-toluidine. Industrial hygiene measurements taken at the plant during the mid 1940s for *ortho*-toluidine in breathing zone or area samples were consistently less than 0.5 ppm, and results of medical surveillance that included measurement of *ortho*-toluidine in urine ranged from less than the limit of detection of 0.3 ppm up to 1.7 ppm. *ortho*-Toluidine was included in a list of raw materials and intermediate products for production of thioindigo, which consisted of four alternately run batch processes involving manufacture of the following dyes: thioindigo (pink B), scarlet G, red 3B, and red 2B; however, no other details on the chemistry of these processes were reported that would indicate which process(es) involved exposure to *ortho*-toluidine. *ortho*-Toluidine might have been used to make intermediates, e.g., anthranilic acid or *ortho*-nitrobenzoic acid, that can be used in the manufacture of thioindigoid dyes (Freeman 2012). In addition to *ortho*-toluidine, raw materials and intermediate products for the four thioindigo processes included 1,2 dihydroacenaphthylamine, sodium nitrite, chloroacetic acid, 4-chloro-*ortho*-toluidine, 4-chloro-acetyl-*ortho*-toluidine, thioindoxyl, chlorosulfonic acid, ethanol, and 2-aminobenzoic acid.

C.2 Manufacture of other intermediates

The chemical intermediate 4-chloro-*ortho*-toluidine (4-COT) can be used in the production of dyes and pigments and of the pesticide chlordimeform. Stasik (1988) studied a facility in Germany that produced and processed 4-COT, but the author did not report the end use for that product. Possible exposure to *ortho*-toluidine existed for a sub-cohort of 4-chloro-*ortho*-toluidine production and processing workers from that cohort (see Section 3). 4-Chloro-*ortho*-toluidine is produced by acetylation of *ortho*-toluidine to yield *N*-acetyl-*ortho*-toluidine, followed by chlorination to yield chloro-*N*-acetyl-*ortho*-toluidines, which are hydrolyzed to yield 4-chloro-*ortho*-toluidine (see Figure 1-5). 6-chloro-*ortho*-toluidine originates from chlorination in the 6-position of *N*-acetyl-*ortho*-toluidine (simultaneous with chlorination in the 4 position) and carries over to the hydrolysis step, creating 6-chloro-*ortho*-toluidine as a by-product (Freeman 2012).

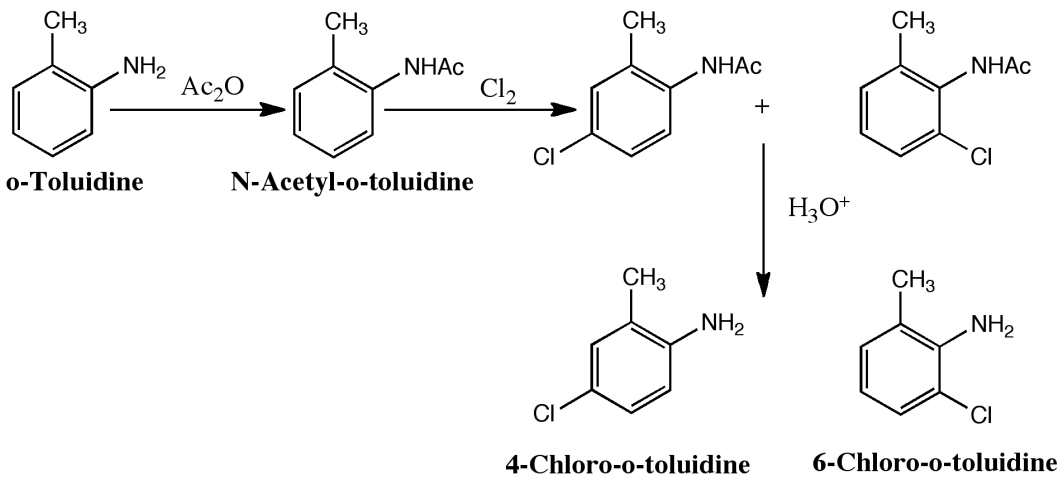


Figure C-5. Chemistry associated with synthesis of 4-chloro-*ortho*-toluidine

C.3 The rubber chemical industry and exposure to *ortho*-toluidine

The major source of information on exposure to *ortho*-toluidine in the rubber chemical production industry is from the cohort studied by Carreón *et al.* (2010) and earlier by Ward *et al.* (1991) (see Section 3). Exposure data for the workers in this cohort have been reported by Ward *et al.* (1996), Ruder *et al.* (1992), Teass *et al.* (1993) and Hanley *et al.* (2012). The exposure data reported by Hanley *et al.* are discussed below. Additional information was obtained from the studies by Sorahan and Pope (1993), Sorahan *et al.* (2000), and Sorahan (2008) of the rubber industry in the United Kingdom.

C.3.1 Manufacture of a rubber antioxidant in the United States: Hanley et al. *(2012)*

The subcohort studied by Carreón *et al.* (2010) (Section 3) was also the subject of a retrospective exposure assessment, which was described in the publication by Hanley *et al.* (2012). Workers were engaged (1) from 1957 onwards in the production of rubber antioxidants from *ortho*-toluidine, aniline, hydroquinone, toluene or xylene, and a proprietary catalyst; phenol and diphenylamine were the reaction byproducts, and (2) from the mid-1950s to either 1970 or 1994, depending on the product, the production of accelerants from nitrobenzene, aniline, and benzothiazole. 4-aminobiphenyl was a suspected contaminant in some of the process chemicals and was found in trace amounts (< 1 ppm) in 3 of 9 bulk samples of process chemicals (Ward *et al.* 1991). Both antioxidants and accelerators were produced and packaged in parallel operations in the same rooms of the plant's rubber chemicals department (Hanley *et al.* 2012). The highest breathing zone exposures to *ortho*-toluidine were measured for the anti-oxidant process and for maintenance (see Figure 1-4), with measurements for all departments ranging from 0.020 to 0.37 ppm (N = 45). The geometric mean for company-collected TWA breathing zone samples from the rubber chemicals department (see Figure 1-5) were highest in 1976 to 1979 (0.1 ppm, N = 30), and declined to 0.015 ppm (N = 200) in 1980 to 1994 and 0.0028 ppm (N = 127) in 1995 to 2004. Ambient air levels of aniline in the

rubber chemicals were approximately half of those for ortho-toluidine, and nitrobenzene levels were almost all non-detectable. Biomonitoring data for ortho-toluidine, aniline, and 4-aminobiphenyl in urine and Hb adducts collected in 1990 (Ward *et al.* 1996), which would integrate ambient and dermal exposure, indicated that exposure to *ortho*-toluidine was approximately 3-4 times that of aniline. Hanley *et al.* identified a number of changes or procedures from the beginning of rubber chemical manufacture in 1954 through 1988 that had the potential to impact exposure to *ortho*-toluidine and other chemicals. The major change that potentially increased exposure was a steady increase in chemical use, including *ortho*-toluidine, for production of rubber chemicals from 1960 to 1970. Changes that could potentially reduce exposure included (1) initiation of an air monitoring program in 1975-1976, (2) replacement of a manual charging operation for adding chemicals with an automated premix reactor feed system in 1978, (3) establishment of a company policy for personal protective equipment in or around 1980, and (4) various changes in shower and laundry facilities, material recycling, leak protection, and automated bagging during the 1990s.

Although quantitative exposure data were not available for individual workers, Hanley *et al.* (2012) were able to assign them to one of three categories (i.e., "definitely exposed, " "probably exposed, " or "probably not exposed") based on the departments in which the individuals had worked using updated information from “a plant walkthrough, interviews with employees, management and union representatives, and review of records.” The same categories had been used to categorize exposure for the earlier study by Ward *et al.* (1991), but the assessment by Hanley *et al.* involved several changes in assignments by departments.

Table C-1. Exposure classifications used in NIOSH rubber chemical cohort studies (Ward *et al.* 1991 and Carreón *et al.* 2010; see also Hanley *et al.* 2012)

Exposure category	Job titles Ward *et al.* 1991	Total (N)	Job titles Carreón *et al.* 2010	Total (N)
Definitely exposed	Ever employed: Rubber chemical dept.	708	Ever employed: Rubber chemical dept., maintenance, laboratory (inc. quality control, R&D)	962
Possibly exposed	Every employed: Maintenance, shipping/packaging/warehouse, janitorial, yard work but never in rubber chemicals dept.	288	Ever employed: Shipping/packaging/warehouse, janitorial, yard work, temporary assignment from headquarters, none assigned depts. but never in rubber chemicals, maintenance or laboratory depts.	187
Probably not exposed to *ortho*-toluidine or aniline	Never employed in above depts. + all work prior to Jan 1, 1957	753	Never in above depts. + all work prior to Jan 1, 1957	600

To return to text citing Table C-1, click here.

C.3.1 Manufacture of a rubber antioxidant in the United Kingdom: Sorahan and coworkers

Sorahan and Pope (1993), Sorahan *et al.* (2000), and Sorahan (2008) studied a cohort of workers at a chemical production factory that manufactured and used 2-mercaptobenzothiazole (MBT) and phenyl-β-naphthylamine (PBN) along with vulcanization inhibitors and accelerators, antioxidants, and other proprietary products for the rubber industry in the United Kingdom (see Section 3). Exposure to *ortho*-toluidine occurred in From 1936 to 1979, in the department manufacturing *o*-tolylbiguanide (also called Sopanox) was made in one department, which was produced by reacting *ortho*-toluidine with dicyanamide in the presence of hydrochloric acid. No information on exposure levels were provided. Exposure to aniline, MBT and PBN occurred in other departments; however, some workers switched departments.

Appendix D: Human Cancer Study Tables

This appendix contains background information related to the cancer assessment on *ortho*-toluidine in humans including (1) detailed data information on study design, methods, and findings for the cohort studies (Table D-1) and case-control studies (Table D-2), (2) detailed information on the quality assessment of the individual studies Table D-3) and (3) background carcinogenicity information on co-exposures in the cohort studies (Table D-3).

To return to text citing Appendix D in the introduction, click here.

To return to text citing Appendix D in Section 3, click here.

Methodologies and study characteristics of the selected epidemiologic studies and identification of cancer endpoints

The data from the eight cohort studies and two nested case-control studies (as delineated in Table 3-1) were systematically extracted from relevant publications, as described in the study protocol and are summarized in the tables below.

To return to text citing Table D-1, click here.

To return to text citing Table D-2, click here.

Abbreviations (for all tables)

CI = confidence interval
GM = geometric mean
ICD = International Classification of Diseases
JEM = job-exposure matrix
NIOSH NOES = National Institute for Occupational Safety and Health National Occupational Exposure Survey
NR = not reported
SIC = Standard Industrial Classification
SIR = standardized incidence ratio
SMR = standardized mortality ratio
SRR = standardized rate ratio
[] = calculated based on observed vs. expected cases, not reported by authors

Table D-1. Cohort studies of *ortho*-toluidine exposure: Study characteristics and overall findings

Case and Pearson 1954: U.K. Dyeworkers	
Related Reference	**Geographic Location**
Case *et al.* 1954	United Kingdom
Population Characteristics	
Exposed Cohort and Ascertainment	***Reference Population***
Eligibility criteria for exposed cohort: Workers without contact with auramine, benzidine, or α- or β-naphthylamine and who worked at least 6 months between 1910 and 1952 (referred to as nominal roll) Exposed cohort All male workers who had contact (manufacture or use) with magenta (N = 85) at 21 British chemical factories Total cohort: Male workers (4622) at 21 firms who had contact with aniline, benzidine, α- or β-naphthylamine from 1910 to 1952 Follow-up: 1921–1952 *Loss* to follow-up: Not reported	General population (men): 15,875 deaths due to urinary bladder cancer in Wales and England (1921–1952) ***All-cause and all-cancer mortality*** Not reported
Study Design and Analytical Methods/ Control for Confounding	
Historical cohort study on urinary bladder cancer mortality Expected number of cases based on mean rate of male deaths from bladder cancer in Wales and England (up to 1952). Comparative composite cohort analysis, which accounts for age Excluded workers with exposure to benzidine, α- naphthylamine, or β-naphthylamine	
Exposure Data and Information Assessment	
Exposure: Levels and Co-Exposures	***Exposure Assessment***
Magenta manufacturing: levels and types of magenta NR Possible (depending on process): *ortho*-nitrotoluene, formaldehyde, aniline: levels NR	Exposure inferred via manufacturing process of magenta
Assessment: Other Exposure	***Disease Assessment***
Not reported	Firm, hospital and death certificates, and coroner's records and confirmed by other sources Missing data: Authors note that cases from earlier time points might have been missed

Pira *et al.* 2010: Italian Dyeworkers	
Related Reference	**Geographic Location**
Decarli *et al.* 1985, Piolatto *et al.* 1991, Rubino *et al.* 1982	Italy
Population Characteristics	
Exposed Cohort and Ascertainment	***Reference Population***
Eligibility criteria: Worked at least 1 year from 1922–1972 and were alive in 1946 Exposed cohort: 47 male workers involved only in the manufacture of fuchsin or *ortho*-toluidine (last update) Total cohort: 906 male dyestuff workers exposed to aromatic amines from 1922 to 1972; 2003 update on 590 Follow-up: 1951–2003; censored at age 85 Loss to follow-up: total cohort: 112 (12.4%) lost to follow-up before 1989, <4% after 1989	1951–1980: national mortality rates 1981–2003: regional mortality rates ***All-cause and all-cancer mortality*** ***Total cohort only*** All causes SMR = 1.50 (1.36–1.66); 394 All cancers SMR = 2.11 (1.80–2.46); 163
Study Design and Analytical Methods/ Control for Confounding	
Historical cohort mortality study SMR and CI calculated using Poisson distribution for observed deaths and adjusted for age (in 5-year age groups) and for 5-year calendar period Workers exposed to benzidine and/or α- or β-naphthylamine were excluded from cohort.	
Exposure Data and Information Assessment	
Exposure: Levels and Co-Exposures	***Exposure Assessment***
ortho-Toluidine: levels not reported *ortho*-Toluidine production section: potentially exposed to *ortho*-nitrotoluene, 4,4'-methylene bis(2-methylaniline): levels NR Fuchsin and safranine T production section: potentially exposed to 2,5-diaminotoluene, aniline, and aminoazotoluene as well as dye products: levels NR	Exposure for each person was assessed by linking individual records with knowledge of chemical processes
Assessment: Other Exposure	***Disease Assessment***
Personnel and factory records	Death certificates from regional registration offices

Ott and Langner 1983: U.S. Dyeworkers	
Related Reference	**Geographic Location**
None	United States
Population Characteristics	
Exposed Cohort and Ascertainment	***Reference Population***
Eligibility criteria Employed as of 1940 or hired subsequently, without high exposure to arsenicals, vinyl chloride, or asbestos Exposed cohort: Bromindigo and thioindigo subcohort; 117 male workers Total cohort: 342 male workers assigned to 3 aromatic amine-based dye production areas; 275 did not have exposure to arsenicals, vinyl chloride, or asbestos Follow-up: 1940–1975 Loss to follow-up: NR; 124 left company, but followed via Social Security	U.S. mortality rates for whites ***All-cause and all-cancer mortality*** ***Bromindigo and thioindigo subcohort*** All causes SMR = [0.79 (0.56–1.09)]; 36 All cancers SMR = [1.5 (0.81–2.56)]; 12
Study Design and Analytical Methods/ Control for Confounding	
Historical cohort mortality study SMR based on Poisson distribution assumptions Expected numbers: mortality rates for whites (5-yr interval) Person-years accumulated on a month by month basis from date of eligibility Excluded individuals with high exposure to arsenicals, vinyl chloride, or asbestos	
Exposure Data and Information Assessment	
Exposure: Levels and Co-Exposures	***Exposure Assessment***
ortho-Toluidine: Breathing zone and area measurements in the 1940's Air < 0.5 ppm Urine – undetected to 1.7 ppm Nitrobenzene, 4-chloro-*ortho*-toluidine, 4-chloro-acetyl-*ortho*-toluidine, 1, 2-dihydroacenaphthylene, 2-aminobenzoic acid, thioindigo dyes: levels NR Odor of nitrobenzene reported (threshold levels for odor is 5 ppb/volume)	Exposure assessed via work history; all jobs held in production areas of interest and dates of employment used to calculate person-years of employment in each area
Assessment: Other Exposure	**Disease Assessment**
Work history	Vital status determined by record search performed by Social Security Administration Underlying causes of death were coded according to the Seventh or Eighth Revision of the International Classification of Diseases (lCD), and were grouped for statistical purposes by categories used in the Eighth Revision

Stasik 1988: 4-COT Production Workers	
Related Reference	**Geographic Location**
Stasik *et al.* 1985	Germany
Population Characteristics	
Exposed Cohort and Ascertainment	***Reference Population***
Eligibility criteria: Workers with higher exposure employed before 1970 Exposed subcohort: 116 higher exposed 4-chloro-*ortho*-toluidine production and processing workers Total cohort: 335 male 4-chloro-*ortho*-toluidine production and processing workers employed between 1929 and 1982 Follow-up: 1967–1985 Loss to follow-up: Not reported	Incidence (sex and age-specific) using non-contiguous regional rates Earlier publication: mortality study: national and regional rates ***All-cause and all-cancer mortality*** ***Subcohort*** All-causes SMR = 1.12 (0.68–1.73); 19 All-cancers SMR = 1.45 (0.47–3.38); 5 (regional mortality rates)
Study Design and Analytical Methods/ Control for Confounding	
Historical cohort study of bladder cancer incidence; post-hoc analysis initiated by findings of cluster of bladder cancer (2 cases) after completion of mortality study Earlier study: historical cohort mortality study SIR: expected rates were calculated by multiplying person years at risk by age-specific bladder cancer incidence (regional)	
Exposure Data and Information Assessment	
Exposure: Levels and Co-Exposures	***Exposure Assessment***
Duration of higher exposure to 4-chloro-*ortho*-toluidine (before 1970); 14.0 years (median); total exposure duration (before and after 1970); 25.5 years (median) 4-chloro-*ortho*-toluidine, *N*-acetyl-*ortho*-toluidine 6-chloro-*ortho*-toluidine Benzidine and β-naphthylamine were not used in the plant	Exposure classification based on employment status, i.e., production or processing worker Information on duration of employment of cases, latency, age at beginning of employment
Assessment: Other Exposure	***Disease Assessment***
Smoking status known for bladder cases	Bladder cancer incidence cases: hospital and clinical records Histopathological diagnosis made (when possible) according to WHO classification Mortality: source not reported, ICD-9 codes Information on age at diagnosis of bladder cancer

Carreón *et al.* 2010: U.S. Rubber Chemical Workers	
Related Reference	**Geographic Location**
Hanley *et al.* 2012, Markowitz and Levin 2004, Prince *et al.* 2000, Ward *et al.* 1991, Ward *et al.* 1996	United States
Population Characteristics	
Exposed Cohort and Ascertainment	**Reference Population**
Eligibility criteria: Employed for 1 day or more at the plant between 1946 and 1988 Exposed cohort: Groups of workers definitely or possibly exposed to *ortho*-toluidine and aniline, classification varies by publication (996 in Ward *et al.*1991; 1149 in Carreón *et al.* 2010) Total cohort: 1749 (majority male) chemical plant workers Follow-up: Incidence: 1973 to 1988 Mortality: 1946 to 1988 Loss to follow-up: Might have missed cases of former workers who moved to other states	Incidence rates: New York State excluding NYC (local) Mortality: United States mortality (national) ***All-cause and all-cancer mortality*** ***Definitely exposed workers*** All-causes SMR = 0.96 (0.7–1.2); 65 All-cancers SMR = 1.1 (0.66–1.8); 17 ***Possibly exposed workers*** All-causes SMR = 0.8 (0.6–1.06); 47 All-cancers SMR = 0.91 (0.5–1.6); 13
Study Design and Analytical Methods/ Control for Confounding	
Historical cohort study on bladder cancer: incidence and mortality SMR: analysis by NIOSH life table system for 3 exposure categories; SIR: Standardized rate ratio also calculated for duration of employment and time since first employment categories Smoking rates in 5% sample of workers cf. US rates used to estimate SIR for bladder cancer attributable to smoking	
Exposure Data and Information Assessment	
Exposure: Levels and Co-Exposures	***Exposure Assessment***
TWA Breathing zone concentrations: Rubber Chemical dept 1976–2004 (Hanley *et al.* 2012)[a] Range, ppm (GM range, ppm) *o*-Toluidine: ND–1.8 (0.003–0.10) Aniline 0.026–1.7 (0.0009–0.081) Nitrobenzene ND–0.16 (0.004–0.038) 4-aminobiphenyl (4-ABP): trace amounts detected in bulk samples 1990 biomonitoring data, (post shift levels[b]): 46 definitely exposed and 27 unexposed (Ward *et al.* 1996) Unexposed / Exposed *Urine (µg/L)* *o*-Toluidine 2.8 / 98.7[c] Aniline 3.9 / 29.8[c] *Adducts (pg/g Hb)* *o*-Toluidine 3,515 / 40,830[c] Aniline 3,163 / 17,441[c] 4-ABP 74.5 / 81.7	Workers classified into categories (definitely, possibly, and probably not) of exposure based on employment history; highest exposure of all dept worked Reanalysis using revised exposure categories (2010) Stratified analysis for employment duration and time since first exposure. Missing data: Work histories truncated for 295 workers actively employed in August 1988 (records obtained)

Carreón *et al.* 2010: U.S. Rubber Chemical Workers	
Assessment: Other Exposure	***Disease Assessment***
Most recent smoking histories collected on 5% sample of current and former employees.	Cases: state cancer registry; company and union medical records and cross-verified against registry Deaths: identified and verified via death certificates in company records or Social Security Administration

[a]Levels within these ranges observed in air monitoring conducted by (NIOSH 1990b).
[b]Post-shift *ortho*-toluidine urine levels significantly higher than pre-shift levels.
[c]Significant difference in *ortho*-toluidine and aniline levels between exposed and non-exposed.

Sorahan 2008: U.K. Rubber Chemical Workers	
Related Reference	**Geographic Location**
Sorahan and Pope (1993); Sorahan *et al.* 2000	Wales (UK)
Population Characteristics	
Exposed Cohort and Ascertainment	***Reference Population***
Eligibility criteria: At least 6 months' employment between 1955 to 1984 Exposed cohort: 53 male workers with potential exposure to *o*-toluidine who worked in the "Sopanox" department of a rubber chemical factory. Total cohort: 2160 male rubber production workers (hourly employees); subcohorts also established for workers exposed to 2-mercaptobenzothiazole (MBT), aniline, and phenyl-ß-naphthylamine (PBN) Follow-up: Censored at age 85 Mortality: 1955 to 2005 Incidence: 1971 to 2005 Loss to follow-up: 14 subject emigrated, 32 untraced	Mortality: Serial mortality rates for England and Wales Incidence: expected numbers from national cancer registration Internal analysis: Cohort members not exposed to *ortho*-toluidine ***All-cause and all-cancer mortality*** ***ortho-Toluidine subcohort*** All-causes SMR = 1.00 [0.60–1.58]; 17 All-cancers SMR = 1.37 [0.60–2.71]; 7
Study Design and Analytical Methods	
Historical mortality and morbidity study of bladder cancer External analysis: SMR and SRR using person years at risk Internal analysis: Poisson regression - exposure duration was categorized into three levels; combined incidence and mortality Adjusted internal analysis: Controlled for exposure to aniline, MBT and PBN, age and calendar period	
Exposure Data and Information Assessment	
Exposure: Levels and Co-Exposures	***Exposure Assessment***
"*ortho*-Toluidine was used in the Sopanox department from 1936 to 1979; aniline, MBT and PBN not used in this department Overlap of membership in 4 subcohorts (*ortho*-toluidine, aniline, MBT, and PBN) Levels of co-exposures not reported except for MBT	Job History (unique job-department titles) for 1930 to 1988 Cumulative duration of employment in *ortho*-toluidine-exposed department calculated using 3 time-dependent variables
Assessment: Other Exposure	***Disease Assessment***
JEM created for MBT - cumulative exposure, cumulative duration of exposure for PBN and aniline	Mortality - death certificate from U.K. Office of National Statistics Morbidity - registration of malignant tumors External analysis: SMR limited to underlying cause on death certificate; SIR limited to malignant urinary bladder tumors [ICD-9: 188] Internal analysis: Primary cancer of the urinary bladder mentioned on death certificate or diagnosis of malignant or benign bladder tumor in cancer registries cancer registry data

Table D-2. Case-control studies of *ortho*-toluidine exposure: study characteristics and findings

Richardson *et al.* 2007: Canadian Case-Control Study	
Related References	**Geographic Location**
None	Canada
Population Characteristics	
Cases: Selection and ascertainment	***Controls: Selection and ascertainment***
Cases: 1062 males with urinary bladder cancer Case eligibility criteria: Diagnosed with urinary bladder cancer at 20 + yr old, between 1983 and 1990 and returned a lifetime occupational questionnaire; identified from the British Columbia Cancer Registry Participation rate: 60.1% (15,463 of the 25,726 eligible cancer registrants returned a questionnaire). Final number of cases and controls based on those that provided completed occupational histories	Referents: 8057 males with other cancer Referent eligibility criteria: All cancers excluding urinary bladder, lung and unknown sites, diagnosed between 1983 and 1990, and completed lifetime occupational questionnaire; identified from the British Columbia Cancer Registry Matching criteria: Matched on year of birth and year of diagnosis of cases; median matching ratio of controls to cases 7:1
Length of follow-back: Lifetime Loss to follow-back: 5.6% of cases and 4.3% controls excluded due to incomplete occupational histories	
Study Design and Analytical methods	
Population cancer registry-based case-control design Analysis by cumulative exposure and test for linear trend Corrected for multiple comparisons; chemicals selected for further analysis if (a) associated with at least 3 or 9 cases or (b) IARC suspected or known bladder carcinogens Confounding: Ethnicity, marital status, education, questionnaire respondent, alcohol, smoking variables analyzed by backwards stepwise conditional logistic regression	
Exposure Data and Information Assessment	
Exposure: Levels and Co-exposures	***Exposure assessment***
Not reported	Lifetime JEM constructed based on self-reported occupational history and NIOSH NOES (1983–1986) occupational exposure survey using U.S. occupational and industry codes Estimated ever-exposed plus estimated cumulative exposure converted to ordinal scale (0 = no exposure, 1 = low, 2 = medium, 3 = high) Exposure truncated 5 yrs before diagnosis
Assessment of co-exposures and other potential confounders	***Disease Assessment***
No assessment of occupational co-exposures Assessment of non-occupational co-exposures assessed via questionnaire	Histologically confirmed urinary bladder cancer (ICD-9) identified from cancer registry

Castro-Jiménez and Orozco-Vargas 2011	
Related References	**Geographic Location**
None	Colombia
Population Characteristics	
Cases: Selection and ascertainment	***Controls: selection and ascertainment***
Cases: 85 cases of acute lymphoblastic leukemia Case eligibility criteria: All children < 15 years old diagnosed Jan 2000 to Mar 2005 not adopted, living with biological parents, no previous cancer, both parents agree to participate. Identified from hospital registries of 6 tertiary care centers, Colombia	Referents: 85 matched controls Referent eligibility criteria: Healthy, never diagnosed with cancer, not adopted, living with biological parents. Residents of neighborhoods in which cases lived Matching criteria: Matched on sex and age at diagnosis of cases ± 2–3 years; ratio of controls to cases = 1:1
Length of follow-back: (a) 2 years prior to conception; (b) pregnancy to diagnosis of case	
Study Design and Analytical methods	
Hospital-based cases; population-based controls Confounding: crude (using age and sex matched cases and controls) and multivariate analysis considering maternal age, education, breastfeeding, periconceptual disease, maternal disease in pregnancy, urban/rural residency, prenatal parental smoking, parental alcohol or drug use, birth weight, gestational age	
Exposure Data and Information Assessment	
Exposure: Levels and Co-exposures	***Exposure assessment***
List of 13 hydrocarbons or hydrocarbon groups based on IARC classification of known or suspected human carcinogens (Group 2A), including *ortho*-toluidine; levels not reported	JEM based on self-reported parental occupation (industry) and home/environment exposure (questionnaire) *ortho*-Toluidine exposure assigned by occupational physician based on SIC code for parental occupation and agents observed in NIOSH 1983-6 NOES Survey by SIC code
Assessment of co-exposures and confounders	***Disease assessment***
JEM used to assign exposure by occupational physician based on parental questionnaire data using SIC-coded parental occupation and agents observed in NIOSH 1983-6 NOES Survey	Cases of acute lymphoblastic leukemia (ICD NR) identified from institutional registers and histologically verified

Assessment of potential bias, analytical methods, and other study quality characteristics

Biases in observational studies are often classified into three major categories: (1) selection bias, (2) information bias, and (3) confounding (discussed in Section 3.3.2). Studies with lower potential for bias are generally considered to be the most informative for cancer evaluation. However, the presence of a potential bias in a study does not necessarily mean that the findings of the study should be disregarded. Therefore, an important step in the process of evaluating biases is to determine the probable impact of the described biases on study results—that is, the magnitude of distortion and the direction in which each bias is likely to affect the outcome of interest (if known). The impact of the potential bias or confounding on the study findings is discussed in the cancer assessment (see Section 3.4).

For this review, overall conclusions on the concern for the potential (unlikely/minimal, possible, or probable) of selection and information bias and the adequacy of other quality factors (good, adequate, or limited) for each study were made using the questions and guidelines outlined in the protocol. In some cases there is inadequate information to evaluate the level of concern. The guidelines describe the ideal methods and design for each study element. The terms used for defining the potential for bias are as follows:

- Unlikely/minimal: Information from study designs and methodologies indicate that the potential for bias is unlikely or minimal and are close to the ideal study characteristics.
- Possible: Study designs or methodologies are close to but less than ideal, recognizing that in observational studies, there is almost always some methodological or informational limitation and thus some potential for certain types of bias.
- Probable: Study designs or methodologies suggest that the potential for a specific type of bias is likely.
- Unknown: Insufficient information is provided to enable an evaluation to be made.

If adequate information is available, each type of bias is also characterized as to whether it is differential or non-differential. Differential (systematic) biases in the selection of study participants or information assessment are related to both exposure and disease status, and have the potential to bias findings in one direction or another, whereas non-differential (random) biases, which are not related to both exposure and disease, tend to reduce the precision of the risk estimates and often bias the findings toward the null. For example, occupational cohort studies may have limited exposure data across exposure groups, increasing the potential for nondifferential exposure misclassification, and may also have the potential for a healthy worker (hire or survival) effect, a type of selection bias that tends to bias findings away from finding an effect (if present) in studies where the comparison group comes from the general population.

An overview of the approach and conclusions is discussed in Section 3.3 and details of the quality assessment are provided below in Table D-3.

Table D-3. Summary of study quality

Study	Selection bias Attrition bias (Loss to follow-up)	*ortho*-Toluidine exposure assessment: Adequacy	Urinary bladder cancer assessment: Adequacy	Ability to detect an effect for urinary bladder cancer and analytical methods: Adequacy
Case and Pearson 1954 U.K. dye workers	*Selection bias* Possible: healthy worker effect, which would bias positive findings towards the null, is always possible in occupational cohort studies, however, authors did not report all-cause mortality *Loss to follow-up bias* Unknown	*Exposure characterization* Limited: Exposure inferred from process[a] *Misclassification of workers' exposure* Possible (non-differential): exposure not assigned at the individual level; exposure category assigned according to production process	*Misclassification of deaths* Probable (differential): urinary bladder cancers identified and cross-verified via multiple sources for cohort, which may differ from assessment of deaths in the general population. Deaths diagnosed outside region may be missed *Misclassification of cases* Possible (non-differential): mortality studies will miss cases that do not result in death, a concern for urinary bladder cancer, which has a higher survival rate.	*Ability to detect an effect* Limited statistical power: 8.9% power to detect 2-fold increase in risk; Adequate: probability of moderate or higher exposure, exposure ND but likely high since workers were employed in the early 1900's. Adequate length of follow-up for total cohort *Analysis* Limited: observed/expected only, using national comparison data
Pira *et al.* 2010 Italian dye workers	*Selection bias* Possible: all-cause mortality not decreased among total cohort but not reported for *ortho*-toluidine subcohort *Loss to follow-up bias* Possible: 12% of total cohort lost to follow-up before 1989, and <4% lost to follow-up after 1989 but no information on loss to follow-up in *ortho*-toluidine subcohort or	*Exposure characterization* Adequate: specified as part of process by authors; no quantitative exposure data *Misclassification of workers' exposure* Possible (non-differential): individual person years of exposure assigned based on detailed work history; workers did not change departments or jobs	*Misclassification of deaths* Possible (non-differential): diagnosis by death certificates subjected to potential misclassification; ICD codes (if used) not stated *Misclassification of cases* Possible (non-differential): mortality data only	*Ability to detect an effect* Limited statistical power; 11.7% power to detect 2-fold increase in risk. Adequate: probability of moderate or higher exposure: level of exposure ND but likely high because workers were employed in the early 1900's. Adequate length follow-up for total cohort *Analysis* Limited: external mortality analysis by department only

Study	Selection bias Attrition bias (Loss to follow-up)	*ortho*-Toluidine exposure assessment: Adequacy	Urinary bladder cancer assessment: Adequacy	Ability to detect an effect for urinary bladder cancer and analytical methods: Adequacy
	whether loss to follow-up is related to exposure and disease.			
Ott and Langner 1983 U.S. dye workers	*Selection bias* Possible: statistically non-significant decrease in all-cause SMR < 1.0 in subcohort suggests a potential healthy worker effect *Loss to follow-up bias* Unlikely/minimal: follow-up was conducted using company and social security records; no evidence to suggest the potential for bias	*Exposure characterization* Limited: limited quantitative exposure assessment of air and urine at one time point, but estimates likely relevant for only some of the workers[b] *Misclassification of workers' exposure* Probable (non-differential): no information on exposure at the individual subcohort level. Subcohort combined workers making thioindigo dyes with those making bromindigo dyes. o*rtho*-Toluidine appears to have been used as an intermediate in thioindigo dye production but its use in four different processes is unclear. Bromindigo dyes were produced in a different section of the building (separated by a firewall) and did not involve *ortho*-toluidine	*Misclassification of deaths* Possible (non-differential): diagnosis by death certificates *Misclassification of cases* Possible (non-differential): mortality study only	*Ability to detect an effect* Limited statistical power:~15% power to detect 2-fold increase in risk;. Limited probability of moderate or higher exposure: only 77% workers were employed < 5 years; level of exposure known only for one time period and number/extent of workers exposed to *ortho*-toluidine unknown; Adequate length of follow-up for subcohort *Analysis* Limited: external mortality analysis by department and duration of employment; reporting also limited; urinary bladder cancer (observed/expected) only reported for the entire cohort (since there were 0 cases)
Stasik 1988 4-COT production workers	*Selection bias* Probable: differential bias towards finding an effect Incidence study was initiated based on findings of 2 urinary bladder cancer cases while conducting a mortality study of these workers.	*Exposure characterization* Limited:[c] no quantitative exposure assessment; not clear if processing workers were exposed to *o*-toluidine *Misclassification of workers' exposure* Probable (non-differential): no exposure assessment at the individual level	*Misclassification of cases* Probable (differential): poor documentation; cases were identified using unspecified hospitals and other institutes, which may differ from methods used to identify expected cases in regional cancer registry	*Ability to detect an effect* Limited statistical power: 8.5% power to detect 2-fold increase in risk. Limited probability of moderate or higher exposure: level/duration exposure ND. Limited follow-up *Analysis* Limited: external incidence analysis of

Study	Selection bias Attrition bias (Loss to follow-up)	*ortho*-Toluidine exposure assessment: Adequacy	Urinary bladder cancer assessment: Adequacy	Ability to detect an effect for urinary bladder cancer and analytical methods: Adequacy
	Loss to follow-up bias Unknown			workers in 4-COT production department included in analysis only if employed prior to 1970; non-contiguous regional comparison; limited data on cancer endpoints
Carreón *et al.* 2010 NIOSH (U.S.) rubber chemical workers	*Selection bias* Unlikely/minimal in analyses using internal controls, possible in external analysis Statistically non-significant decrease in all-cause mortality among definitely exposed workers suggests a potential healthy worker effect, which would bias towards the null *Loss to follow-up bias* Unlikely/minimal: multiple sources of data used to ascertain vital status at end of follow-up period	*Exposure characterization* Good: extensive quantitative measurement of *ortho*-toluidine in air; also in urine and Hb adducts measured in sample of workers *Misclassification of workers' exposure* Unlikely/minimal (non-differential): workers grouped according to definitely, possibly, and probably not exposed based on updated detailed occupational histories (including jobs and dept.), exposure characterization of work areas/processes by investigators and company plus biological monitoring (described above)	*Misclassification of cases* Unlikely/minimal (non-differential): Incident cases identified and cross-verified via multiple sources Cases not reported to NY State cancer registry would be missed *Misclassification of deaths* Possible (non-differential): death certificates, company records or SSA used to identify deaths	*Ability to detect an effect* Limited statistical power: 30.5% (incidence) and 11.1% (mortality) statistical power to detect 2-fold increase risk among definitely exposed workers. Good probability of moderate or higher exposure: based on extensive industrial hygiene and biomonitoring data. Adequate length of follow-up *Analysis* Good: workers assigned by revised exposure probability category based on individual job history; external (SIR) and SRR both analyzed by duration of employment and TSFE; SMR analyzed only by 1990 exposure categories (definitely, possibly, or probably not exposed); no formal methods for controlling for confounding from co-exposures or smoking but biomonitoring data provide adequate data to evaluate (see Table D.2) and smoking information on subset of workers
Sorahan 2008	*Selection bias* Unlikely/minimal in analyses	*Exposure characterization* Adequate:[d] no quantitative exposure	*Misclassification of cases* Unlikely/minimal (non-	*Ability to detect an effect* Limited statistical power: 17.3% power

Study	Selection bias Attrition bias (Loss to follow-up)	*ortho*-Toluidine exposure assessment: Adequacy	Urinary bladder cancer assessment: Adequacy	Ability to detect an effect for urinary bladder cancer and analytical methods: Adequacy
U.K. rubber chemical workers	using internal controls, possible in external analysis All-cause mortality not reported for *ortho*-toluidine subcohort *Loss to follow-up bias* Unlikely/minimal: 2% (emigration + not traced) for mortality; 3% for incidence	data *Misclassification of workers' exposure* Possible (non-differential): Person-years at risk in *ortho*-toluidine department based on individual work histories	differential): cases identified via national regional cancer registry using ICD-8, 9, and 10 coding) *Misclassification of deaths* Possible (non-differential): national death registry used	to detect 2-fold increase in risk. Adequate: probability of moderate or higher exposure: level/duration exposure ND but levels likely to be high. Adequate length of follow-up for total cohort *Analysis* Good: included external analysis and internal RR analysis by duration of exposure, adjusted for 3 other exposures
Richardson *et al.* 2007 Canadian Case-control study	*Selection bias* Possible: use of cancer cases as controls may bias towards the null if *ortho*-toluidine is a risk factor for those cancers, but unknown if *ortho*-toluidine causes cancers at other sites; participation rate 60% which may increase potential for bias	*Exposure characterization* Limited: study is population-based; JEM is limited because exposure classification by industry and occupation based on a (separate) qualitative walk-through exposure survey in one calendar year; no information on specific jobs *Exposure misclassification* Probable (non-differential): Cumulative exposure is the product of the probability of exposure, based on the limited JEM, and duration of employment based on self-reported occupational history, which may have been subject to recall error.	*Misclassification of cases* Unlikely/minimal (non-differential): Cases and controls identified via cancer registry	*Ability to detect an effect* Good 95% statistical power to detect 2-fold increase in risk (exact power could not be calculated but large number of cases and controls). Unknown probability of moderate or higher levels of exposure: levels/duration exposure ND but likely to be imprecise over lifetime *Analysis* Limited: ORs adjusted for demographic/lifestyle factors but no control for potential confounding by co-exposures; analysis by 3 categories of exposure level but categories likely to be imprecise

FU = follow-up; HWE = healthy worker (hire or survival) effect; JEM = job-exposure matrix; ICD = International Classification of Diseases; ND = not determined; OR = odds ratio; RR = relative risk; SIR = standardized incidence ratio; SMR = standardized mortality ratio; SRR = standardized rate ratio; TSFE = time since first employment.

[a]*o*-Toluidine exposure can be inferred among the magenta production group via knowledge of the processes used in the UK (Howe 1977) (also see Appendix C).

[b]Inadequate data on the thioindigo and bromindigo dye manufacturing process were provided to determine the probability or levels of potential exposure to *ortho*-toluidine and it is not used in conventional methods of making these specific dyes (see Section 2); however, ambient and urine levels of *ortho*-toluidine were reported in only one (1940s) survey.
[c]*ortho*-Toluidine is a precursor in the synthesis of 4-chloro-*ortho*-toluidine (by acetylation of *ortho*-toluidine to producing *N*-acetyl-*o*-toluidine and further chlorination and hydrolysis to produce 4-chloro-*ortho*-toluidine) and would be expected to occur in comparable amounts relative to the product, based on the amount of feedstock (see Section 2); however, no detailed data on the process, or qualitative or quantitative data on levels of *ortho*-toluidine were provided.
[d]*ortho*-Toluidine is the principal precursor in the synthesis of Sopanox (*ortho*-tolylbiguanide) where it is reacted with dicyanamide and hydrochloric acid; workers in the Sopanox department reportedly had "appreciable" exposure to *ortho*-toluidine (Sorahan and Pope 1993).
[e] Number of exposed controls were not provided but were estimated from odds rations and number of exposed cases

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Background carcinogenicity information on co-exposure of interest

Table D-4. Carcinogenicity information on co-exposures of interest[a]

Co-exposure	Studies	Comments	Cancer evaluation	Urinary bladder cancer evaluation
N-acetyl-*o*-toluidine	Stasik 1988[b]		No evaluation	
o-Aminoazotoluene	Pira *et al.* 2010[b]	No human data	IARC Group 2B	Limited evidence in animals
2-Aminobenzoic acid	Ott and Langner 1983[b]	Insufficient data in experimental animals for evaluation	IARC Group 3	
4-Aminobiphenyl	Carreón *et al.* 2010[b]		IARC Group 1 RoC RAHC	IARC/RoC Sufficient evidence in humans
Aniline	Pira *et al.* 2010[c] Sorahan 2008[c] Carreón *et al.* 2010[c]		IARC Group 3	Not a target site in experimental animals; no evidence from human studies
4-Chloro-acetyl-*ortho*-toluidine	Ott and Langner 1983[b]		No evaluation	
4-Chloro-*ortho*-toluidine	Ott and Langner 1983[b] Stasik 1988[c]		RoC RAHC IARC Group 2A	IARC/RoC Limited evidence in humans
6-Chloro-*ortho*-toluidine	Stasik 1988[c]		No evaluation	
2,5-Diaminotoluene	Pira *et al.* 2010[c]	No human data Insufficient data in experimental animals for evaluation	IARC Group 3	
1,2-Dihydroacenaphthylene	Ott and Langner 1983[b]		No evaluation	
Formaldehyde	Case and Pearson 1954[b,e]		IARC/RoC Group 1/Known to be a human carcinogen	Not a target site in humans or experimental animals

Co-exposure	Studies	Comments	Cancer evaluation	Urinary bladder cancer evaluation
Fuchsin (New Magenta)/Magenta III[e]	Case and Pearson 1954[ce] Pira *et al.* 2010[c]	IARC: Magenta production is a known human bladder carcinogen (Group 1); IARC could not separate effects of magenta from its co-exposures (which include *ortho*-toluidine) Magenta I inadequate studies in experimental animals CI Basis Red 9 (IARC/RoC) Sufficient evidence of carcinogenicity in experimental animals (not urinary bladder)	Magenta (not defined) IARC Group 2B CI basic red 9 (Magenta 0/para-magenta) RoC RAHC	
4,4-Methylene-bis (2-methylaniline)	Pira *et al.* 2010[c]	No human data	RoC RAHC IARC Group 2B	Not a target site in experimental animals
2-Mercaptobenzothiazole	Sorahan 2008[c]		Not evaluated	Increased risk in Sorahan study, which is diminished after controlling for exposure to *ortho*-toluidine ; no independent evidence in other epidemiologic studies (Collins *et al.* 1999, Vey 1996)
Nitrobenzene	Ott and Langner 1983[b]	No human data	RoC RAHC IARC Group 2B	Not a target site in experimental animals
ortho-Nitrotoluene	Case and Pearson 1954[b,d] Pira *et al.* 2010[c]	No human data	RoC RAHC IARC Group 2A	Not a target site in experimental animals

Co-exposure	Studies	Comments	Cancer evaluation	Urinary bladder cancer evaluation
phenyl-β-naphthylamine	Sorahan 2008[c]		IARC Group 3	Increased risk in Sorahan study, which is diminished after controlling for exposure to *ortho*-toluidine; no independent evidence
Safranine T	Pira *et al.* 2010[c]		No evaluation	
thioindigo dyes	Ott and Langner 1983[c]		No evaluation	
1-tolylbiguanidine (“Sopanox”)	Sorahan 2008[c]		No evaluation	Product in *ortho*-toluidine dept; no independent evidence

IARC = International Agency for Research on Cancer: Group 1 = carcinogenic to humans, Group 2A = probably carcinogenic to humans, Group 2B = possibly carcinogenic to humans, Group 3 = not classifiable as to its carcinogenicity in humans; RoC = Report on Carcinogens: RAHC = reasonably anticipated to be a human carcinogen.

[a]Carcinogenicity information is reported for co-exposures where there was more than trace amounts of exposure to a chemical (unless it was a known human bladder carcinogen); carcinogenicity information was obtained from IARC and RoC evaluations or from literature searches (in the absence of an IARC or RoC evaluation).

[b]Little evidence of exposure.

[c]Probably exposed.

[d]According to Howe (1977), U.K. magenta was prepared by condensing *ortho*-toluidine with formaldehyde in the presence of *ortho*-nitrotoluene as an oxidizing agent.

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Appendix E: Assessment of the Quality of the Individual Animal Cancer Studies on exposure to *ortho*-toluidine

Seven publications, reporting on eleven studies, were identified that were either long-term carcinogenicity studies or reported neoplastic lesions in experimental animals exposed to *ortho*-toluidine (See Section 4, Cancer studies in Experimental Animals). Each of these primary studies was systematically evaluated in a two-step process by first evaluating whether the level of detail reported for key elements of study design, experimental procedures, and cancer endpoints was adequate for evaluating its quality and interpreting its results. Studies that were adequately reported were further evaluated for concerns for study quality that might negatively impact the ability to assess carcinogenicity. Those studies with adequate reporting and that did not have major concerns of study quality are included in the cancer assessment described in Section 4, Cancer Studies in Experimental Animals.

Adequacy of reporting for *ortho*-toluidine studies

The reporting quality of key elements for two of the eleven studies was considered to be inadequate for cancer evaluation: a study in mice exposed to *ortho*-toluidine by subcutaneous injection (Pliss 2004) and a tumor initiation study in genetically altered fish (Anders *et al.* 1991). In the study in mice, the total number of animals exposed, and the duration period were not clearly defined; the authors noted that some deaths occurred in the exposed animals, and more animals were added later, but did not provide any details on the cause of death, the exposure duration of the animals that died, and the timing of the addition of new mice to the study.

There is no reference to validation or standardization of this fish model for cancer detection. The almost complete lack of description of study design, study validation, and data analysis make this study inadequate for evaluation of carcinogenicity. The reporting is inadequate for details such as the tumor incidence of untreated fish, necropsy procedures, the sex used, dose selection rationale or toxicities, duration of observation, and purity of chemical.

Study quality assessment

Tables E-1 (rats) and E-2 (other animals) report the assessment of nine studies that were considered to have adequate reporting quality, including feeding studies in rats (Weisburger *et al.* 1978, NCI 1979, Hecht *et al.* 1982, NTP 1996), mice (Weisburger *et al*. 1978, NCI 1979) dogs (Pliss 2004) and subcutaneous injection studies in hamsters (Hecht *et al.* 1983) and rats (Pliss 2004). Study quality was assessed using questions related to the following study performance elements: substance characterization, animal husbandry, study design, endpoint assessment, and data interpretation. In most cases, each question inquires whether there are concerns (minimal, some, major, unknown, i.e., no information reported) that the quality of a specific study element is adequate for attributing any neoplastic endpoints to exposure to *ortho*-toluidine. In general, the

ranking of the concerns for the study elements is based on how far each study element deviates from the ideal (see below).

The assessment of the overall quality of a study is based on consideration of the individual elements and how they impact the usefulness of that study in assessing carcinogenicity. Studies that were given the most weight in the evaluation (e.g., those with no or minimal concerns in key elements) are those with the following characteristics:

- Use a chemical that is representative of the candidate substance (in terms of purity and stability) so that any observed effects can be attributed to the candidate substance.
- No evidence of poor animal husbandry conditions (such as high mortality due to infection). Often information on animal husbandry conditions is not known and while this information is desirable, it is not a requirement.
- Exposure of animals to high enough doses (resulting in tolerable toxicities) for a sufficiently long duration (approaching the lifetime of the animal), but not to a dose that limits survival over the exposure period. The use of more than one dose level is ideal, but is not a requirement.
- Have an appropriate comparison group (e.g., ideally unexposed, sham treated concurrent controls). The absence of an appropriate control group, by itself, is sufficient for judging a study to be inadequate for cancer evaluation.
- Have adequate statistical power to detect an effect, which is based on the number of animals used in a study, the incidence of tumors in control vs. treated group, and the rarity of the tumor.
- Perform full necropsies and histopathological examinations on all tissues. Ideally, animals are exposed to multiple doses that allow for statistical comparisons to the control group and dose-response analysis.

An ideal study would have the following characteristics, which are related to interpreting the study. In general, with the exception of route of exposure, these do not contribute as much weight to the overall evaluation of the study as the characteristics related to the validity of the study discussed above.

- The use of an exposure route comparable to human exposure.
- The use of animal model that is sensitive for detecting tumors and does not have high background rates for the observed tumors. Studies in both sexes are more informative than those testing only one sex. Often this information is not available.
- Availability of historical control data, which can helpful in assessing the significance of a finding, especially in the case of rare tumors, lower powered studies, or assessment of background tumor incidences. Rare tumors will be considered in the assessment even if their incidences do not reach significance.
- Appropriate reporting of incidence data and statistical methods. If statistical tests are not reported, the study should at a minimum present incidence data for specific tumors so that statistical tests can be run.

Studies having elements that are judged to have some or major concerns may still be considered in the evaluation or can be considered to provide support to the more informative studies. It should also be noted that some concerns about a study element (such as inadequate observation and exposure period and statistical power) would decrease the sensitivity of a study to detect an effect; however, if despite these limitations positive findings were described, these studies would inform a cancer assessment. In contrast, other concerns (poor purity of the chemical) may lead to false positive or false negative results, and thus in general, studies having major concerns are considered to be inadequate for cancer evaluation.

Table E-1. Assessment of the quality of cancer studies in rats

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1982	NTP 1996	Pliss 2004
Substance characterization					
Are there concerns that the purity solubility and stability of the chemical are not adequate for attributing any neoplastic effects to the substance?	**Concerns: minimal** Tested for purity, but only a non-specific purity was reported as 97% to 99% for most chemicals. Stability was only tested for 3 days and results were not reported.	**Concerns: minimal** Purity was tested and found to be >99% . Stability testing was not reported.	**Concerns: minimal** Reported as purified by recrystallization and melting point determination. No stability tests were reported.	**Concerns: minimal** Purity (100%) and stability in feed tested.	**Concerns: minimal** Purity reported as > 99.7% with 0.2% *p*-toluidine as a contaminant. No stability tests were reported.
Animal husbandry					
Are there concerns that the quality of the animal husbandry (e.g., care, diet, maintenance and disease surveillance) is not adequate for attributing any neoplastic effects to the substance?	Few details were reported.	**Concerns: minimal**	**Concerns: some** No information on disease surveillance. Housing, diet described.	**Concerns: minimal** Studies done under U.S. FDA Good Laboratory Practice regulations; subclinical disease surveillance performed.	Minimal information on housing reported. No other information reported.
Study design					
Are there concerns that the study design did not include randomization of animals to dose groups and blinding of dose groups?	No information reported	No information reported	No information reported	**Concerns: minimal** Animals were distributed randomly into groups of approximately equal initial mean body wts.	No information reported

	Weisburger *et al.* 1978	**NCI 1979**	**Hecht *et al.* 1982**	**NTP 1996**	**Pliss 2004**
Are there concerns that the dosing regimen (dose selection and dose groups, or other factors) is either not adequate for detecting a neoplastic effect (if present) or for attributing any tumor effects to the substance?	**Concerns: minimal** Two dose levels were tested and were based on the "maximum tolerated dose" of a 30-day study. Results of the 30-day study were not reported. Initial doses caused >10% body weight loss and were decreased after 3 months.	**Concerns: minimal** Two dose levels were tested and were based on the "MTD" of a 7-week study. These dose levels did not significantly decrease survival.	**Concerns: minimal** Only one exposed dose level tested; dose was toxic based on decreased survival after 88 wk (20% survival) compared to untreated controls (60% survival). Survival in control and treated groups comparable through week 68 of study.	**Concerns: minimal** One dose level tested, dose was toxic based on decreased of body weight gain (up to 27%) in the exposed group.	**Concerns: some** Only one dose level (30 mg, s.c.) tested, reported as "maximally tolerated dose;" however, no other information was provided
Are there concerns that the study duration (exposure and observation) is not adequate to detect a neoplastic effect, if present?	**Concerns: minimal** Exposure occurred for 18 months and observation was for 2 years.	**Concerns: minimal** Exposure and observation occurred for two years.	**Concerns: minimal** The exposure (73 wk) and observation duration (93 wk) were adequate although do not quite meet the ideal conditions of close to lifetime exposure.	**Concerns: major** Exposure (13 wk) and observation (26 wk) durations were short, only one dose level.	**Concerns: minimum** Study duration 2 years
Are there concerns that the concurrent control group was not adequate for evaluating the study?	**Concerns: minimal** A single group control and pooled control were used.	**Concerns: minimal** A concurrent control group was used that had less, but still sufficient numbers of, mice (20 per sex) than the exposed groups (50 per sex).	**Concerns: minimal**	**Concerns: minimal**	**Concerns: minimal**

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1982	NTP 1996	Pliss 2004
Are there concerns that the study does not have adequate statistical power (number of animal per exposure and control group) to detect a neoplastic effect, if present?	**Concerns: some** 25 animals per exposed group and untreated control group, though a pooled control group had 111 animals.	**Concerns: minimal**	**Concerns: minimal** 30 males per exposed group. Some concern for rare tumors.	**Concerns: some** 20 animals per exposed group in the exposed groups; 10 animals in untreated control group.	**Concern: some** 25 animals per exposed group and untreated controls.
Endpoint assessment					
Are there concerns that the assessment of study outcome (gross and microscopic tissue analysis) was not done blind?	No information reported	No information reported	No information reported	No information reported	No information reported
Are there concerns that the methods to access tumor outcome and the pathology procedures (necropsy, histology, or diagnosis) are not adequate for attributing the effects?	**Concerns: minimal** Complete necropsies and histological examinations were done on all major organs and gross lesions of animals that died after the first 6 months.	**Concerns: minimal** Complete necropsies and histological examinations were done on all major organs and gross lesions.	**Concerns: minimal** Complete necropsies and histological examinations were done on all major organs and gross lesions.	**Concerns: minimal** Complete necropsies and histological examinations were done on all organs and confirmed by an independent pathology laboratory.	**Concerns: some** Necropsies and histology were performed; however, it is unclear whether all major organ systems were examined.
Data interpretation					
Are there concerns that survival-related effects could affect attributing the study findings to exposure?	**Concerns: minimal** No treatment related survival effects.	**Concerns: some** Decrease in survival at the high-dose group in both sexes. The study of males was stopped three weeks early because of low survival.	**Concerns: some** Survival was decreased to 20% in the exposed group compared with 60% in the untreated controls; however, survival did not sharply	**Concerns: minimal** No treatment related survival effects	**Concerns: some** Authors state that 30 animals (presumably of the 50 males and females combined) were available after 19.5 months and that 38 of 50

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1982	NTP 1996	Pliss 2004
			decrease until 18 months exposure.		controls survived until 23 months
Are there concerns that the route of exposure is not adequate for evaluating the potential for human carcinogenicity?	**Concerns: minimal** Feeding	**Concerns: minimal** Feeding	**Concerns: minimal** Feeding	**Concerns: minimal** Feeding	**Concerns: some** Subcutaneous exposure
Are there concerns about the animal model (source, species, strain, or sex) that could affect study interpretation?	**Concerns: some** Only males were tested.	**Concerns: minimal**	**Concerns: minimal** Only male Fischer 344 rats were tested; concerns would be if no effects were observed.	**Concerns: minimal** Only male Fischer 344/N rats were tested; concern would be if no effects were observed.	**Concerns: some** An unspecified strain of male and female rats from an unreported source were tested.
Are historical control data reported? If not this would be a concern for rare tumors, or tumors with high background.	**No**	**Yes**	**No**	**No**	**No**
Are there concerns that reporting of the data and statistical analyses are inadequate for evaluating the results?	**Concerns: minimal**	**Concerns: minimal**	**Concerns: some** Authors used chi-squared method to test for statistical significance, but no evidence that analyses were on o-tol exposed vs. control animals. Incidence data was available to perform pairwise comparisons using Fisher exact test.	**Concerns: minimal**	**Concerns: major** Data were not presented in a format that would allow for statistical analyses. All tumors combined for statistical analyses; no comparison of tumor burden to controls.

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1982	NTP 1996	Pliss 2004
Overall assessment of study quality and utility for cancer assessment					
Does this study have utility for cancer assessment? What is the overall level of concern for the quality of the study, and how would any concerns affect its interpretation?	**Yes**, minimal concerns in most key elements	**Yes**, minimal concerns in most key elements;	**Yes**, minimal concerns in most key elements	Positive findings (such as neoplasia, pre-neoplastic lesions), **yes**, minimal concerns Negative findings, **no**, major concerns Insufficient exposure and observation duration period.	**Yes**, some concerns: Most of the concerns would affect negative findings: one dose level, limited statistical power, uncertainty of completeness of necropsies

Table E-2. Assessment of the quality of cancer studies in other experimental animals: mice, hamsters, and dogs

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1983 (hamsters)	Pliss 2004 (dogs)
Substance characterization				
Are there concerns that the purity solubility and stability of the chemical are not adequate for attributing any neoplastic effects to the substance?	**Concerns: minimal** Tested for purity, but only a non-specific purity was reported as 97% to 99% for most chemicals. Stability was only tested for 3 days and results were not reported.	**Concerns: minimal** Purity was tested and found to be >99%. Stability testing was not reported.	**Concerns: minimal** Reported as "pure" as determined by gas and thin layer chromatography; no stability tests were reported.	**Concerns: minimal** Purity reported as > 99.7% with 0.2% *p*-toluidine as a contaminant. No stability tests were reported.

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1983 (hamsters)	Pliss 2004 (dogs)
Animal husbandry				
Are there concerns that the quality of the animal husbandry (e.g., care, diet, maintenance and disease surveillance) is not adequate for attributing any neoplastic effects to the substance?	Few details were reported.	**Concerns: minimal**	**Concerns: some** No information on disease surveillance. Housing, diet described.	Minimal information on housing reported. No other information reported.
Study design				
Are there concerns that the study design did not include randomization of animals to dose groups and blinding of dose groups?	No information reported	No information reported	No information reported	No information reported
Are there concerns that the dosing regimen (dose selection and dose groups, or other factors) is either not adequate for detecting a neoplastic effect (if present) or for attributing any tumor effects to the substance?	**Concerns: minimal** Two dose levels were tested and were based on the "maximum tolerated dose" of a 30-day study. Results of the 30-day study were not reported. Initial doses caused >10% body weight loss and were decreased after 3 months.	**Concerns: minimal** Two dose levels were tested and were based on the "MTD" of a 7-week study. These dose levels did not significantly decrease survival.	**Concerns: minimal** Only one dose level tested, dose was toxic based on decreased survival in the exposed group compared to control group.	**Concerns: some** Maximum tolerated dose exceeded (125 mg/kg, s.c.) in the first month; route of exposure changed to gelatin capsules by mouth for first month followed by gavage. No further lethal toxicities. Only one dose group (125 mg/kg) was tested.
Are there concerns that the study duration (exposure and observation) is not adequate to detect a neoplastic effect, if present?	**Concerns: minimal** Exposure occurred for 18 months and observation was for 21 months.	**Concerns: minimal** Exposure and observation occurred for two years.	**Concerns: some** The duration of exposure (52 wk) was short at 52 wk, observation duration (87 wk) was adequate although does not quite meet ideal condition (lifetime 2.5–3 yr).	**Concerns: minimal** Exposed close to lifespan (9 years)

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1983 (hamsters)	Pliss 2004 (dogs)
Are there concerns that the concurrent control group was not adequate for evaluating the study?	**Concerns: minimal** A single group control and pooled control were used.	**Concerns: minimal** A concurrent control group was used that had less, but still sufficient numbers of, mice (20 per sex) than the exposed groups (50 per sex).	**Concerns: minimal**	**Concerns: major** No untreated control group was tested
Are there concerns that the study does not have adequate statistical power (number of animal per exposure and control group) to detect a neoplastic effect, if present?	**Concerns: some** 25 animals per sex per exposed group and untreated control group, though a pooled control group had 99 males and 102 females.	**Concerns: minimal**	**Concerns: some** 15 animals per group per sex	**Concerns: major** Only 3 dogs were exposed for more than 3 years
Endpoint assessment				
Are there concerns that the assessment of study outcome (gross and microscopic tissue analysis) was not done blind?	No information reported	No information reported	No information reported	No information reported
Are there concerns that the methods to access tumor outcome and the pathology procedures (necropsy, histology, or diagnosis) are not adequate for attributing the effects?	**Concerns: minimal** Complete necropsies and histological examinations were done on all major organs and gross lesions of animals that died after the first 6 months.	**Concerns: minimal** Complete necropsies and histological examinations were done on all major organs and gross lesions.	**Concerns: minimal** Complete necropsies and histological examinations were done on all major organs and gross lesions.	**Concerns: some** Necropsies and histology were performed; however, it is unclear whether all major organ systems were examined.

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1983 (hamsters)	Pliss 2004 (dogs)
Data interpretation				
Are there concerns that survival-related effects could affect attributing the study findings to exposure?	**Concerns: minimal** No treatment related survival effects.	**Concerns: minimal** No treatment related survival effects.	**Concerns: some** Mean survival time (wk) was decreased in the exposed groups compared to the untreated controls (males 61.3 vs. 75.5; and females 57.8 vs. 68.7); may have decreased sensitivity for late occurring neoplasms.	**Concerns: some** Authors state that 2 of the 5 dogs died within a month after exposure, a 3rd dog died after ~ 3 yrs.
Are there concerns that the route of exposure is not adequate for evaluating the potential for human carcinogenicity?	**Concerns: minimal** Feeding	**Concerns: minimal** Feeding	**Concerns: some** Subcutaneous exposure	**Concerns: minimal** Feeding/gavage
Are there concerns about the animal model (source, species, strain, or sex) that could affect study interpretation?	**Concerns: minimal**	**Concerns: minimal**	**Concerns: minimal** Both sexes of Syrian Golden hamsters were tested.	**Concerns: minimal** Dog considered to be a sensitive model human urinary bladder cancer.
Are historical control data reported? If not this would be a concern for rare tumors, or tumors with high background.	**No**	**Yes**	No	No
Are there concerns that reporting of the data and statistical analyses are inadequate for evaluating the results?	**Concerns: minimal**	**Concerns: minimal**	**Concerns: major** Incidence data and statistical analyses were not reported. Stated that the incidence was not significantly different from control group.	**Concerns: major** No statistics were reported.

	Weisburger *et al.* 1978	NCI 1979	Hecht *et al.* 1983 (hamsters)	Pliss 2004 (dogs)
Overall assessment of study quality and utility for cancer assessment				
Does this study have utility for cancer assessment? What is the overall level of concern for the quality of the study, and how would any concerns affect its interpretation?	**Yes**, minimal concerns in most key elements	**Yes**, minimal concerns in most key elements	**Yes**, some concerns in key elements. Most of the concerns would affect negative findings: short duration of exposure and observation; only one dose, limited statistical power	**No**, major concerns with key elements The lack of concurrent controls prevents attributing any tumor findings to exposure.

To return to text citing Appendix E, click here.

To return to text citing Appendix E in Section 4, click here.

Appendix F: Data tables for genotoxicity and other relevant data

The 14 tables on the following pages contain data discussed in the "Mechanisms and Other Relevant Effects" section

Genotoxicity data are reported for *in vitro* studies of *ortho*-toluidine mutagenicity in bacteria and yeast (Table F-1), co-mutagenic effects of *ortho*-toluidine and norharman in bacteria (Table F-2), genetic effects of *ortho*-toluidine in non-mammalian eukaryotes (Table F-3), *in vitro* genotoxicity studies of *ortho*-toluidine in mammalian cells (Table F-4), cell transformation studies of *ortho*-toluidine in rodent cells (Table F-5), DNA adducts from *ortho*-toluidine exposure *in vivo* (Table F-6), *ortho*-toluidine-releasing DNA adducts in bladder tissue from cancer patients and sudden death victims (Table F-7), genotoxicity effects of *ortho*-toluidine *in vivo* (Table F-8), mutagenicity of *ortho*-toluidine metabolites (Table F-9), hemoglobin and albumin adducts formed *in vitro* and *in vivo* (Table F-10).

To return to text citing Appendix F, click here.

Table F-1. Genetic effects of *ortho*-toluidine in bacteria

Bacteria strains	Endpoint	Res. [a] – S9	Res. [a] + S9	HID (μg/plate)[b]	LED (μg/plate)[b]	Comments
S. typhimurium TA92 TA100 TA102 TA1535 G46	Reverse mutation (base pair: plate incorporation, pre-incubation, or fluctuation method)	0/1 0/26 0/2 0/17 0/1	0/1 5/26 0/2 0/18 0/1	2000 10000 10000 10000 1000 μg/mL	1000 μg/mL	TA100 positive in one study with 30% hamster S9 but negative with rat S9. Two positive studies with rat S9 (30%) and one positive study with the fluctuation test with rat S9. Most recent study (An *et al.* 2010) reported weak positive response in TA100 with rat S9 (concentration not specified) at 2,000 to 4,000 μg/plate
S. typhimurium TA97 TA98 TA1537 TA1538 C3076 D3052	Reverse mutation (frameshift: plate incorporation, pre-incubation, or fluctuation method)	0/3 0/25 0/16 0/15 0/1 0/1	0/3 2/26 0/16 2/16 0/1 0/1	10000 10000 10000 10000 1000 μg/mL 1000 μg/mL	500 μg/mL 1250 μg/mL	One positive study with TA98 required 30% rat S9. The other positive study with TA98 required phenobarbitol-induced rat S9. One positive study with TA1538 used the fluctuation test and a mixed-induced S9 (phenobarbitone + β-naphthoflavone) and the other positive study used the standard plate incorporation method and Aroclor-induced rat S9.
S. typhimurium TA98 TA100	Reverse mutation (host-mediated assay)	0/1 0/1	1/1 0/1	1000 1000	500	Urine extracts from rats administered 300 mg/kg *o*-toluidine was mutagenic in TA98 with 30% hamster S9.
S. typhimurium BA13 TM677	Forward mutation arabinose resistance 8-azaguanine resistance	NT 0/1	1/1 0/2	965 500	480	BA13 positive only with 30% rat S9, negative with 10% rat S9 at 965 μg/plate. TM677 studies used standard protocols with Aroclor or phenobarbitol induced rat liver S9.
S. typhimurium TA1535/pSK102	Prophage induction, SOS repair, DNA strand breaks or cross-links	0/1	0/1	1670		

Bacteria strains	Endpoint	Res. [a] – S9	Res. [a] + S9	HID (μg/plate)[b]	LED (μg/plate)[b]	Comments
E. coli WP2 *uvrA*	Reverse mutation	0/5	1/5	1000	50 μg/mL	Positive in one study with 10% rat S9 but negative in four other studies.
E. coli EMT-1,-2,-3,-4	Zorotest lambda prophage, *gal* gene expression	0/1	0/1	5000		
E. coli JC2921 JC5519	rec assay (growth inhibition)	0/1 0/1	1/1 1/1	NR	NR	Negative in four other DNA repair deficient strains (JC7623, 7689, 8471, and 9238).
E. coli *rec* strains	Differential toxicity	1/3	0/2	2500	20 μL/disc	Positive result was not confirmed in repeat studies in two different labs.
E. coli W3110 (pol A^+) P3478 (pol A^-)	Differential toxicity (liquid suspension)	0/1	0/1	250		No difference in survival in the polymerase deficient strain compared to the wild type strain.
E. coli 58-161 envA C600	Prophage lambda induction, SOS repair	NT	1/1		2500	Tested with metabolic activation only. Chemical-induced induction was 25 fold greater than spontaneous induction.
B. subtilis H17 rec^+ M45 rec^-	rec assay (DNA damage)	1/1	1/1		NR	Only one study conducted. Used the more sensitive spore method rather than vegetative cells. Only reported the maximum dose tested (20 μL/disc). Rat and yellowtail fish S9 used.

Sources: An *et al*. 2010, Danford 1991, IARC 2010a.
HID = highest ineffective dose, LED = lowest effective dose, NR = not reported, NT = not tested, Res. = Results.
[a]Number of positive studies/number of studies reviewed.
[b]HIDs are the same value with or without S9. Since no studies were positive without S9, the LEDs values apply only to the few positive studies with S9.
To return to text citing Table F-1, click here.

Table F-2. Co-mutagenic effects of *ortho*-toluidine and norharman in bacteria

Bacteria strains	Endpoint	Results[a] – norharman (HID/LED μg/mL)	Results[a] + norharman (HID/LED μg/mL)	Reference
S. typhimurium TA98 TA100	Reverse mutation (plate incorporation)	 – (100) – (100)	 + (20) + (20)	Nagao *et al.* 1978 (cited in Danford 1991)
S. typhimurium TA98 TA100 TA1537	Reverse mutation (plate incorporation)	 – (500) – (500) – (500)	 + (25) + (25) + (25)	Nagao and Takahashi 1981 (cited in Danford 1991)
S. typhimurium TA98	Reverse mutation (pre-incubation)	– (25)	+ (25)	Nagao *et al.* 1978 (cited in Danford 1991)
S. typhimurium TA98 TA100 TA1535 TA1538	Reverse mutation (pre-incubation)	 – (100) – (100) – (100) – (100)	 + (20) – (100) – (100) + (20)	Sugimura *et al.* 1982 (cited in Danford 1991)
S. typhimurium TA98	Reverse mutation (pre-incubation)	– (100)	+ (100)	Mori *et al.* 1996
S. typhimurium TA98	DNA adducts	– (4 mg)	+ (4 mg)	
S. typhimurium YG1024	DNA adducts	– (4 mg)	+ (4 mg)	Hada *et al.* 2001

– = negative, + = positive, HID = highest ineffective dose, LED = lowest effective dose.
[a]All positive responses occurred with metabolic activation.
To return to text citing Table F-2, click here.

Table F-3. Genetic effects of *ortho*-toluidine in non-mammalian eukaryotes

Test system	Endpoint	Results[a] – S9	Results[a] + S9	HID (µg/mL)	LED (µg/mL)
Aspergillus nidulans	Forward mutation	0/1	NT	504	
	Genetic crossing-over	0/1	NT	2520	
Saccharomyces cerevisiae	Differential toxicity	1/2	1/2	1000	300
	Gene conversion	1/8	2/8	2000	50
	Mutations	2/8	1/7	2500	378
	Deletion assay	2/2	1/1		1000
	Interchromosomal recombination	0/2	0/2	8000	
	Aneuploidy	2/3	2/2	1.5 µL/mL	50
Schizosaccharomyces pombe	Forward mutation	0/1	0/1	1920	
Drosophila melanogaster	Somatic mutation and recombination	5/6		2 mM (feed)	0.94 mM (feed)

Sources: Danford 1991, IARC 2010a.
HID = highest ineffective dose, LED = lowest effective dose, NT = not tested.
[a]Number of positive studies/number of studies reviewed.
To return to text citing Table F-3, click here.

Table F-4. *In vitro* genetic toxicology studies in mammalian cells

Endpoint	Cell type (assay)	Results[a] –S9 No. studies	LED (μg/mL)	HID (μg/mL)	Results[a] + S9 No. studies	LED (μg/mL)	HID (μg/mL)
Human cells							
DNA damage/strand breaks	MCL-5[b] (comet assay)	1/1	454				
	Exfoliated milk cells[b] (comet assay)	1/1	[91]				
	Urinary bladder mucosa[b] (comet assay)	1/1	[1714]				
Unscheduled DNA synthesis	HeLa cells	0/3		250	3/3	25	
Gene mutations	TK6 lymphoblasts (TK)	0/1		750	1/1	450	
	AHH-1 lymphoblasts[b] (HGPRT)	1/1	300				
Sister chromatid exchange	Lymphocytes	1/2[c]	[21.4]		0/1		600
Micronucleus	Lymphocytes	1/1	[214]		0/1		[960]
Rodent cells							
DNA damage/strand breaks	Rat hepatocytes[b] (alkaline elution)	1/1	319				
	Rat urinary bladder mucosa[b] (comet assay)	1/1	[857]				
	Chinese hamster ovary (CHO) (alkaline sucrose gradient)	1/2	4280	5360	2/2	2140	
Unscheduled DNA synthesis	Rat hepatocytes[b]	1/6	107	53.5			
	Syrian golden hamster hepatocytes[b]	0/2		10.7			
Gene mutations	CHO (*Hprt*, ouabain resistance)	0/1		500	?/1		
	Chinese hamster lung (CHL) V79 (*Hprt*, ouabain resistance)	1/4	500	2000	0/4		1000
	Mouse lymphoma L5178Y (*Tk*)	2/6	10	1004	0/5		1004
	Mouse lymphoma L5178Y (*Hprt*)	1/2	200	1300	1/2	200	1300

Endpoint	Cell type (assay)	Results[a] –S9 No. studies	LED (μg/mL)	HID (μg/mL)	Results[a] + S9 No. studies	LED (μg/mL)	HID (μg/mL)
	L5178Y (ouabain resistance)	0/2		1004	0/2		1004
	Mouse BALB/c 3T3 (ouabain resistance)				1/1	250	
Sister chromatid exchange	CHO	3/5	300	[2140]	1/5	?	[2140]
	CHL	1/1	268		1/1	268	
	Rat liver epithelial cells (RL_4)[b]	1/1	21.8				
	CHO (plasma from exposed rats)	1/1	400[d]				
Chromosomal aberrations	Chinese hamster liver fibroblasts (CH1-L)[b]	1/1	12				
	CHO	1/3	500	[2140]	2/3	250	[2140]
	CHL	0/1		1500	1/1	1000	
	RL_4[b]	1/1	700				
Micronucleus	CHO	0/1		[4286]	0/1		[4286]
	Syrian hamster embryo (SHE)	1/1	NR				
Aneuploidy/ polyploidy[e]	CH1-L[b]	1/1	60				
	CHL	1/1	1000		0/1		1500
	RL_4[b]	0/1		700			
Mitotic spindle	CH1-L[b]	0/1		120			
Inhibition cellular communication	CHL V79[b]	2/3	5	535			

Sources: Danford 1991, IARC 2010a, Martin *et al.* 2000a, Martin *et al.* 2000b (DNA damage in human exfoliated milk cells), Robbiano *et al.* 2002 (DNA damage in human bladder mucosa and rat bladder mucosa cells).
HID = highest ineffective dose, LED = lowest effective dose, NR = not reported, ? = inconclusive
[ ] Indicates data provided by original author (e.g., as molarity) was converted to μg/ml for ease of comparison.
[a]Number of positive studies/number of studies reviewed.
[b]Cells with an intrinsic metabolizing system; no testing +S9.

[c]One test was positive and the other was inconclusive.
[d]*In vivo* metabolism: CHO cells exposed to plasma from rats treated with 400 mg/kg *ortho*-toluidine.
[e]All studies examined 100 metaphases with 2 to 3 replicates/dose and compared results to negative and positive controls.
To return to text citing Table F-4, click here.

Table F-5. Cell transformation studies of *ortho*-toluidine in rodent cells

Cell type	Results – S9	Results + S9	HID (μg/mL)	LED (μg/mL)	Reference
Mouse BALB/c 3T3	–	NT	2		Maeshima *et al.* 2010
	+[a]	NT		800	Tanaka *et al.* 2012
	–	+	330	150	Matthews *et al.* 1985
Mouse Bhas 42[b] initiation assay promotion assay	 – +	 NT NT	800	 300	Sakai *et al.* 2010
Syrian hamster embryo (SHE) cells[c]	+	NT		50	Ahmadzai *et al.* 2012
	+[d]	NT		40	Pant *et al.* 2012
	+	NT		20–600[e]	Maire *et al.* 2012
	+	NT		1	Barrett and Lamb 1985
	+	NT		100	Sanner and Rivedal 1985
	+	NT		750	Kerckaert *et al.* 1998
SHE-SA7[c]	(+)	NT		965	Hatch and Anderson 1985
Mouse C3H/10T1/2	–	(+)		600	Lawrence and McGregor 1985
	+	NT		500	Nesnow *et al.* 1985
Chinese hamster ovary cells	–	–	500		Zdzienicka *et al.* 1985
Baby hamster kidney (BHK-21) cells	+	+		362	Daniel and Dehnel 1981
	NT	+		250	Styles 1981
RLV/F344 rat embryo cells[c]	(+)	NT		10	Suk and Humphreys 1985

– = negative, + = positive. (+) = weak positive.
HID = highest ineffective dose, LED = lowest effective dose, NT = not tested, RLV =Rauscher-leukemia virus, SA7 = Simian Agent 7 adenovirus.
[a]Tested in three labs: initial results were positive in 2 labs and negative in another although the number of foci was increased at the highest dose. Retest was clearly positive.
[b]BALB/c 3T3 clone transfected with an oncogenic murine *ras* gene (v-Ha-*ras*).
[c]Cells with an intrinsic metabolizing system.
[d]Tested in three labs: initial result in one lab was inconclusive due to cytotoxicity. Retest at lower concentration was positive.
[e]Tested positive in four labs but different LEDs in each lab.
To return to text citing Table F-5, click here.

Table F-6. DNA adducts from *ortho*-toluidine exposure *in vivo*

Reference	Sex:species (no/group)	Tissue	Exp. Route[a]	Dose or HID/LED (mg/kg)	Results	Evaluation: comments
Brock *et al.* 1990	M:Crl:CD rats (4-5)	Liver	gavage	500	< 1 pmol/µg	Positive: binding peaked at 24 hr. Levels were lower than measured with *para*-toluidine (see Section 5.2.2), specific adduct was not identified
Jones and Sabbioni 2003	F:Wistar rats (2)	Liver	gavage	~54[b]	Possible dG adduct	Negative: tentatively identified dG adduct determined to be false positive. Detection limit: < $3.1/10^8$ bases
Duan *et al.* 2008	M:F344 rats (3)	liver nose bladder WBCs	gavage (1 or 7 daily doses)	54 54 322 322	$1.2/10^7$ nt $0.55/10^7$ nt ND ND	Positive: liver and nasal mucosa, single and multiple doses, specific adducts were not identified Negative: urinary bladder and WBCs Detection limit: ~$1/10^8$ bases

Exp. = Exposure, HID = highest ineffective dose, LED = lowest effective dose, ND = not detected, nt = nucleotides, WBCs = white blood cells.
[a]Single dose unless otherwise noted.
[b]Administered 0.5 mM/kg = ~54 mg/kg.
To return to text citing Table F-6, click here.

Table F-7. *ortho*-Toluidine-releasing DNA adducts (fmol/µg DNA ± S.D.)in bladder tissue from cancer patients (CP) and sudden death victims (SDV)

Group	CP			SDV	
	(N)	Epithelial	Submucosal	(N)	Bladder tumor
Non-smokers	27	0.136 ± 0.280	0.292 ± 0.784	7	10.580 ± 3.055***
Smokers	19	0.378 ± 0.910	0.232 ± 0.571	5	6.120 ± 5.193*
All	46	0.236 ± 0.625	0.267 ± 0.697	12	8.722 ± 4.491***

Source: Böhm *et al.* 2011.
*$P < 0.05$ (Mann-Whitney test; compared with bladder tissue from sudden death victims).
***$P < 0.001$ (Mann-Whitney test; compared with bladder tissue from sudden death victims).
To return to text citing Table F-7, click here.

Table F-8. Genotoxic effects of *ortho*-toluidine *in vivo*

Reference	Test system (time after dosing hr)	Sex:species (no/group)	Tissue	Exp. Route[a]	Dose or HID/LED (mg/kg)	Results	Evaluation: comments
Cesarone *et al.* 1982	DNA SSB (4)	M: Swiss CD1 mice (8)	liver kidney	i.p.	0 100 0 100	21×10^{-3}/mL[b] 63×10^{-3} 22×10^{-3} 51×10^{-3}	Positive: Results reported as mean elution rate (see footnote).
Robbiano *et al.* 2002	DNA damage (20)	M: Sprague-Dawley rats (3)	bladder kidney liver	gavage	¼ LD_{50}[c] ½ LD_{50} ½ LD_{50} ½ LD_{50}	7.4* 9.7* ~ 1 ~ 1	Positive (bladder): Comet assay. Results reported as the ratio of treated/control tail moment. Negative (kidney and liver)
Neal and Probst 1983	SCE (18)	F: Chinese hamsters (3)	bone marrow	i.p. or gavage[d]	0 100 200 300	4.1 ± 1.3 4.5 ± 1.6 5.6 ± 2.0* 5.6 ± 2.1*	Weak positive: 25 metaphases/animal were scored (SCE/metaphase).
McFee *et al.* 1989	SCE (23)	M: $B6C3F_1$ mice (4)	bone marrow	i.p.	0 150 300 600 Trend	3.3 ± 0.21 4.5 ± 0.28 6.1 ± 0.69 6.5 ± 0.35* *P* = 0.0001	Positive: 2nd trial conducted at 450 and 600 mg/kg. Significant at 450 but not at 600. 25 metaphases/animal scored. Pronounced sedation occurred at doses > 300 mg/kg.
	CA (17)	M: $B6C3F_1$ mice (7-8)	bone marrow	i.p.	0 150 300 600 Trend	1.5 ± 0.69 0.75 ± 0.37 1.1 ± 0.60 0.57 ± 0.37 *P* = –0.14	Negative: 50 metaphases/animal scored, results represent % aberrant cells.
	MN (24, 48, 72)	M: $B6C3F_1$ mice (8)	bone marrow	i.p.	0 75 150	2.16–2.65 0.56–2.39 1.57–2.28	Negative: Data are the mean MN/1000 PCEs scored. Considerable fluctuation in percentage of PCEs observed but no apparent pattern. Values shown

Reference	Test system (time after dosing hr)	Sex:species (no/group)	Tissue	Exp. Route[a]	Dose or HID/LED (mg/kg)	Results	Evaluation: comments
					300 Trend	2.00–3.02 *P* = 0.15–0.31	indicate range from 24 to 72 hrs.
Salamone *et al*. 1981	MN (30, 48, 72, 96)	M: B6C3F$_1$ mice (5)	bone marrow	i.p.	270 × 2 169 337	1 (72 hr) 5 (30 hr) 2 (72 hr)	Negative: Data are the sum of MN/500 PCEs/mouse for 4 to 5 mice at peak sampling time. Multiple sampling times used to increase sensitivity. Phase 1 mice received 2 injections (24 hr apart) at 80% LD$_{50}$ and sampled at 48, 72, and 96 hr. Phase 2 mice received single injection at 50% or 100% LD$_{50}$ and sampled at 30, 48, and 72 hr). LD$_{50}$ = 0.338 mL/kg or about 337.3 mg/kg.
Tsuchimoto and Matter 1981	MN (6)	M/F: CD-1 mice (4)	bone marrow	i.p.	0 40 × 2 80 × 2 160 × 2	0.08 (0.07–0.13) 0.08 (0.0–0.13) 0.05 (0.0–0.13) 0.15 (0.0–0.27)	Negative: Two doses given 24 hr apart. Mice were killed 6 hr after the second dose. Data are the mean % micronucleated PCEs and range (1,500 PCEs scored per animal).
Suzuki *et al.* 2005	MN (3-5 days)	M: F344 or SD rats[d] (4)	liver	i.p. or gavage[d]	Lab 1 0 300 600 Lab 2 0 300 600	 0.05 0.1–0.11 0.01–0.06 0.04 0.04–0.08 0.01–0.04	Negative: Data are the mean % micronucleated hepatocytes (2,000 hepatocytes scored per animal) and range over sampling times (3 to 5 days) Experiments conducted independently in two laboratories.
	MN (2 days)	M: F344 or SD rats[d] (4)	blood	i.p. or gavage[d]	Lab 1 0 300	 0.08 ± 0.06 0.25 ± 0.11*	Positive: Data are mean % micronucleated reticulocytes (2,000 scored per animal on day 2) ± S.D.

Reference	Test system (time after dosing hr)	Sex:species (no/group)	Tissue	Exp. Route[a]	Dose or HID/LED (mg/kg)	Results	Evaluation: comments
					600 Lab 2 0 300 600	0.36 ± 0.09** 0.21 ± 0.06 0.19 ± 0.03 0.46 ± 0.11**	
Fernandez *et al.* 1989	MN (12 days)	Newt larvae (15)	RBCs	Tank water	0 ppm 4 ppm 20 ppm 40 ppm	5.3 (87) 9.3 (140) 13.1 (197)* 27.2 (408)*	Positive: Results are mean frequencies of micronucleated RBCs/1000 cells (total no. cells with MN).
Topham 1980	Transmissible genetic damage: abnormal sperm morphology (5 wk)	M: (CBA × BALB/c)F_1 mice (5)	Sperm	i.p.	400 × 5	Small increase at high doses	Negative: Dose range 50 to 500 mg/kg, 500 mg/kg dose was toxic, repeat studies did not confirm original observation. All tests included positive controls.
Topham 1981					100 × 5 250 × 5	1.4% increase 1.7% increase	Inconclusive: Dose range 50 to 500 mg/kg, 500 mg/kg dose was lethal. Increase was statistically significant compared to controls but did not fulfill all criteria for a positive response (i.e., response was < double the response in negative controls). At least 250 sperm examined. All tests included positive controls.
Amlacher and Ziebarth 1979 (cited in Danford 1991)	DNA synthesis inhibition. Mitotic index (?)	?: Mouse (?)	Kidney	?	?	No effect	Negative: Few details provided in Danford (1991).

Reference	Test system (time after dosing hr)	Sex:species (no/group)	Tissue	Exp. Route[a]	Dose or HID/LED (mg/kg)	Results	Evaluation: comments
Seiler 1977	DNA synthesis inhibition	M: Mouse (3-4)	Testes	gavage	200	75%*	Positive: Results reported as % of tritiated thymidine incorporation compared to concurrent controls. Only one dose tested.

CA = chromosomal aberration, Exp. = Exposure, HID = highest ineffective dose, i.p.= intraperitoneal, LED = lowest effective dose, MN = micronucleus, PCEs = polychromatic erythrocytes, RBCs = red blood cells, SCE = sister chromatid exchange, SSB = single strand breaks
* $P < 0.05$ compared with controls.
** $P < 0.01$ compared with controls.
[a]Single dose unless otherwise noted.
[b]Values represent the elution rate (K) where K = ln (DNA% retained on filter)/eluted volume
[c]LD_{50} value was not reported, HSDB (2011) reported rat oral LD_{50} of 750 mg/kg, NTP (1996) reported values of 900 to 2,951 mg/kg.
[d]Authors tested multiple chemicals but did not provide further detail.
To return to text citing Table F-8, click here.

Table F-9. Mutagenicity of *ortho*-toluidine metabolites in *Salmonella* strains

Metabolite	TA100 (–S9)	TA100 (+S9)	TA1535 (–S9)	TA1535 (+S9)	TA98 (–S9)	TA98 (+S9)	HID/LED (μM/ plate)
N-Hydroxy-*o*-toluidine	–	+	–	+	–	–	0.5/1
o-Nitrosotoluene	–	+	–	+	–	–	0.5/1
N-Acetyl-*o*-toluidine	–	–	NT	NT	–	–	10
N-Acetyl-*N*-hydroxy-*o*-toluidine	–	–	+	–	–	+	5/10
N-Acetoxy-*N*-acetyl-*o*-toluidine	–	–	NT	NT	–	–	10
2-Hydroxy-6-methyl-acetanilide[a]	–	–	NT	NT	–	–	10
o-Azoxytoluene	–	–	NT	NT	–	–	10
o-Azotoluene	–	–	NT	NT	–	–	10
Anthranilic acid[b]	–	–	–	–	–	–	5,000 μg/plate

Sources: Chung *et al.* 1981, Gadupudi and Chung 2011, Gupta *et al.* 1987, Hecht *et al.* 1979.
HID/LED = highest ineffective dose/lowest effective dose.
– = negative, + = positive, NT = not tested.
[a]*N*-acetyl-2-amino-*meta*-cresol.
[b]Also tested negative in *S. typhimurium* strains TA1537, TA1538, and TA102.
To return to text citing Table F-9, click here.

Table F-10. Hemoglogin and albumin adducts formed *in vitro* and *in vivo*

Reference	Exposure conditions Route of exposure o-Toluidine concentration Time of sacrifice	Protein	Adduct detection	Results	Comments
***In vitro* (protein)**					
Stettler *et al.* 1992	130 nmol rat liver microsomes and cofactors 10 to 60 minutes	Albumin (rat or human)	Radioactivity	Not appreciable binding	Authors state that conditions may not have been optimal
Stettler *et al.* 1992	130 nmol rat liver microsomes and cofactors 10 to 60 minutes	Hb	Radioactivity	8–9 ng/mg Hb	Microsomes prepared from phenobarbital-induced animals increased *o*-toluidine binding 1.5 fold (27.2 ng/mg) compared to control microsomes (16.2 ng)
***In vivo* studies**					
Birner and Neuman 1988	$B6C3F_1$ mice (female) Gavage 0.47 to 0.6 mmol/kg 24 hr sacrifice	Hb	Base hydrolysis GC	HBI = 2.1 ± 0.4	
Birner and Neuman 1988	Wistar rats (female) Gavage 0.47 to 0.6 mmol/kg 24 hr sacrifice	Hb	Base hydrolysis GC	HBI = 4.0 ± 0.65	

Reference	Exposure conditions Route of exposure o-Toluidine concentration Time of sacrifice	Protein	Adduct detection	Results	Comments
DeBord *et al.* 1992	Sprague-Dawley (male) i.p.: 0, 20, 40 or 100 mg/kg bw p.o. 100 mg/kg 2 to 72 hr; 7 to 28 days	Hb	Radioactivity	*i.p. 100 mg/kg; 4 hr* 23.0 ± 5.1 ng/ mg Hb HBI = 51.8 *Time course i.p (50 mg/kg)* Highest level at 24 hr 14.2 ± 2.6 ng/mg Hb p.o. 10.0 ± ng/mg Hb	Radioactivity still available at 28 days Half-life 12.3 days Pretreatment with phenobarbital and [3-naphthoflavone Non-statistically significant increased in phenobarbital; large rat to rat variability in the treatment group Due to high variability of findings, study considered inadequate to determine role of metabolic activation.
DeBord *et al.* 1992	Sprague-Dawley (male) i.p. 0, 20, 40 or 100 mg/kg bw p.o. 100 mg/kg	Albumin	Albumin i.p.	*i.p. 100 mg/kg; 4 hr* 32 ng /mg albumin *Time course i.p (50 mg/kg)* Highest level at 4 hr 15.6 ng/mg Hb	Albumin peak at 4 hr No radioactivity at 72 hr Half life = 2.3 hr
Stettler *et al.* 1992	Sprague-Dawley rats (male)[a] i.p. 110, 20, 40, 50 100 mg/kg 4 hr	Hb	Base hydrolysis Radioactivity/ HPLC or GC	Dose–related response	Higher doses: decreased in the percent of bound *o*-toluidine that could be hydrolyzed suggesting other adducts are formed that are not susceptible to base-hydrolysis

Reference	Exposure conditions Route of exposure o-Toluidine concentration Time of sacrifice	Protein	Adduct detection	Results	Comments
Cheever *et al.* 1992	Sprague-Dawley rats (male)[a] i.p. and p.o. 10 to 100 mg/kg bw 4 hr to 28 days	Hb	Base hydrolysis Thin layer chromatography/ HPLC or GC-MS Hemoglobin	*Route of exposure study* 50 mg/kg/wt i.p. 3.5 ± 1.6 ng/mg Hb p.o. 0.4 ± 0.6 ng/mg Hb Time course Highest level (100 mg/kg) 7.5 ± 0.9 ng/mg Hb at 24 hr	Half life = 11 day
Cheever *et al.* 1992	Sprague-Dawley (male) i.p. and p.o. 10 to 100 mg/kg bw 4 hr to 28 days	Albumin	Albumin	*Highest level (100 mg/kg)* 2.5 ng/mg albumin at 4 hr	Not detected at 24 hr

HBI = hemoglobin binding index = mmol bound/mmol Hb)/mmol dose/kg body wt; Hb = hemoglobin.
[a]Species and sex not clear, but male Sprague-Dawley specified as being used for the preparation of the phenobarbital-induced microsomes.
To return to text citing Table F-10, click here.

Part 2

Draft RoC Substance Profile

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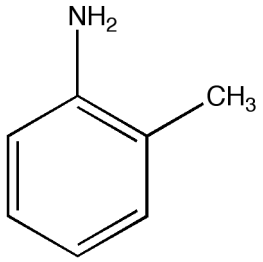
o-Toluidine

CAS No. 95-53-4

Known to be a human carcinogen

o-Toluidine was first listed in the *Third Annual Report on Carcinogens* (1983), and its hydrochloride was first listed in the *Second Annual Report on Carcinogens* (1981).

Also known as 2-methylbenzenamine



Carcinogenicity

o-Toluidine is *known to be a human carcinogen* based on sufficient evidence of carcinogenicity from studies showing that it causes urinary-bladder cancer in humans, together with studies showing that it causes urinary-bladder cancer in rats and studies demonstrating the biological plausibility of mechanisms of its carcinogenicity in humans. *o*-Toluidine was first listed in the *Third Annual Report on Carcinogens* as *reasonably anticipated to be a human carcinogen* based on sufficient evidence from studies in experimental animals. Since that time, additional cancer studies in humans have been published, and the listing was changed to *known to be a human carcinogen* in the *Thirteenth Report on Carcinogens* (2014).

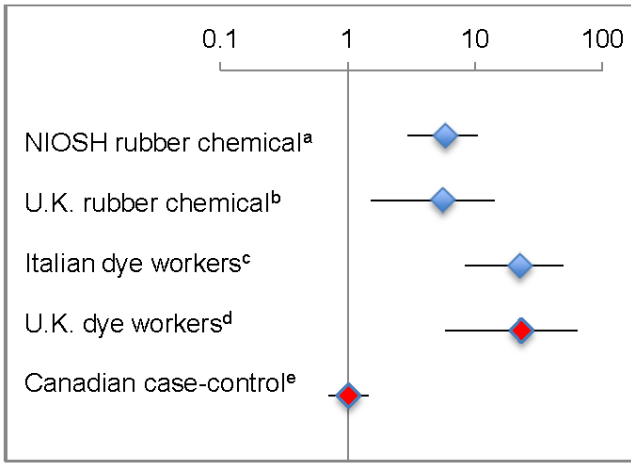
Cancer Studies in Humans

Epidemiologic studies have demonstrated a causal association between exposure to *o*-toluidine and urinary-bladder cancer in humans. This conclusion is based on an evaluation of three cohort studies of dye workers (Case and Pearson 1954, Ott and Langner 1983, Pira *et al.* 2010), two cohort studies of rubber-chemical workers (Sorahan 2008, Carreón *et al.* 2010), and a population-based case-control study (Richardson *et al.* 2007). The most informative study is the National Institute for Occupational Safety and Health (NIOSH) cohort study of rubber-chemical workers, because it provided the best assessment of *o*-toluidine exposure and co-exposures (Carreón *et al.* 2010).

Overall, there is credible evidence of an association between increased urinary-bladder cancer risk and exposure to *o*-toluidine based on consistent findings across studies, the presence of a clear exposure-duration response relationship in two studies (Carreón *et al.* 2010, Sorahan 2008), and large magnitudes of effect across studies. An increased risk of urinary-bladder cancer (incidence or mortality) was consistently observed in all four studies with adequate latency that used statistical or other methods capable of detecting an association (Case and Pearson 1954, Sorahan 2008, Carreón *et al.* 2010, Pira *et al.* 2010) (the risk estimates are shown in the figure below). Two studies did not find an

excess of urinary-bladder cancer mortality among *o*-toluidine–exposed workers; however, the statistical power to detect an effect was very low in the U.S. dye workers study (Ott and Langner 1983), and misclassification of exposure is a serious concern in both the U.S. dye-workers cohort and the Canadian case-control study (Richardson *et al.* 2007).

Risk estimates for urinary bladder cancer



Risk estimates and 95% confidence intervals for four of the five studies that were considered in the assessment. Where available, relative risks for urinary-bladder cancer incidence (standardized incidence ratios or odds ratios) were reported (NIOSH and U.K. rubber-chemical workers and Canadian case-control study). In the absence of incidence data, standardized mortality ratios for urinary-bladder cancer were reported (Italian and U.K. dye workers). No deaths were observed in the U.S. dye-worker study (Ott and Langner 1983). Blue represents studies of high-to-moderate quality, and red represents studies of lower quality.

[a]Carreón *et al.* 2010. [b]Sorahan 2008. [c]Pira *et al.* 2010. [d]Case and Pearson 1954. [e]Richardson *et al.* 2007.

The NIOSH cohort study of rubber-chemical workers is the most informative study for evaluation of potential confounding from occupational co-exposures, because it had good occupational hygiene data on exposure to *o*-toluidine and other chemicals (Carreón *et al.* 2010). This study provided substantial evidence that *o*-toluidine was the agent causally related to the observed increase in urinary-bladder cancer risk among *o*-toluidine–exposed workers. These findings are supported by the study of U.K. rubber-chemical workers (Sorahan 2008), which found an increased risk of urinary-bladder cancer in analyses adjusting for several occupational co-exposures. Occupational co-exposures, including exposures to animal carcinogens, are of greater concern for the two cohort studies of workers manufacturing magenta dyes (Case and Pearson 1954, Pira *et al.* 2010); possible positive interactions among exposures might help to explain the large risk estimates observed. Although information on cigarette smoking was limited in these studies, potential confounding from smoking could reasonably be ruled out in the NIOSH cohort study (based on analysis of a subset of workers for whom smoking information was available), and it is unlikely to explain the large risk estimates found in the smaller studies. Finally, the finding of increased urinary-bladder cancer risk in different cohorts with different exposure conditions and different co-exposures lends strong support to the conclusion that *o*-toluidine is the common causal risk factor.

Cancer Studies in Experimental Animals

There is significant evidence for the carcinogenicity of *o*-toluidine from studies in experimental animals based on significantly increased the incidence of malignant tumors or benign and malignant tumors combined in rats and mice at several tissue sites. This

conclusion is based on four studies in two different strains of rats (Weisburger *et al.* 1978, NCI 1979, Hecht *et al.* 1982, NTP 1996) and two studies in two different strains of mice (Weisburger *et al.* 1978, NCI 1979). All of these studies were two-year carcinogenicity studies except for one high-dose subchronic exposure study in which animals were exposed to *o*-toluidine for 13 or 26 weeks (NTP 1996).

Dietary exposure to *o*-toluidine caused tumors of the urinary bladder and connective tissue (sarcoma) in rats of both sexes, subcutaneous tissue and mesothelium in male rats, blood vessels in male and female mice, and liver in female mice. Importantly, rats developed tumors at the same tissue site (urinary bladder) as observed in humans. The urinary-bladder cancer findings in female rats are considered to be robust because of the relatively high tumor incidences, the rarity of the tumor in this species, and the shorter time to first observed tumor in the high-dose females than in the low-dose females (NCI 1979). Although the incidences of urinary-bladder cancer were lower in male rats, increased tumor incidences were observed in three carcinogenicity studies in male rats (Weisburger *et al*. 1978, NCI 1979, Hecht *et al.* 1982), supported by the observation of a significantly increased incidence of transitional-cell hyperplasia of the urinary bladder in male rats after 13 or 26 weeks of exposure in subchronic exposure study (NTP 1996).

Observations of tumors at tissue sites in addition to the urinary bladder also support the conclusion that *o*-toluidine is a carcinogen. Increased incidences of sarcoma in the spleen and other tissue sites were observed in rats of both sexes (NCI 1979) and in male rats in two different studies (NCI 1979, Hecht *et al.* 1982). Several types of sarcoma from different organs were combined in the statistical analyses, because the histologic appearance of the various types of sarcoma, which were of mesenchymal origin, was similar, and many sarcomas had invaded adjacent organs and soft tissue (NCI 1979). All three carcinogenicity studies in rats, including studies in two different strains (Weisburger *et al.* 1978, NCI 1979, Hecht *et al.* 1982), reported tumors of the subcutaneous tissues (fibroma or fibrosarcoma) in male rats. Statistically significant increased incidences of mesothelioma (of the tunica vaginalis or abdominal cavity and organs) were observed in male rats in the National Cancer Institute (NCI) study. These findings are supported by observations of malignant mesothelioma and mesothelial hyperplasia of the epididymides in male rats after dietary exposure to *o*-toluidine for 13 weeks followed by 13 weeks of observation. In mice, tumors of the blood vessels (hemangioma and hemangiosarcoma combined) were observed in two different strains (Weisburger *et al*. 1978, NCI 1979) and in both sexes of one strain (NCI 1979). Dose-related increases in the incidences of liver tumors (hepatocellular adenoma and carcinoma) in female mice were reported in the NCI study (1979).

In rats, dietary exposure to *o*-toluidine also caused benign tumors (fibroadenoma) of the mammary gland in males (Hecht *et al.* 1982) and females (NCI 1979). Although these tumors do not usually progress to malignancy, their increased incidence supports the findings of sufficient evidence of the carcinogenicity of *o*-toluidine from studies in experimental animals.

In two studies of exposure to *o*-toluidine by subcutaneous injection, one in Syrian golden hamsters (Hecht *et al*. 1982) and one in rats (Pliss 2004), no treatment-related effects were observed. However, these studies had methodological limitations, and subcutaneous injection is a less relevant route of exposure for evaluating potential human carcinogenicity.

Studies on Mechanisms of Carcinogenesis

Although the mechanisms of carcinogenicity of *o*-toluidine are not completely understood, the available evidence suggests that they are complex and involve several key modes of action, including metabolic activation that results in binding of reactive metabolites to DNA and proteins, mutagenicity, oxidative DNA damage, chromosomal damage, and cytotoxicity (Skipper *et al.* 2010). The key metabolic activation steps and genotoxic effects occur in both experimental animals and humans.

Metabolism of monocyclic aromatic amines, including *o*-toluidine, involves many competing activating and deactivating pathways, including *N*-acetylation, *N*-oxidation and -hydroxylation, and ring oxidation. Cytochrome P450–mediated *N*-hydroxylation to *N*-hydroxy-*o*-toluidine, a carcinogenic metabolite, occurs in the liver. *N*-hydroxy-*o*-toluidine is transported to the urinary bladder and can be bioactivated via conjugation by sulfation or acetylation by cytosolic sulfotransferases or *N*-acetyltransferases. The postulated conjugated form (based on comparison with other aromatic amines), *N*-acetoxy-*o*-toluidine, is a reactive ester that forms electrophilic arylnitrenium ions that can bind to DNA (Kadlubar and Badawi 1995, Riedel *et al.* 2006, English *et al.* 2012).

Studies of other aromatic amines that cause urinary-bladder cancer have shown that during the transport of the *N*-hydroxy arylamines to the urinary bladder, bioreactive metabolites (nitroso compounds) can form and bind to hemoglobin in the blood (Skipper and Tannenbaum 1994). Evidence suggesting that this pathway is relevant to humans comes from numerous studies that detected *o*-toluidine hemoglobin adducts in humans (following both occupational and nonoccupational exposures), consistent with observations in experimental animals. Hemoglobin adducts are thought to be formed from the *o*-toluidine metabolite *o*-nitrosotoluene (Eyer 1983, English *et al.* 2012), which also causes urinary-bladder cancer in rats (Hecht *et al.* 1982).

o-Toluidine does not bind strongly to the human *N*-acetyltransferase isozyme NAT1 (Zhang *et al.* 2006), which suggests that other modes of action may play a role in *o*-toluidine urinary-bladder carcinogenesis. Other activation pathways (ring-oxidation pathways) for aromatic amines include peroxidase-catalyzed reactions that form quinone imines from nonconjugated phenolic metabolites. The urinary bladder, a primary target for carcinogenic aromatic amines, contains high levels of peroxidase. Semiquinone-quinone redox cycling of unconjugated phenolic metabolites in the transitional epithelium can produce reactive oxygen species, resulting in oxidative cellular damage and compensatory cell proliferation (Skipper *et al.* 2010, English *et al.* 2012). Support for this mechanism comes from studies of several *o*-toluidine metabolites that were shown to induce oxidative damage in the human c-Ha-*ras* oncogene and *p53* tumor-suppressor gene and in calf thymus DNA in the presence of copper(II) and NADH (Ohkuma *et al.*

1999). In addition, *o*-toluidine caused DNA strand breaks in human and rat urinary mucosa cells *in vitro* and in urinary-bladder tumors in rats exposed *in vitro*.

Overall, the extensive data on genetic and related effects of *o*-toluidine indicate that it can cause DNA and chromosomal damage and induce mutations (see Part 1, Section 5.1). Although *o*-toluidine is a weak mutagen in bacteria, it causes mutations in human lymphocytes, and two *o*-toluidine metabolites (*N*-hydroxy-*o*-toluidine and *o*-nitrosotoluene) are potent mutagens in bacteria with mammalian metabolic activation. DNA adducts have been detected in liver and nasal (but not urinary-bladder) tissue from exposed rats, and *o*-toluidine–releasing DNA adducts have been found in human urinary-bladder tumors and in normal human urinary-bladder tissue (presumably as a result of background environmental exposure). There is evidence that *o*-toluidine causes large-scale chromosomal damage in yeast and mammalian cells (e.g., deletions, insertions, translocations, and aneuploidy) and oxidative damage to DNA. Exposure to aromatic amines has been shown to induce chromosomal instability in genetically stable urinary-bladder-cancer cells. Chromosomal instability is associated with aneuploidy and loss of heterozygosity. Aneuploidy is a common feature of urinary-bladder cancer in humans, and loss of heterozygosity is an important mechanism for inactivation of tumor-suppressor genes (Höglund *et al.* 2001, Sandberg 2002, Phillips and Richardson 2006).

Properties

o-Toluidine is a synthetic chemical that may be classified as a monocyclic aromatic amine, arylamine, or alkylaniline (Yu *et al.* 2002, IARC 2010, Skipper *et al.* 2010). It exists at room temperature as a light-yellow liquid that darkens rapidly on exposure to air and light, and is described as having an aromatic odor (IPCS 1998). It is slightly soluble in water, soluble in dilute acids, and miscible with ethanol, diethyl ether, and carbon tetrachloride (HSDB 2011). *o*-Toluidine hydrochloride (HCl) is the solid salt form of *o*-toluidine, which exists at room temperature as a green or white crystalline solid that is very soluble in water (Akron 2012). Physical and chemical properties of *o*-toluidine and its hydrochloride are listed in the following table.

Property	***o*-Toluidine**	***o*-Toluidine HCl**
Molecular weight	107.2[a]	143.6[b]
Density	0.998 g/cm^3 at 20°C[a]	1.288 g/cm^3 at 20°C[a]
Melting point	< –15°C[a]	215°C[c]
Boiling point	198°C to 201°C[a]	242.2°C[c]
Log K_{ow}	1.32[c]	1.62[c]
Water solubility	1.66×10^4 mg/L at 25°C[c]	8,290 mg/L at 25°C[d]
Vapor pressure	0.33 mm Hg at 25°C[a]	0.293 mm Hg at 25°C[d]
Vapor density relative to air	3.69[a]	–

Sources: [a]Akron 2012, [b]NTP 1996, [c]HSDB 2011, [d]ChemIDplus 2012.

Use

Major uses for *o*-toluidine have included manufacture of (1) rubber chemicals (Hanley *et al.* 2012), (2) pesticide intermediates such as ethyl-*o*-toluidine (2-methyl-6-aniline), which is used to manufacture the widely used herbicides metolachlor and acetochlor and 4-chloro-*o*-toluidine, and (3) more than 90 dyes and pigments, including acid-fast dyestuffs, azo dyes and pigments, triarylmethane dyes, sulfur dyes, and indigo compounds, either directly or via dye intermediates; four major intermediates are acetoacet-*o*-toluidine, 3-hydroxy-2-naphthoyl-*o*-toluidine, 2-toluidine-5-sulfonic acid, and *o*-aminoazotoluene (Bowers 2011). Data submitted to the U.S. Environmental Protection Agency's (EPA's) Toxics Release Inventory (TRI) and Chemical Data Reporting Rule programs provide evidence for the continuing use of *o*-toluidine for all of these manufacturing uses except dye production and manufacture of the pesticide intermediate 4-chloro-*o*-toluidine. Other, minor uses for *o*-toluidine are as an intermediate in the synthesis of pharmaceuticals (e.g., prilocaine) (Vardanyan and Hruby 2006) and in the clinical laboratory as an ingredient in a reagent for glucose analysis and for tissue staining (IARC 2012).

Production

o-Toluidine is a high-production-volume chemical in the United States. In the early 1970s, production exceeded 454,000 kg (1 million pounds) (HSDB 2011). In 2011, *o*-toluidine was reported to be manufactured by at least 15 companies worldwide, including at least 3 in the United States (SRI 2012); however, in 2013, one company reported that it was the only domestic producer of toluidines (DuPont 2013). Reported recent and historical volumes of U.S. production, imports, and exports of *o*-toluidine are listed in the following table.

Category	Year	Quantity (million lb)
Production + imports (EPA Chemical Data Reporting Rule[a])	2006	10 to < 50
U.S. imports:[b] recent	2011	58
Historical	1989	10.1
U.S. exports:[b] recent	2011	3.2
Historical	1989	5.1

Sources: [a]EPA 2009; formerly the "Inventory Update Rule." [b]USITC 2012.

Exposure

Several lines of evidence indicate that a significant number of people living in the United States are exposed to *o*-toluidine. This evidence includes widespread use, production or imports of large amounts of *o*-toluidine, and biological monitoring data demonstrating exposure in both occupationally and nonoccupationally exposed individuals and in both smokers and nonsmokers.

The highest exposure to *o*-toluidine occurs in the workplace; urinary exposure levels were over 26-fold higher among workers exposed to *o*-toluidine than among unexposed workers (Ward *et al.* 1996). Occupational exposure to *o*-toluidine can occur by inhalation or dermal contact (IARC 2010) during its production or during its use in production of rubber chemicals, chemical intermediates for pesticides, or intermediates for dyes and pigments. Medical and laboratory personnel also are exposed to low concentrations of *o*-toluidine in air (IARC 2012).

The highest levels of occupational exposure to *o*-toluidine in air were reported from a study of *o*-toluidine production workers at a chemical plant in the former Soviet Union. Concentrations of *o*-toluidine in the air were 2 to 7 times the maximum permissible concentration of 3 mg/m^3 [0.7 ppm] for the Soviet Union (IARC 2012). Most of the air-monitoring data in the United States suggest that occupational exposure levels of *o*-toluidine are usually less than 1 ppm (e.g., up to 0.5 ppm in the dye and pigment industry), but may have been higher in the past. The most detailed occupational exposure data are air-monitoring data from a NIOSH assessment in 1990 and company data collected from 1976 to 2004 for workers at a rubber-chemical department in a U.S. chemical manufacturing plant involved in antioxidant production, accelerant production, recycling processing, and maintenance (Hanley *et al.* 2012). In the 1990 NIOSH assessment, *o*-toluidine exposure levels (geometric mean breathing-zone concentrations) were approximately 0.1 ppm for antioxidant production workers and maintenance personnel and approximately 0.5 ppm for accelerant production and recycling processing workers. The company data indicated that geometric mean *o*-toluidine exposure levels among rubber-chemical workers decreased from 0.1 ppm for 1976 to 1979 to less than 0.02 ppm for 1995 to 2004.

The presence of *o*-toluidine in urine and as hemoglobin adducts in individuals without known occupational exposure indicates more widespread population exposure. *o*-Toluidine–releasing adducts were detected in urinary-bladder tissue and tumors from individuals with no known exposure to *o*-toluidine (Böhm *et al.* 2011), and *o*-toluidine was detected in breast milk (DeBruin *et al.* 1999). Potential sources of exposure include tobacco smoking, dental products (e.g., prilocaine), consumer products (e.g., hair dyes, dyestuff in clothing and cosmetics), food, and the environment (El-Bayoumy 1986, Riffelmann *et al.* 1995). Although nonoccupational exposure levels are lower than occupational exposure levels, these exposures are common, indicating that more people living in the United States are potentially exposed to *o*-toluidine from these sources than occupationally.

o-Toluidine has been measured in mainstream cigarette smoke at 9 to 144 ng per cigarette (Stabbert *et al.* 2003). In the absence of occupational exposure, *o*-toluidine urinary concentrations and hemoglobin adducts have generally been reported to be somewhat higher in smokers than in nonsmokers (El-Bayoumy *et al.* 1986, Riffelmann *et al.* 1995, Riedel *et al.* 2006); however, no such difference was noted between occupationally exposed smokers and nonsmokers (Riffelmann *et al.* 1995, Ward *et al.* 1996, Korinth *et al.* 2007).

Exposure to *o*-toluidine can occur from prilocaine, a product used for dental anesthesia, which is metabolized to *o*-toluidine. In a study among patients who received prilocaine for local anesthesia, hemoglobin adducts had increased approximately 41-fold by 24 hours after surgery (Gaber *et al.* 2007, IARC 2012). *o*-Toluidine has also been found in hair dyes sold in Turkey (at levels of up to 1,547 µg/g) (IARC 2012), and *o*-toluidine–based dyes are found in many commercial products. Most of these dyes are manufactured outside the United States, but no U.S. import restrictions were found, and such products, including hair dyes, potentially may be sold on the Internet (Alibaba 2013, Allbiz 2013).

o-Toluidine or toluidine (isomer not specified) was found in some food samples, primarily vegetables in German surveys from the 1970s; for example, levels in carrots ranged from less than 0.1 ppm to 7.2 ppm (HSDB 2011). *o*-Toluidine also was detected as a volatile in black tea (IARC 2012). No information on *o*-toluidine content was found in the U.S. Food and Drug Administration's Total Diet Study for market baskets collected between September 1991 and October 2003 (FDA 2006).

Evidence suggesting potential exposure to *o*-toluidine from the environment comes from the TRI database. On- and off-site environmental releases of *o*-toluidine from 15 facilities in 2010 totaled slightly over 6,600 pounds, of which 77.4% was released to air, 19.6% to underground injection, and 3.0% to water (TRI 2012). *o*-Toluidine has been detected in water and sediment worldwide. In addition, a biological monitoring study in Europe reported that *o*-toluidine hemoglobin adduct levels in children varied with geographical residence, being lower in a largely rural location than in urban locations, suggesting the importance of environmental sources of exposure.

Regulations

U.S. Environmental Protection Agency (EPA)

Clean Air Act

National Emission Standards for Hazardous Air Pollutants: Listed as a hazardous air pollutant.

Comprehensive Environmental Response, Compensation, and Liability Act

Reportable quantity (RQ) = 100 lb.

Resource Conservation and Recovery Act

Hazardous Waste Codes for which the listing is based wholly or partly on the presence of *o*-toluidine = U222, U328, K112, K113, K114.

Listed as a hazardous constituent of waste.

Occupational Safety and Health Administration (OSHA)

While this section accurately identifies OSHA's legally enforceable PELs for this substance in 2010, specific PELs may not reflect the more current studies and may not adequately protect workers.

Permissible exposure limit (PEL) = 5 ppm.

Guidelines

American Conference of Governmental Industrial Hygienists (ACGIH)

Threshold limit value – time-weighted average (TLV-TWA) = 2 ppm.

National Institute for Occupational Safety and Health (NIOSH)

Immediately dangerous to life and health (IDLH) limit = 50 ppm.

Listed as a potential occupational carcinogen.

References

Akron. 2012. The Chemical Database. The Department of Chemistry at the University of Akron. http://ull.chemistry.uakron.edu/erd and search on CAS number. Last accessed: 5/12.

Akyüz M, Ata S. 2008. Determination of aromatic amines in hair dye and henna samples by ion-pair extraction and gas chromatography-mass spectrometry. *J Pharm Biomed Anal* 47(1): 68-80.

Alibaba. 2013. Alibaba.com. http://www.alibaba.com and search on "hair dye," then narrow search by country, Turkey. Last accessed: 6/13.

Allbiz. 2013. *Hair-dye in Turkey*. Allbiz. http://www.tr.all.biz/en/hair-dye-bgg1059300. Last accessed: 5/13.

Böhm F, Schmid D, Denzinger S, Wieland WF, Richter E. 2011. DNA adducts of *ortho*-toluidine in human bladder. *Biomarkers* 16(2): 120-128.

Bowers JS. 2011. Toluidines. In *Ullman's Encyclopedia of Industrial Chemistry*, vol. 37. Weinheim: Wiley-VCH Velrag GmbH & Co KGaA. pp. 119-126.

Carreón T, Hein MJ, Viet SM, Hanley KW, Ruder AM, Ward EM. 2010. Increased bladder cancer risk among workers exposed to *o*-toluidine and aniline: a reanalysis. *Occup Environ Med* 67(5): 348-350.

Case RA, Pearson JT. 1954. Tumours of the urinary bladder in workmen engaged in the manufacture and use of certain dyestuff intermediates in the British chemical industry. II. Further consideration of the role of aniline and of the manufacture of auramine and magenta (fuchsine) as possible causative agents. *Br J Ind Med* 11(3): 213-216.

ChemIDplus. 2012. *ChemIDplus Advanced.* National Library of Medicine. http://chem.sis.nlm.nih.gov/chemidplus/chemidheavy.jsp and select Registry Number and search on CAS number. Last accessed: 5/12.

DeBruin LS, Pawliszyn JB, Josephy PD. 1999. Detection of monocyclic aromatic amines, possible mammary carcinogens, in human milk. *Chem Res Toxicol* 12(1): 78-82.

DuPont. 2013. *About Our Products.* First Chemical — Pascagoula Site. First Chemical Corporation, E. I. du Pont de Nemours and Company. http://www2.dupont.com/Pascagoula/en_US/products.html. Last accessed: 8/13.

El-Bayoumy K, Donahue JM, Hecht SS, Hoffmann D. 1986. Identification and quantitative determination of aniline and toluidines in human urine. *Cancer Res* 46(12 Pt 1): 6064-6067.

English JC, Bhat VS, Ball GL, McLellan CJ. 2012. Establishing a total allowable concentration of *o*-toluidine in drinking water incorporating early lifestage exposure and susceptibility. *Regul Toxicol Pharmacol* 64(2): 269-284.

EPA. 2009. *Non-confidential 2006 IUR Production Volume Information.* U.S. Environmental Protection Agency. http://cfpub.epa.gov/iursearch and search on CAS number.

Eyer P. 1983. The red cell as a sensitive target for activated toxic arylamines. *Arch Toxicol Suppl* 6: 3-12.

FDA. 2006. *Total Diet Study Market Baskets 1991-3 through 2003-4.* U.S. Food and Drug Administration. http://www.fda.gov/downloads/Food/FoodSafety/FoodContaminantsAdulteration/TotalDietStudy/UCM184304.pdf.

Gaber K, Harreus UA, Matthias C, Kleinsasser NH, Richter E. 2007. Hemoglobin adducts of the human bladder carcinogen *o*-toluidine after treatment with the local anesthetic prilocaine. *Toxicology* 229(1-2): 157-164.

Hanley KW, Viet SM, Hein MJ, Carreón T, Ruder AM. 2012. Exposure to *o*-toluidine, aniline, and nitrobenzene in a rubber chemical manufacturing plant: a retrospective exposure assessment update. *J Occup Environ Hyg* 9(8): 478-490.

Hecht SS, El-Bayoumy K, Rivenson A, Fiala E. 1982. Comparative carcinogenicity of *o*-toluidine hydrochloride and *o*-nitrosotoluene in F-344 rats. *Cancer Lett* 16(1): 103-108.

Höglund M, Säll T, Heim S, Mitelman F, Mandahl N, Fadl-Elmula I. 2001. Identification of cytogenetic subgroups and karyotypic pathways in transitional cell carcinoma. *Cancer Res* 61(22): 8241-8246.

HSDB. 2011. Hazardous Substances Data Bank. National Library of Medicine. http://toxnet.nlm.nih.gov/cgi-bin/sis/htmlgen?HSDB and search on CAS number. Last accessed: 1/11.

IARC. 2010. *ortho*-Toluidine. In *Some Aromatic Amines, Organic Dyes, and Related Exposures*. IARC Monographs on the Evaluation of Carcinogenic Risk of Chemicals to Humans, vol. 99. Lyon, France: International Agency for Research on Cancer. pp. 407-469.

IARC. 2012. *ortho*-Toluidine. In *A Review of Human Carcinogens: Chemical Agents and Related Occupations*. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans, vol. 100F. Lyon, France: International Agency for Research on Cancer. pp. 93-100.

IPCS. 1998. *Concise International Chemical Assessment Document 7. o-Toluidine*. Geneva, Switzerland: World Health Organization. 22 pp.

Kadlubar FF, Badawi AF. 1995. Genetic susceptibility and carcinogen-DNA adduct formation in human urinary bladder carcinogenesis. *Toxicol Lett* 82-83: 627-632.

Korinth G, Weiss T, Penkert S, Schaller KH, Angerer J, Drexler H. 2007. Percutaneous absorption of aromatic amines in rubber industry workers: impact of impaired skin and skin barrier creams. *Occup Environ Med* 64(6): 366-372.

NCI. 1979. *Bioassay of o-Toluidine Hydrochloride for Possible Carcinogenicity.* Technical Report Series No. 153. DHEW (NIH) Publication No. 78-1394. Bethesda, MD: National Institutes of Health. 104 pp.

NTP. 1996. *NTP Technical Report on Comparative Toxicity and Carcinogenicity Studies of* o-*Nitrotoluene and* o-*Toluidine Hydrochloride (CAS Nos. 88-72-2 and 636-21-5) Administered in Feed to Male F344/N Rats.* Toxicity Report Series No. 44. NIH Publication No. 96-3936. Research Triangle Park, NC: National Toxicology Program. 99 pp.

Ohkuma YY, Hiraku S, Oikawa S, Yamashita N, Murata M, Kawanishi S. 1999. Distinct mechanisms of oxidative DNA damage by two metabolites of carcinogenic *o*-toluidine. *Arch Biochem Biophys* 372(1): 97-106.

Ott MG, Langner RR. 1983. A mortality survey of men engaged in the manufacture of organic dyes. *J Occup Med* 25(10): 763-768.

Phillips JL, Richardson IC. 2006. Aneuploidy in bladder cancers: the utility of fluorescent *in situ* hybridization in clinical practice. *BJU Int* 98(1): 33-37.

Pira E, Piolatto G, Negri E, Romano C, Boffetta P, Lipworth L, McLaughlin JK, La Vecchia C. 2010. Bladder cancer mortality of workers exposed to aromatic amines: a 58-year follow-up. *J Natl Cancer Inst* 102(14): 1096-1099.

Pliss GB. 2004. Experimental study of ortho-toluidine carcinogenicity [translated from Russian]. *Vopr Onkol* 50(5): 567-571.

Richardson K, Band PR, Astrakianakis G, Le ND. 2007. Male bladder cancer risk and occupational exposure according to a job-exposure matrix — a case-control study in British Columbia, Canada. *Scand J Work Environ Health* 33(6): 454-464.

Riedel K, Scherer G, Engl J, Hagedorn HW, Tricker AR. 2006. Determination of three carcinogenic aromatic amines in urine of smokers and nonsmokers. *J Anal Toxicol* 30(3): 187-195.

Riffelmann M, Muller G, Schmieding W, Popp W, Norpoth K. 1995. Biomonitoring of urinary aromatic amines and arylamine hemoglobin adducts in exposed workers and nonexposed control persons. *Int Arch Occup Environ Health* 68(1): 36-43.

Sandberg AA. 2002. Cytogenetics and molecular genetics of bladder cancer: a personal view. *Am J Med Genet* 115(3): 173-182.

Skipper PL, Kim MY, Sun HL, Wogan GN, Tannenbaum SR. 2010. Monocyclic aromatic amines as potential human carcinogens: old is new again. *Carcinogenesis* 31(1): 50-58.

Skipper PL, Tannenbaum SR. 1994. Molecular dosimetry of aromatic amines in human populations. *Environ Health Perspect* 102(Suppl 6): 17-21.

Sorahan T. 2008. Bladder cancer risks in workers manufacturing chemicals for the rubber industry. *Occup Med (Lond)* 58(7): 496-501.

SRI. 2012. *Directory of Chemical Producers.* Menlo Park, CA: SRI Consulting. Database edition. Last accessed: 1/12.

Stabbert R, Schafer KH, Biefel C, Rustemeier K. 2003. Analysis of aromatic amines in cigarette smoke. *Rapid Commun Mass Spectrom* 17(18): 2125-2132.

TRI. 2012. *TRI Explorer Chemical Report.* U.S. Environmental Protection Agency. http://www.epa.gov/triexplorer and select 2010 and select o-Toluidine. Last accessed: 8/09.

Vardanyan R, Hruby V. 2006. Synthesis of Essential Drugs, San Diego, CA: Elsevier, Inc. p. 17.

Ward EM, Sabbioni G, DeBord DG, Teass AW, Brown KK, Talaska GG, Roberts DR, Ruder AM, Streicher RP. 1996. Monitoring of aromatic amine exposures in workers at a chemical plant with a known bladder cancer excess. *J Natl Cancer Inst* 88(15): 1046-1052.

Weisburger EK, Russfield AB, Homburger F, Weisburger JH, Boger E, Van Dongen CG, Chu KC. 1978. Testing of twenty-one environmental aromatic amines or derivatives for long-term toxicity or carcinogenicity. *J Environ Pathol Toxicol* 2(2): 325-356.

Yu MC, Skipper PL, Tannenbaum SR, Chan KK, Ross RK. 2002. Arylamine exposures and bladder cancer risk. *Mutat Res* 506-507: 21-28.

Zhang N, Liu L, Liu F, Wagner CR, Hanna PE, Walters KJ. 2006. NMR-based model reveals the structural determinants of mammalian arylamine *N*-acetyltransferase substrate specificity. *J Mol Biol* 363(1): 188-200.