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

# Revised Draft:
# Report on Carcinogens
# Monograph on Cobalt and Cobalt Compounds That Release Cobalt Ions *In Vivo*

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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 13th Edition (2014), is available at http://ntp.niehs.nih.gov/go/roc.

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.

# Background and Methods

Cobalt is a naturally occurring element that is present in several different forms. Elemental cobalt is a hard, silvery grey metal that can combine with other elements, e.g., with oxygen (cobalt oxide), sulfur (cobalt sulfate) or arsenic (cobalt arsenide). The most common oxidation states of cobalt are +2 and +3; for most simple cobalt compounds, the valence is +2, designated as cobalt(II). Cobalt compounds can be organic or inorganic as well as water-soluble or -insoluble. Cobalt compounds are used in a variety of industrial applications and as a colorant for glass, ceramics, and paint, and as catalysts, as driers for inks and paints, and in feed supplements and batteries. Cobalt is used in alloys or composites, such as cobalt-tungsten carbide, and in cobalt-containing prosthetics. Cobalt nanoparticles are used in medical tests and treatments as well as in the textile and electronics industries.

Cobalt and cobalt compounds that release cobalt ions in *vivo* (collectively referred to as cobalt) was selected for review for possible listing in the Report on Carcinogens (RoC) based on evidence of widespread exposure and an adequate database of cancer studies to evaluate the potential carcinogenicity of cobalt. The listing does not include cobalt as part of the vitamin $B_{12}$ molecule because of the stability of that molecule in biological fluids. Cancer and toxicological studies of forms of cobalt that have confounding exposures, such as cobalt alloys and radioactive forms of cobalt, were not included in the review of the cobalt compounds. Two cobalt-containing substances, 'cobalt sulfate' and 'cobalt-tungsten carbide: powders and hard metals,' are currently listed in the Report on Carcinogens (RoC) as *reasonably anticipated to be human carcinogens* (NTP 2014d, 2014a). Cobalt sulfate, which has been listed since 2004 based on sufficient evidence of carcinogenicity from studies in experimental animals (NTP 2002b), is included in the current review of cobalt as a class. Cobalt-tungsten carbide: powders and hard metals, which was first listed in 2011 based on limited evidence of carcinogenicity from studies in humans and supporting evidence from studies on mechanisms of carcinogenesis (NTP 2009) falls outside the review.

### Monograph contents

This RoC monograph on cobalt 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 cobalt, 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 cobalt and cobalt compounds and cobalt compounds that release cobalt ions *in vivo*.

The methods for preparing the RoC monograph on cobalt are described in the "Cobalt Protocol" (NTP 2014c). The cancer evaluation component for cobalt provides information on the following topics that are relevant to understanding the relationship between exposure to cobalt compounds and cancer: Introduction and properties (Section 1), human exposure (Section 2), disposition and toxicokinetics (Section 3), human cancer studies (Section 4), studies in experimental animals (Section 5), mechanisms and other relevant effects (Section 6), and an overall cancer evaluation that provides a synthesis of Sections 1 through 6 and rationale for listing cobalt and cobalt

compounds and cobalt compounds that release cobalt ions *in vivo* as a class (Section 7). The information reviewed in Sections 3 through 7 (except for information on exposure and properties) must come from publicly available, peer-reviewed sources. The appendices in the RoC Monograph contain important supplementary information, such as the literature search strategy, exposure-related information and regulations, study description and quality tables, and and a discussion of the results from the genotoxicity studies.

### Process for preparation of the cancer hazard 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). [Links are provided within the document to the appendices, and specific tables or sections can be selected from the table of contents.]

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 the carcinogenicity of cobalt compounds, 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 monograph. The ORoC presented the concept document for cobalt to the NTP Board of Scientific Counselors (BSC) at the April 17, 2014 meeting, which provided opportunity for written and oral public comments, after which the concept was finalized and cobalt was approved by the NTP Director as a candidate substance for review. The concept document is available on the RoC website (http://ntp.niehs.nih.gov/go/730697).

#### *Key scientific questions and issues relevant for the cancer evaluation*

The scientific issues in this review concern the evaluation of the topics mentioned earlier, including human exposure, disposition and toxicokinetics, cancer studies in humans and experimental animals, and mechanistic data. The key questions for each topic are as follows:

**Questions related to the evaluation of human exposure information**

- How are people in the United States exposed to cobalt?
- How do we measure exposure?
- What are the non-occupational sources and levels of exposure?
- What are the occupational settings and levels of exposure?
- Has exposure changed over time?
- What federal regulations and guidelines limit exposure to cobalt?
- Are a significant number of people residing in the United States exposed to cobalt?

**Questions related to the evaluation of disposition and toxicokinetics**

- How is cobalt absorbed, distributed, metabolized, and excreted (ADME)?
- What, if any, are the qualitative and/or quantitative species or sex differences for ADME?
- What is known about the form of cobalt (particulate, ion) from ADME studies in exposed tissue, particularly in the lung?
- How can toxicokinetic models (if any) inform biological plausibility, interspecies extrapolation, or other mechanistic questions for cobalt?

**Questions related to the evaluation of human cancer studies**

- Which epidemiologic studies should be included in the review?
- What are the methodological strengths and limitations of these studies?
- What are the potential confounders for cancer risk for the tumor sites of interest in these studies?
- Is there a credible association between exposure to cobalt and cancer?
- If so, can the relationship between cancer endpoints and exposure to cobalt be explained by chance, bias, or confounding?

**Questions related to the evaluation of cancer studies in experimental animals**

- What is the level of evidence (sufficient or not sufficient) of carcinogenicity of cobalt from animal studies?
- What are the methodological strengths and limitations of the studies?
- What are the tissue sites?

**Questions related to the evaluation of mechanistic data and other relevant data**

- What are the genotoxic effects due to cobalt exposure? Does genotoxicity vary by cobalt compound?
- What are the cytotoxic or toxic effects of cobalt exposure? Does cytotoxicity or toxicity vary by cobalt compound?
- What are the major mechanistic modes of action for the carcinogenicity of cobalt?
    - What are the common key steps or mode(s) of action of toxicity or carcinogenicity across different cobalt compounds? What role and contribution does cobalt ion play in the proposed mechanism? What are the effects from exposure to particulate cobalt?
    - What factors influence biological or carcinogenic effects? How do particle size, solubility, and cellular uptake of a cobalt compound affect biological or carcinogenic effects?
    - Is there evidence that supports grouping cobalt and cobalt compounds that release cobalt ions *in vivo* together in the assessment?

### *Approach for obtaining scientific and public input*

To help address the approach to identify a common mode of action involving the cobalt ion for cobalt compounds, additional scientific input was requested early in the review process to define the scope of the review, i.e., what cobalt compound(s) could reasonably be included in this evaluation? Based on input from several scientific experts at a Cobalt Information Group Meeting convened at NIEHS on October 7, 2104, the scope of the evaluation was recommended to include cobalt and cobalt compounds that release cobalt ions in biological fluids. Technical advisors for the review of cobalt are identified on the "CONTRIBUTORS" page.

Public comments on scientific issues were requested at several times prior to the development of the 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 preparing the draft RoC monograph on cobalt for public input on the ORoC webpage for cobalt (http://ntp.niehs.nih.gov/go/730697) prior to the release of the draft monograph. Four written public comments on cobalt have been received from the public as of the date on this document.

### *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 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 cobalt began with development of a literature search strategy to obtain information relevant to the topics listed above for Sections 1 through 6 using search terms developed in collaboration with a reference librarian (see Protocol). The approximately 7500 citations identified from these searches were uploaded to web-based systematic review software for evaluation by two separate reviewers using inclusion/exclusion criteria, and 484 references were selected for final inclusion in the monograph using these criteria.

Information for the 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 cobalt compounds in humans (see Appendix C) and experimental animals (see Appendix D) were assessed based on a series of *a priori* considerations (questions and guidelines for answering the questions), which are available in the protocol (available at http://ntp.niehs.nih.gov/go/730697). Two reviewers evaluated the quality of each study. Any disagreements between the two reviewers were resolved by mutual discussion or consultation with a third reviewer in reference to the original data source. Relevant genotoxicity and mechanistic studies were also assessed for their strengths and weaknesses.

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 cobalt 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 evaluation of the mechanistic data included a complete discussion and assessment of the strength of evidence for potential modes of action for cobalt-induced neoplasia, including those involving, e.g., cytotoxicity, genotoxicity, and oxidative stress. Mechanistic data are discussed across cobalt compounds. The RoC listing criteria were then applied to the body of knowledge (cancer studies in humans and experimental animals and mechanistic data) for cobalt and cobalt compounds that release cobalt ions *in vivo* 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.

# Contributors

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# PEER REVIEW

Peer review of the Draft RoC Monograph on Cobalt and Certain Cobalt Compounds was conducted by an *ad hoc* expert panel at a public meeting held July 22, 2015, in the Rodbell Auditorium at the National Institute of Environmental Health Sciences, David P. Rall Building, Research Triangle Park, NC (see http://ntp.niehs.nih.gov/go/38854 for materials, minutes, and panel recommendations from meeting). The selection of panel members and conduct of the peer review were performed in accordance with the Federal Advisory Committee Act and Federal policies and regulations. The panel members served as independent scientists, not as representatives of any institution, company, or governmental agency.

The charge to the Peer-Review Panel was as follows:

1. To comment on the draft cancer evaluation component for cobalt and certain cobalt compounds, specifically, whether it was technically correct and clearly stated, whether the NTP had objectively presented and assessed the scientific evidence, and whether the scientific evidence was adequate for applying the RoC listing criteria.

2. To comment on the draft profile for cobalt and certain cobalt compounds, specifically, whether the scientific justification presented in the profile supported the NTP's preliminary policy decision on the RoC listing status of the substance.

The Panel was asked to vote on the following questions:

1. Whether the scientific information presented from human cancer studies supported the NTP's preliminary level of evidence conclusion of *inadequate evidence of carcinogenicity* of cobalt and certain cobalt compounds.

2. Whether the scientific information presented from studies in experimental animals supported the NTP's preliminary level of conclusion of *sufficient evidence of carcinogenicity* of cobalt and cobalt compounds that release cobalt ions *in vivo*.[1]

3. Whether NTP's preliminary policy decision to list 'cobalt and cobalt compounds that release cobalt ions *in vivo*' in the Report on Carcinogens as *reasonably anticipated to be human carcinogens* was supported by sufficient evidence of carcinogenicity from studies in experimental animals and supporting data from studies on mechanisms of carcinogenesis.

The RoC Monograph on Cobalt and Cobalt Compounds That Release Cobalt Ions *In Vivo* has been revised based on NTP's review of the Panel's peer-review comments. The Peer-Review Panel Report, which captures the Panel recommendations for listing status of cobalt and cobalt compounds that release cobalt ions *in vivo* in the RoC and their scientific comments, and the NTP Response to the Peer-Review Report are available on the Peer-Review Meeting webpage for cobalt and certain cobalt compounds (http://ntp.niehs.nih.gov/go/38854).

[1]During the meeting the Panel recommended using the definition of "certain cobalt compounds," i.e., "cobalt compounds that release cobalt ions *in vivo*" in the listing rather than the word "certain."

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# Part 1

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# 1 Chemical identification and properties

The candidate substance reviewed in this monograph is "Cobalt and cobalt compounds that release cobalt ions *in vivo*." The available database on cobalt and cobalt compounds vary by cobalt form; however, there are carcinogenicity, genotoxicity, and toxicity studies on cobalt metal and of some water-soluble and poorly soluble compounds. Of note are the two NTP bioassay studies, one with a very soluble cobalt compound, cobalt sulfate (NTP 1998), and one with cobalt metal (NTP 2014b). Together, the carcinogenicity, genotoxicity, and other mechanistic information on these representative forms of cobalt inform the discussion in this document on cobalt and cobalt compounds that release cobalt ions *in vivo*. Water-soluble cobalt compounds dissolve in the fluids outside cells for cellular uptake, while particles of poorly soluble cobalt compounds can be taken up intact by cells and release ions within the cell (see Table 1-1). Of note, vitamin $B_{12}$, which is an essential cobalt-containing nutrient, does not meet the criteria for this review because it does not release cobalt ions in acidic gastric or lysosomal fluids and passes through the body intact while bound to specific carrier proteins (Neale 1990).

Cobalt (Co) is a naturally occurring transition element with magnetic properties. It is the 33$^{rd}$ most abundant element and makes up approximately 0.0025% of the weight of Earth's crust. Cobalt is a component of more than 70 naturally occurring minerals including arsenides, sulfides, and oxides. The only stable and naturally occurring cobalt isotope is $^{59}$Co. Metallic cobalt, Co(0), exists in two allotropic forms, hexagonal and cubic, which are stable at room temperature (WHO 2006, ATSDR 2004, IARC 1991). Cobalt predominantly occurs in two oxidation states, +2 (Co(II)) and +3 (Co(III)).

## 1.1 Properties of cobalt metal and cobalt compounds, both soluble and poorly soluble

Table 1-1 presents physical and chemical properties (molecular weight, crystalline form, density or specific gravity, water solubility, and bioaccessibility) for cobalt and cobalt compounds for which animal or genotoxicity testing data are available or that are in commercial use greater than 100,000 pounds per year in the United States (per EPA Chemical Data Reporting rule). Additional cobalt compounds that do not meet either of these criteria are described in Table B-1. The physical and chemical properties are divided into three groups, including metals, soluble cobalt compounds, and poorly soluble cobalt compounds, to provide a framework for relating chemicals for which potential biological effects are unknown to chemicals for which biological effect data are available.

## 1.2 Water solubility and bioaccessibility

Evaluation of toxicological and carcinogenic effects of cobalt compounds depends largely on the release of cobalt ions that can either be transported to and taken up at target sites or released within cells from particles (see Section 6, Mechanistic and Other Relevant Effects).

### 1.2.1 Water solubility

Cobalt sulfate, chloride, and nitrate tend to be soluble in water, while oxides (including the mixed oxide, $Co_3O_4$), hydroxides, and sulfides tend to be poorly soluble or insoluble (Lison 2015). Organic cobalt compounds can be either soluble (e.g., cobalt(II) acetate) or insoluble (e.g., cobalt carbonate, cobalt(II) oxalate, cobalt propionate, cobalt stearate, cobalt naphthenate,

cobalt 2-ethyl-hexanoate) (CDI 2006) (see Table 1-1). The water solubility of cobalt compounds is largely pH dependent, and cobalt is generally more mobile in acidic solutions than in alkaline solutions.

Co(0) metal nano- (reported particle size range = 20 nm to 500 nm) and microparticles (reported particle size range = 1.9 µm to 2.7 µm) dissolve in cell-free culture medium in a concentration- and time-dependent manner while cobalt(II,III) oxide particles (reported average particle size = 372 nm) are practically insoluble in water or culture medium (Ortega *et al.* 2014, Sabbioni *et al.* 2014, Ponti *et al.* 2009). Smaller particles dissolve faster than larger particles (Lison 2015, Kyono *et al.* 1992).

**Table 1-1. Physical and chemical properties for cobalt metal and representative cobalt compounds[a]**

| Name (+2 valence unless otherwise indicated) | CAS No. | Formula | Molecular weight | Physical form | Density or specific gravity | Solubility (grams per 100 cc cold water) | Particle size, μm (surface area, $m^2/g$) | Bioaccessiblity (% solubility in gastric/lysosomal fluids) |
|---|---|---|---|---|---|---|---|---|
| **Metal** | | | | | | | | |
| *Cobalt* | 7440-48-4 | Co | 58.9 | Grey hexagonal or cubic metal | 8.92 | 0.00029 | 7.2 (1.20) | 100/100 |
| *Cobalt nanoparticles* | 7440-48-4 | Co | 58.9 | – | – | – | – | – |
| **Soluble cobalt compounds** | | | | | | | | |
| *Sulfate heptahydrate* | 10026-24-1 | $CoSO_4•7H_2O$ | 281.1 | Red pink, monocl. | 1.95 | 60.4 | 942.0 (3.49) | 100/100 |
| *Chloride* | 7646-79-9 | $CoCl_2$ | 129.9 | Blue hexagonal leaflets | 3.36 | 45 | 458.0 (0.78) | 100/100 |
| *Acetate* (org.) | 71-48-7 | $Co(C_2H_2O_2)_2$ | 249.1 | Red-violet, monocl. | 1.70 | 34.8 | – | 98/80 |
| *Nitrate* | 10141-05-6 | $CoN_2O_6$ | 182.9 | Red powder or crystals | 2.49 | 67.0 | – | 96/100 |
| **Poorly soluble compounds** | | | | | | | | |
| *(II) Oxide* | 1307-96-6 | CoO | 74.9 | Green-brown cubic | 6.45 | 0.00049 | 0.692 (4.79) | 100/92.4 |
| (II, III) Oxide | 1308-06-1 | $Co_3O_4$ | 240.8 | Black, cubic | 6.07 | 0.00016 | – | 2/2 (50%[b]) |
| 2-ethyl-hexanoate (org.) | 136-52-7 | $Co(C_8H_{15}O_2)_2$ | 173.7 | Blue liquid (12% Co) | 1.01 | 0.630 | 0.73 (ND) | 100/100 |
| Carbonate (org.) | 513-79-1 | $CoCO_3$ | 118.9 | Red, trigonal | 4.13 | 0.00114 | 1.834 (103.05) | 100/100 |
| Naphthenate (org.) | 61789-51-3 | $Co(C_{11}H_7O_2)_2$ | 401.3 | Purple liquid (6% Co) | 0.97 | 0.0293 | 0.70 (ND) | 100/100 |
| Hydroxide | 21041-93-0 | $Co(OH)_2$ | 93.0 | Rose-red, rhomb | 3.60 | 0.00032 | – | 95/98 |
| *Sulfide* | 1317-42-6 | CoS | 91.0 | Reddish octahedral | 5.45 | 0.00038 | – | 1/1 |
| Oxalate (org.) | 814-89-1 | $CoC_2O_4$ | 147.0 | White or reddish | 3.02 | 0.00322 | – | 37/55 |
| Propionate (org.) | 1560-69-6 | $Co(C_3H_5O_2)_2$ | 205.1 | Reddish solid | – | 7.49 | – | 91/94 |
| Stearate (org.) | 1002-88-6 | $Co(C_{18}H_{35}O_2)_2$ | 625.9 | Grey solid | – | 0.00705 | – | 14/16 |

Sources: SciFinder; PubChem Compounds Database; ChemIDplus Database; Cobalt Development Institute (CDI) Report (2006); Hazardous Substances Data Bank (HSDB); Stopford *et al*. (2003). Personal communication, CDI, July 21, 2015, and October 19, 2015.

org. = organic compound; all others are inorganic..

[a]Cobalt forms or compounds tested for carcinogenicity or genetic toxicity, or for possible mechanisms of action are italicized.

### 1.2.2 Bioaccessibility

While water solubility represents a measure of a compound's tendency to release ions available for biological uptake, solubilization of some water-insoluble compounds may be enhanced in biological fluids at low pH and in the presence of binding proteins (IARC 2006) (see below). The bioavailability (i.e., extent of systemic absorption) of cobalt and other metal species is determined by its solubility in biological fluids and these studies have been conducted on cobalt compounds using synthetic equivalents of gastric and intestinal fluids (for ingestion exposure); alveolar, interstitial, and lysosomal fluids (for inhalation exposure); perspiration fluids (for dermal exposure); and synovial fluid (for metal joint prostheses), identified from exposure scenarios including drawing with soft pastels and manufacturing and use of alloy materials (Hillwalker and Anderson 2014, Brock and Stopford 2003, Stopford *et al.* 2003, Personal communication from CDI to Dr. Ruth Lunn). For metals like cobalt, with several species with different valence states having dissimilar solubility characteristics existing in different compounds, *in vivo* bioavailability testing can be cost prohibitive and time consuming *in vivo* bioavailability. Therefore, in lieu of *in vivo* testing, measured solubility of compounds in artificial fluids (i.e., bioaccessibility) can often be used as a surrogate for bioavailability. However, a simple model with an artificial biological fluid and a cobalt compound does not provide for potential equilibrium between cellular compartments such as the lysosomes and the cytoplasm and ultimately the extracellular fluid. Some compounds that appear to be insoluble in these tests may actually be soluble in biological fluid soluble *in vitro* and would be expected to release ions in *vivo;* thus, insoluble compounds should be tested by additional assays.

Cobalt metal, and several water-soluble compounds (e.g., cobalt sulfate heptahydrate, chloride, cobalt acetate) and poorly soluble compounds (e.g., cobalt(II) oxide, bis(2-ethyl-hexanoate), carbonate, naphthenate) were found to be soluble in biological fluids, suggesting that they release cobalt ions (see the right-hand column of Table 1-1 and Appendix Table B-1). Although very low values ($\leq$ 2%) for bioavailability have been reported for the sulfide and mixed (II,III) oxide and intermediate values (14% to 55%) for stearate and oxalate under the same test conditions, more sensitive tests have indicated that $Co_3O_4$ (cobalt II, III oxide) is soluble in biological fluids. Kreyling et al. (1990) reported that cobalt ions dissolved from $Co_3O_4$ particles of different sizes were ultimately released into the culture medium with up to 50% solubilized from 0.3 μm particles after 2 weeks of culture (larger particles released 2% to 5% under the same conditions). The differences in findings between this study and the 2% solubility in gastric or lysosomal fluid may be due to the interaction of cobalt particles within cells as the soluble fraction of an initial particle mass of $Co_3O_4$ increased with time when the particles were taken up by alveolar macrophages in culture compared with the solubility in culture medium alone. Moreover, Ortega *et al*. 2014), found that intracellular concentrations of solubilized cobalt ions were similar for $Co_3O_4$ and cobalt chloride in human lung cells, suggesting that $Co_3O_4$ would release cobalt ions *in vivo* (see Section 6.1 for details)

The intra- and inter-laboratory variability of bioaccessibility testing results for metals and metal compounds including cobalt powder and cobalt oxide in synthetic gastric, perspiration, lysosomal, and interstitial fluids was reported by Henderson *et al.* (2014, and the authors concluded that results demonstrated overall satisfactory within-laboratory variability. Relative standard deviation (RSD) values and associated threshold levels were used to assess sample-to-sample result variability (i.e., repeatability) and lab-to-lab result variability (i.e., reproducibility).

Acceptable variability for this analysis was defined as RSD for repeatability < 10% (per Wragg *et al.* 2011) and RSD for reproducibility < 20% (per Wragg *et al.* 2011 and Ashley *et al.* 2012). Henderson *et al.* (2014) further noted that absolute bioaccessibility results in some biological fluids might vary between different laboratories.

Cobalt(II) ions released into solution can form complexes with organic or inorganic anions with equilibrium conditions determined by activity of electrons (Eh), activity of hydrogen ions (pH), and anion presence (Smith and Carson 1981). In general, lower pH generates higher free Co(II) concentrations in solution, and higher pH gives rise to cobalt-carbonate complex formation (WHO 2006). The *in vivo* concentration of free Co(II) ions is relatively low because these cations are complexed in the presence of physiological concentrations of phosphates and also bind nonspecifically to proteins such as albumin (Lison 2015).

### 1.3 Variability of valence

As noted above, cobalt exists primarily as (Co(II)) and (Co(III)), and Co(II) is much more stable in aqueous solution (Paustenbach *et al.* 2013, Nilsson *et al.* 1985). Electron-donor ligands (e.g., $NH_3$) can stabilize Co(III) in aqueous solution (IARC 1991). In acid solution, Co(II) is the stable form in the absence of electron-donor ligands, and Co(III) ions are so unstable that they quickly reduce to Co(II), oxidizing water and liberating oxygen. In contrast, air or hydrogen peroxide can oxidize Co(II) to the Co(III) complex which is more stable in alkaline solutions containing ammonium hydroxide or cyanide. This interconversion between Co(II) and Co(III) is important in the use of cobalt compounds as catalysts and paint driers, and in biological reactions involving vitamin $B_{12}$ (Paustenbach *et al.* 2013, IARC 1991).

Cobalt is present in its stable +2 valence state in the environment and in most commercially available cobalt compounds, with the exception of the mixed oxide (Co(II,III) or $Co_3O_4$) (Paustenbach *et al.* 2013, IARC 1991). Some simple salts of cobalt in its +3 valence state (e.g., $Co_2O_3$) have been used commercially. Cobalt compounds of commercial and toxicological interest include cobalt metal, alloys, and composite materials; oxides (e.g., cobalt oxide and tetraoxide); and salts (e.g., cobalt(II) chloride, sulfide, and sulfate) (Lison 2015). Important salts of carboxylic acids include formate, acetate, citrate, naphthenate, linoleate, oleate, oxalate, resinate, stearate, succinate, sulfamate, and 2-ethylhexanoate. (See Tables 1-1 and B-1.)

Cobalt can also exist in -1, +1, and +4 oxidation states (Nilsson *et al.* 1985). Cobalt is in its -1 state in cobalt carbonyls such as $[Co(CO)_4]H$ and in cobalt-nitrosyls, in its +1 state in some cobalt-cyanide complexes, and in its +4 state in compounds with cobalt bonded to fluoride or oxygen.

### 1.4 Summary

Cobalt metal particles have been found to be 100% bioaccessible (i.e., dissolving to release cobalt ions) in artificial gastric and lysosomal fluids. The soluble compounds, cobalt(II) sulfate heptahydrate and cobalt(II) chloride, and the poorly soluble compounds, cobalt(II) oxide, cobalt bis(2-ethyl hexanoate), cobalt carbonate, and cobalt naphthenate, also were completely (or almost completely) soluble in the two acidic fluids. Although very low values ($\leq$ 2%) for bioavailability have been reported for the sulfide and mixed (II,III) oxide and intermediate values (14% to 55%) for stearate and oxalate under the same test conditions, more sensitive tests have found higher bioavailability values for cobalt(II, III) oxide (i.e., $Co_3O_4$) and have reported its uptake by lung cells, which suggests that $Co_3O_4$ would release ions *in vivo.* The metals and poorly soluble compounds tended to be less bioaccessible in neutral biological fluids, which is consistent with the pH dependence for releasing cobalt ions in solution.

# 2 Human Exposure

This section describes cobalt mining and production (Section 2.1); use (Section 2.2); recycling of electronic and electrical waste (Section 2.3); biomonitoring and environmental monitoring studies and methods to measure exposure to cobalt and cobalt compounds (Section 2.4); exposure in the workplace (Section 2.5); surgical implants (Section 2.6); potential exposure from other sources such as food, consumer products, tobacco, and medical products (Section 2.7); and potential for environmental exposure (Section 2.8). The material presented in Sections 2.1 through 2.8 is summarized in Section 2.9. Studies of cobalt alloys were not considered informative for either animal tumor studies or human carcinogenicity studies because they are not useful for evaluating potential carcinogenic effects from cobalt *per se*; cobalt alloys are a source of exposure to humans, and thus are discussed in this section.

### 2.1 Mining and production

Cobalt is most often found in ores associated with copper or nickel, but may also be a by-product of zinc, lead, and platinum-group metals (CDI 2006, Davis 2000). Cobalt-containing ores often contain arsenic, such as safflorite, $CoAs_2$; skutterudite, $CoAs_3$; erythrite, $Co_3(AsO_4)_2 \cdot 8H_2O$; and glaucodot, CoAsS (CDI 2006, ATSDR 2004, Davis 2000). The largest cobalt reserves are in the Congo (Kinshasa), Australia, Cuba, Zambia, Canada, Russia, and New Caledonia (Shedd 2014a). Most U.S. cobalt deposits are in Minnesota, but other important deposits are in Alaska, California, Idaho, Missouri, Montana, and Oregon. Except for Idaho and Missouri, future production from these deposits would be as a by-product of another metal.

Except for a negligible amount of by-product cobalt produced as an intermediate product from mining and refining platinum-group metals ore, the United States did not refine cobalt in 2012 (Shedd 2014b). Since 2009, no cobalt has been sold from the National Defense Stockpile. In 2012, 2,160 metric tons of cobalt was recycled from scrap. Cobalt has not been mined in the United States in over 30 years (ATSDR 2004); however, a primary cobalt mine, mill, and refinery are currently being established in Idaho that will produce more than 1,500 tons of high-purity cobalt metal annually to capitalize on increasing cobalt demand driven in part by growth in "green" energy technology (e.g., rechargeable batteries for electric and hybrid electric vehicles or portable electronics applications (Farquharson 2015, Mining Technology Market and Customer Insight 2015, Rufe 2010). Based on a presentation dated May 2015, preliminary work on the site has been completed (Formation Metals, Inc. 2015).

Cobalt and several cobalt compounds are high-production-volume chemicals based on their production or importation into the United States in quantities of 1 million pounds or more per year. Table 2-1 shows U.S. cobalt and cobalt compound production volumes for 2012 that exceed 100,000 pounds per year; the highest United States production volume is for cobalt (7440-48-4) (23,384,002 lb). Table 2-2 lists recent U.S. imports and exports of cobalt and cobalt compounds; the highest import value is for "unwrought cobalt excluding alloys, including powders" (16,151,599 lb) and the highest export value is for "cobalt, wrought, and articles thereof" (4,841,750 lb).

**Table 2-1. U.S. cobalt compounds production volumes for 2012 exceeding 100,000 pounds per year[a]**

| CAS Number[b] | Cobalt compound | Quantity (lb)[c] |
|---|---|---|
| 7440-48-4 | Cobalt | 23,384,002 |
| 21041-93-0 | Cobalt hydroxide ($Co(OH)_2$) | 4,709,137 |
| 136-52-7 | Cobalt 2-ethylhexanoate | 4,294,523 |
| 1307-96-6 | Cobalt oxide (CoO) | 1,385,848 |
| 513-79-1 | Cobalt carbonate | 1,038,821 |
| 10124-43-3 | Cobalt sulfate | 1,000,000–10,000,000 |
| 10141-05-6 | Cobalt nitrate | 1,000,000–10,000,000 |
| 1308-06-1 | Cobalt oxide ($Co_3O_4$) | 1,000,000–10,000,000 |
| 1560-69-6 | Cobalt propionate | 1,000,000–10,000,000 |
| 71-48-7 | Cobalt acetate | 1,000,000–10,000,000 |
| 814-89-1 | Cobalt oxalate | 600,000 |
| 1317-42-6 | Cobalt sulfide (CoS) | 254,733 |
| 61789-52-4 | Cobalt tallate | 192,900 |
| 61789-51-3 | Cobalt naphthenate | 100,000–500,000 |

[a]Three cobalt compounds for which properties are reported in Table 1-1 are not listed in Table 2-1 because of the production level or lack of reported production data. Cobalt oxide (11104-61-3) production levels were 94,139 lb in 2012. Cobalt sulfide (12013-10-4, $CoS_2$) and cobalt chloride (7646-79-9, $CoCl_2$) production levels for 2012 were withheld by the manufacturers.
[b]CAS# were identified from multiple sources: ChemIDplus Database; EPA Chemical Data Reporting (2012); PubChem Compounds Database; Ullmann's Encyclopedia of Industrial Chemistry (2012).
[c]EPA Chemical Data Reporting (2012). See reference list for specifics.

**Table 2-2. U.S. imports and exports of cobalt compounds for 2013 (converted from kg by NTP)**

| Cobalt-compound/category | U.S. imports (lb) | U.S. exports (lb) |
|---|---|---|
| Cobalt acetates | 342,918 | 520,996 |
| Cobalt carbonates | 1,193,856 | –[a] |
| Cobalt chloride | 215,661 | 14,304 |
| Cobalt ores and concentrates | 82,376 | 1,004,825 |
| Cobalt oxides and hydroxides; commercial cobalt oxides | 5,300,984 | 902,467 |
| Cobalt sulfate | 1,319,004 | –[a] |
| Cobalt waste and scrap | 1,549,151 | 1,557,515 |
| Cobalt, wrought, and articles thereof | 550,887 | 4,841,750 |
| Other cobalt mattes and intermediate products of cobalt metallurgy; powders | 1,992,434 | –[a] |
| Unwrought cobalt alloys | 2,132,331 | –[a] |
| Unwrought cobalt excluding alloys, including powders | 16,151,599 | –[a] |

Source: (USITC 2014).
[a]No specific Schedule B code (i.e., 10-digit classification numbers administered and used by the U.S. Commerce Department to collect and publish statistics on physical goods exported from the United States to another country) was identified.

## 2.2 Use

Cobalt is used in numerous commercial, industrial, and military applications. On a global basis, the largest use of cobalt is in rechargeable battery electrodes; however, rechargeable battery production in the United States has been very limited (NIST 2005).

In 2012, the reported U.S. consumption of cobalt was approximately 8,420 metric tons (Shedd 2014b) for the uses shown below in Table 2-3.

**Table 2-3. 2012 U.S. consumption and use pattern for cobalt**

| End use | Consumption (metric tons cobalt content) | Percent of total consumption (%) |
|---|---|---|
| Superalloys | 4,040 | 48 |
| Chemical and ceramic | 2,300 | 27.3 |
| Cemented carbides | 774 | 9.2 |
| Other alloys[a] | 699 | 8.3 |
| Steels | 548 | 6.5 |
| Miscellaneous and unspecified | 63 | 0.7 |

Source: (Shedd 2014b).
[a]Includes magnetic, nonferrous, and wear-resistant alloys and welding materials.

The main uses of cobalt can be grouped into the following general categories: metallurgical; cemented carbides and bonded diamonds; chemicals; and electronics and "green" energy (CDI 2006). Cobalt nanoparticles are used for medical applications (e.g., sensors, MRI contrast enhancement, drug delivery); nanofibers and nanowires also are being used for industrial applications.

### 2.2.1 Metallurgical uses

Metallurgical uses of cobalt include use in superalloys; magnetic alloys, low expansion alloys, nonferrous alloys, steels, coatings, and bone and dental prostheses (IARC 1991, Davis 2000, CDI 2006, Ohno 2010). Support structures for heart valves are also manufactured from cobalt alloys (IARC 1991).

### 2.2.2 Cemented carbides and bonded diamonds

Cemented tungsten carbides ("hard metals") are composites of tungsten carbide particles (either tungsten carbide alone or in combination with smaller amounts of other carbides) with metallic cobalt powder as a binder, pressed into a compact, solid form at high temperatures by a process called sintering (NTP 2009, IARC 1991). Cobalt is also used in diamond tools from steel with microdiamonds impregnated into a surface cobalt layer (CDI 2006, IARC 2006).

### 2.2.3 Chemical uses

Uses of cobalt compounds include as pigments for glass, ceramics, and enamels, as driers for paints, varnishes, or lacquers, as catalysts, as adhesives and enamel frits (naphthenate, stearate, oxide), as trace mineral additives for animal diets, and in rechargeable batteries (see Section 2.2.4) (CDI 2006, WHO 2006, ATSDR 2004, IARC 1991) (see Table 2-4). Compounds of

commercial importance are the oxides, hydroxide, chloride, sulfate, nitrate, phosphate, carbonate, acetate, oxalate, and other carboxylic acid derivatives (IARC 1991). A past use of cobalt (as cobalt sulfate) was as an additive in some beers to increase the stability of the foam (NTP 1998).

**Table 2-4. Uses for representative inorganic and organic cobalt compounds**

| | Inorganic | | | | | Organic | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Use** | **$Cl^-$** | **$OH^-$** | **$NO_3^-$** | **$O^{2-}$** | **$SO_4^{2-}$** | **2-EH** | **$C_2H_3O_2^-$** | **$CO_3^{2-}$** | **Pro** |
| Adhesives | | | | X | | X | | | |
| Animal diets | | | X | X | X | | X | X | |
| Batteries | | X | X | | | | | | |
| Catalysts | X | X | X | X | | | X | X | |
| Driers | | X | | X | | X | X | | X |
| Pigments | X | | X | X | X | | X | X | |

Sources: CDI 2006, Donaldson and Beyersmann 2012, Richardson and Meshri 2001.
$Cl^-$ = chloride, $OH^-$ = hydroxide, $NO_3^-$ = nitrate, $O^{2-}$ = oxide, $SO_4^{2-}$ = sulfate, 2-EH = 2-ethyl-hexanoate, $C_2H_3O_2^-$ = acetate, $CO_3^{2-}$ = carbonate, Pro = propionate

### 2.2.4 Electronics and "green" energy

Due to increased demand for portable rechargeable electronic devices, one of the fastest growth areas for cobalt use worldwide is in high-capacity, rechargeable batteries (Shedd 2014b, CDI 2006, Davis 2000). Cobalt is used in nickel-cadmium, nickel-metal hydride, and lithium-ion battery technologies. Applications for batteries containing cobalt compounds include portable computers, mobile telephones, camcorders, toys, power tools, and electric vehicles. Cobalt is also used in integrated circuit contacts and leads and in the production of semiconductors (CDI 2006, IARC 1991).

Cobalt is the key element in several forms of "green" energy technology applications including gas-to liquid (GTL) and oil desulfurization, coal-to liquid (CTL), clean coal, solar panels, wind and gas turbines, and fuel cells (Rufe 2010). Research is ongoing on use of cobalt-based catalysts in sunlight-driven water splitting to convert solar energy into electrical and chemical energy (Deng and Tüysüz 2014).

## 2.3 Recycling of electronic and electrical waste

Electronic and electrical waste (i.e., e-waste) includes components of electrical and electronic equipment such as rechargeable batteries. Automobile rechargeable battery recycling is generally considered to be in its infancy, though more developed for nickel-metal hydride batteries than for lithium-ion batteries (Gaines 2014, Evarts 2013).

Recycling for Li-ion batteries is more difficult because these batteries have various active material chemistries (e.g., lithium cobalt oxide, lithium manganese oxide, lithium nickel manganese cobalt oxide, etc.), contain a wider variety of materials in each cell, are not currently subject to recycling regulations, and will not be ending their useful lives in large numbers for about 10 years (Gaines 2014, Cadex Electronics Inc. 2015). Further, recent trends to reduce costs of battery manufacturing and to optimize performance (e.g., safety, durability, and output) have

lead manufacturers to seek other non-cobalt-based constituents (e.g., iron phosphate, manganese spinel, and nickel manganese), which might reduce the economic incentive for recycling (Retriev Technologies 2015).

### 2.4 Biomonitoring and environmental monitoring for cobalt

Information on biomonitoring and environmental monitoring for cobalt discussed below includes evidence of exposure (Section 2.4.1) and exposure surrogates and analytical methods (Section 2.4.2).

#### 2.4.1 Evidence of exposure

Evidence for widespread exposure to cobalt and cobalt compounds comes from biological monitoring data measuring cobalt levels in urine, blood, hair, nails, and tissues in individuals exposed to cobalt from occupational and non-occupational sources (see Appendix B, Tables B-2 and B-3 for levels reported in these studies, source of exposure, and geographical location, and Figures 2.1 and 2.2). Several publications measured trace metals (e.g., heavy metals and essential metals) in tissue from cancer patients with a referent group or tissue. Several clinical surveys have compared levels of cobalt in cancer patients and non-cancer patients (see Appendix B, Table B-4). Several of the studies are of people residing in the United States, and thus demonstrate U.S. exposure. Data are reported for both a surrogate of recent (urine) and longer term (hair) exposure to cobalt.

Studies measuring cobalt in the urine of people exposed to cobalt from different sources indicate that the highest levels were generally seen for occupational exposures and failed hip implants; with lower levels of exposure from normal implants, the environment, or in the general public (source of exposure unknown). (See Figure 2.1, which depicts the mean (or median) levels of urinary cobalt in these populations from the studies reported in Appendix B, Table B-2.) The geometric mean urinary cobalt concentration for the U.S. general public for the most recent National Health and Nutrition Examination Survey (NHANES) year (2011 to 2012) for which data are available is 0.326 µg/L; urinary cobalt measurements in the U.S. general public have remained consistent since 1999, with the geometric mean values ranging from 0.316 to 0.379 µg/L (CDC 2015).

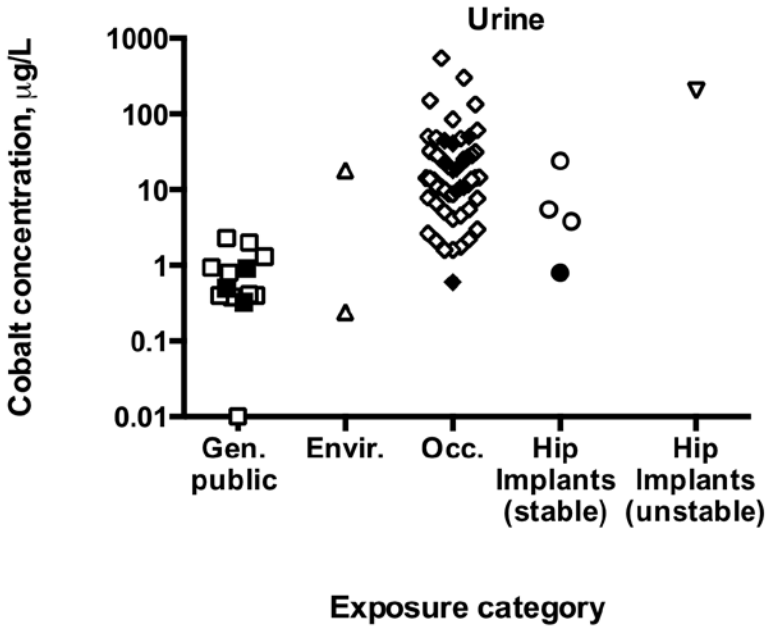


**Figure 2-1. Cluster graph of urine cobalt levels**

Filled symbols = U.S. data; open symbols = non-U.S. data.

Reported mean levels of cobalt in hair are highest among some workers and among patients with unstable hip implants (Figure 2-2). Cobalt levels in samples from patients with stable hip implants are next highest, with levels taken from populations at risk of environmental exposure and in the general public being the lowest. Measurements of cobalt in hair in the latter groups overlap significantly; while one study indicates that cobalt levels among environmentally exposed populations are similar to levels in workers.

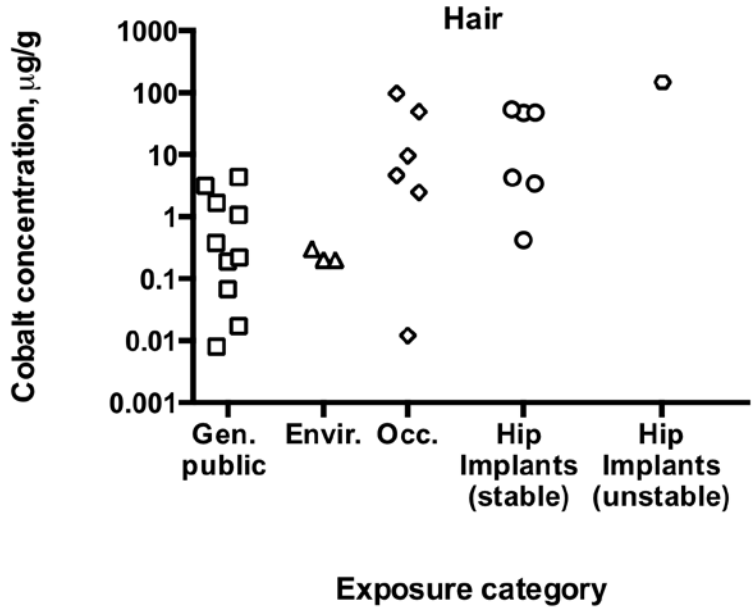


**Figure 2-2. Cluster graphs of cobalt levels in hair**

Filled symbols = U.S. data; open symbols = non-U.S. data.

### 2.4.2 Exposure surrogates and analytical methods

#### Exposure surrogates

Urinary cobalt is considered a good indicator of absorbed cobalt (IARC 2006, WHO 2006), especially from recent exposures (ATSDR 2004). Urinary and blood cobalt levels are more reflective of recent exposure for soluble compounds than less soluble compounds (ATSDR 2004). Although investigators have reported measurements of cobalt in whole blood, plasma, and serum, no consensus seems to exist for which of these provides the best relationship with levels of exposure to cobalt.

Because hair fixes trace elements in a permanent, chemically homogeneous matrix, hair samples reflect a time-integrated exposure (i.e., current and past exposure levels) over the previous few months, depending on the length of the hair sample (Suzuki and Yamamoto 1982) and hair metal contents provides a better estimate than blood in assessing the environmental risk to toxic metals for infrequent and highly variable exposures (Bax 1981, Petering *et al.* 1973). The average concentration of cobalt in hair is over 100 times greater than that in blood (Underwood 1977). Average metal concentration can be obtained by measuring bulk concentration from a length of hair equal to a few weeks' growth, by measuring the variation along the length of long hair equal to several months (Suzuki and Yamamoto 1982), or by taking periodic samples over time (Laker 1982).

Toenail clippings reflect time-integrated exposure occurring in the timeframe of 12 to 24 months prior to clipping, and thus are useful biomarkers of exposure when a single sample is assumed to represent long-term exposure (He 2011, Fleckman 1985). However, toenails generally provide larger samples and represent more distant past exposures because they take longer to grow out. Nails are considered to be relatively sheltered from environmental contaminants (relative to hair, which, though formed from the same keratinous tissue of nail, can be contaminated by dyeing, bleaching, and permanent waving). Toenails are also more convenient to collect and store than blood (Garland *et al.* 1993). However, nails can become contaminated through the use of nail polishes, some medications, and use of contaminated cutters to produce clippings (He 2011).

The source of exposure for urinary cobalt levels in the general public (see Figure 2-1) is unknown. Likewise, the source of exposure for the general public is unknown for the exposure surrogates (e.g., hair and nails).

#### Analytical methods

Analytical methods for cobalt in biological materials include graphite furnace atomic absorption spectrometry (GF-AAS), inductively coupled plasma-atomic emission spectrometry (ICP-AES), differential pulse cathodic stripping voltammetry (DPCSV), and colorimetric determination (ATSDR 2004). Technical improvements using the Zeeman background correction in GF-AAS have increased specificity and lowered the background (see IUPAC guidelines in Cornelis *et al.* 1995). The colorimetric method generally has limited utility because it has poor sensitivity (Alessio and Dell'Orto 1988). The ICP-AES method is used by NIOSH for exposure to elements in blood and urine (NIOSH 1994), and NHANES uses a related method of inductively coupled plasma-mass spectrometry (ICP-MS) for urine heavy metals. With the exception of the colorimetric method, these methods require wet (acid) digestion followed by flame ionization to

liberate free cobalt ions for detection of total cobalt. Thus, in any biological sample, the original form of the cobalt, whether inorganic cobalt or part of an organic molecule like vitamin $B_{12}$, cannot be determined with these methods (IARC 2006, WHO 2006).

The analytical method for air sampling (NIOSH Method 7027) involves collecting the sample on a 0.8 µm pore size cellulose ester membrane filter and analyzing the sample using a flame atomic absorption spectrophotometer. This is an elemental analysis and is not compound specific (NIOSH 1994). For surface sampling, the analytical method (NIOSH Method 9102) involves collecting a wipe sample on a pre-packaged moist disposable towelette (e.g., Wash 'n Dri or ASTM equivalent per ASTM E1792-01) and analyzing the sample using ICP-AES. Likewise, this method also is an elemental analysis and is not compound specific (NIOSH 2003).

### 2.5 Characterization of exposure in the workplace

The primary route of occupational exposure to cobalt is via inhalation of dust, fumes, or mists or gaseous cobalt carbonyl; however, dermal contact with hard metals and cobalt salts can result in systemic uptake. Occupational exposure to cobalt occurs during (1) the refining of cobalt, (2) the production of cobalt powders, (3) use in the hard metal, diamond tool and alloy industries (including the production and use of these cobalt-containing products), use to make chemicals, pigments and electronics, and (4) in the recycling of electronics. Workers regenerating spent catalysts may also be exposed to cobalt sulfides. U.S. occupational exposure data are available for the following industries: metallurgical; cemented carbides and bonded diamonds; chemicals and pigments; and electronics, "green" energy, and recycling.

Occupational exposure has been documented by measurements of cobalt in ambient workplace air, in worker blood and urine, and in deceased worker lung tissue (CDC 2013, IARC 2006, ATSDR 2004, IARC 1991). The NIOSH National Occupational Exposure Survey (NOES) estimated that approximately 386,500 workers were potentially exposed to cobalt and cobalt compounds (NIOSH 1990). The survey was conducted from 1981 to 1983, and the NOES database was last updated in July 1990.

**Table 2-5. Workplace air levels of cobalt**

| Exposure scenario (Country) | Cobalt in workplace air mean (range) in µg/m$^3$ | Reference(s) |
|---|---|---|
| ***Cobalt production*** | | |
| Production of cobalt metal and cobalt salts (Belgium) | 127.5 (2–7,700) | (Swennen *et al.* 1993) |
| Production of cobalt salts (Russian Federation) | (0.05–50) | (Talakin *et al.* 1991) |
| Nickel refining (Russian Federation) | Up to 4 | (Thomassen *et al.* 1999) |
| Production of cobalt metal and cobalt salts (Finland) | < 100 | (Linna *et al.* 2003) |
| Conversion of cobalt metal to cobalt oxide (South Africa) | 9,900 (highest reported) | (Coombs 1996) |
| Nickel refining (Norway) | < 150[a] | (Grimsrud *et al.* 2005) |

| Exposure scenario (Country) | Cobalt in workplace air mean (range) in µg/m$^3$ | Reference(s) |
|---|---|---|
| ***Metallurgical*** | | |
| Metallurgical (United States) | ND–32,000[b] | (Beaucham *et al.* 2015, Daniels *et al.* 1986, Decker 1991, Deitchman *et al.* 1994, Deng *et al.* 1990, Hervin and Reifschneider 1973, Kiefer *et al.* 1994, Marsh and Esmen 2007, McCleery *et al.* 2001, NIOSH 1972) |
| Production of Stellite, a cobalt-containing alloy (NR) | Several hundred µg/m$^3$ | (Simcox *et al.* 2000) |
| Production of Stellite, a cobalt-containing alloy (NR) | 9 | (Kennedy *et al.* 1995) |
| Welding with Stellite, a cobalt-containing alloy (NR) | 160 | (Ferri *et al.* 1994) |
| ***Cemented carbides and bonded diamonds*** | | |
| Cemented carbides and bonded diamonds (United States) | ND–1,622.1 | (Bryant *et al.* 1987, Burr *et al.* 1988, Burr and Sinks 1988, Edmonds *et al.* 1981, Kerndt *et al.* 1986, McManus 1982, Sahakian *et al.* 2009, Salisbury and Seligman 1987, Tharr and Singal 1987) |
| Use of cobalt-containing diamond tools (Italy) | 690<br>115 (with improved ventilation) | (Ferdenzi *et al.* 1994) |
| Use of cobalt-containing diamond tools (NR) | (0.1–45) | (van den Oever *et al.* 1990) |
| ***Chemicals and pigments*** | | |
| Chemicals (United States) | ND–21 | (Almaguer 1987, Apol 1976, Burr *et al.* 2005, Chen *et al.* 2008, Durgam and Aristeguieta 2010, Hall 2003, Rosensteel and Meyer 1977, Zey 1985) |
| Painting porcelain plates with cobalt compounds (Denmark) | 80<br>26 (after Danish surveillance program) | (Christensen 1995, Poulsen *et al.* 1995, Christensen and Poulsen 1994) |
| ***Electronics, "green" energy, and recycling*** | | |
| Electronics and "green" energy (United States) | ND–1.17 | (Beaucham *et al.* 2014, Thoburn and Larsen 1976) |
| Recycling batteries to recover cobalt (NR) | Up to 10 | (Hengstler *et al.* 2003) |

Source: (IARC 2006, http://www2a.cdc.gov/hhe/search.asp).
NR = Not reported.
[a]Reported as 0.15 mg/m$^3$. Among the 3,500 personal samples from the breathing zone taken, cobalt values above 50 mg/m$^3$ [50,000 µg/m$^3$] (3 measurements) were excluded.
[b]OSHA noted that this sample appeared to be tampered with. The next highest value was 21,000 µg/m$^3$.

### 2.5.1 Cobalt production (metals and salts)

Cobalt concentrations in workplace air have been reported to range from 2 to 50,000 µg/m$^3$ from hydrometallurgical purification (to produce cobalt metal, cobalt oxide, and cobalt salt products), battery recycling (to recover cobalt for reuse), and cobalt compound (acetate, chloride, nitrate, and sulfate) production. Worker urinary cobalt for these facilities ranged from 1.6 to 2,038 µg/g creatinine (IARC 2006).

Available data on emissions of cobalt from electrochemical production of cobalt (in nickel refining plants) indicate that exposure to cobalt is expected to be low. Based on analysis of nearly 3,500 personal breathing zone samples analyzed for cobalt at a Norwegian nickel refinery, the median 8-hour time-weighted arithmetic average exposures were less than 0.1 µg/m$^3$ (Grimsrud *et al.* 2005). A European report of processes to produce nickel and cobalt noted that total emissions of cobalt to air from grinding/leaching, solvent extraction, and final recovery or transformation were 0.9 kilograms per metric ton of cobalt produced (IPPC 2014).

### 2.5.2 Cemented carbides and bonded diamonds

Exposure to cobalt can occur in hard-metal production, processing, and use and during the maintenance and re-sharpening of hard-metal tools and blades. Air levels of cobalt vary across different stages of the hard-metals manufacturing process, with levels for operations involving cobalt metal powder often reaching maximum levels between 1,000 and 10,000 µg/m$^3$ (NTP 2009). Continuous recycling of coolants used during the grinding of hard-metal tools after sintering and during maintenance and re-sharpening has been reported to increase concentrations of dissolved cobalt in the metal-working fluid, which can be a source of exposure to ionic cobalt in aerosols from the coolants (IARC 2006). Wet grinding processes are reported to produce higher cobalt concentrations than dry grinding processes due to coolant mist emissions.

Diamond polishers inhale metallic cobalt, iron, and silica from the use of cobalt discs to polish diamond jewels. Cobalt concentrations in workplace air have been reported to range from 0.1 to 45 µg/m$^3$ in diamond jewel polishing and as high as 690 µg/m$^3$ in wood and stone cutting (air concentrations dropped to 115 µg/m$^3$ after implementation of ventilation system improvements in the wood and stone cutting factory) (IARC 2006).

U.S. cobalt occupational exposure level data available from NIOSH Hazard Evaluation and Technical Assistance (HETA) surveys for cemented carbides and bonded diamonds indicate the following: workplace air levels range from not detected to approximately 1,620 µg/m$^3$; workplace arithmetic mean, median, or geometric mean urine levels range from 9.6 µg/L or µg/g creatinine to 27 µg/L or µg/g creatinine (it is generally accepted that 1 L of urine contains 1 g of creatinine); the one reported geometric mean blood cobalt level was 2.0 µg/L; surface wipe levels range from not detected to 4,400 µg/100 cm$^2$; skin (i.e., hand or neck) wipe levels range from 2 µg/sample to approximately 22,330 µg/sample (from charging operations in a cemented tungsten carbide plant); geometric mean exhaled breath condensate levels range from 5.5 µg/L to 6.2 µg/L; cobalt in bulk samples of work materials ranges from 0.033% to 8.97%; cobalt in settled dust samples from work areas ranges from 0.2% to 2% (Bryant *et al.* 1987, Burr *et al.* 1988, Burr and Sinks 1988, Edmonds *et al.* 1981, Kerndt *et al.* 1986, McManus 1982, Sahakian *et al.* 2009, Salisbury and Seligman 1987, Tharr and Singal 1987). One extreme value of 438,000

µg/m$^3$ was reported for weighing and mixing operations in a plant in the United States (Sprince *et al.* 1984).

#### 2.5.3 Metallurgical-related industries

Occupational exposure results from production and use (e.g., welding, grinding, and sharpening) of cobalt alloys. Concentrations of cobalt in workplace air of facilities producing and using Stellite have been reported to range from 9 to several hundred micrograms per cubic meter (IARC 2006).

U.S. cobalt occupational exposure level data available from NIOSH HETA surveys for metallurgical-related industries indicate the following: workplace air levels range from not detected to 32,000 µg/m$^3$; workplace arithmetic mean, median, or geometric mean urine levels range from 0.6 µg/L or µg/g creatinine to 50.4 µg/L or µg/g creatinine (it is generally accepted that 1 L of urine contains 1 g of creatinine); surface wipe levels range from 2.1 µg/100 cm$^2$ to 760 µg/100 cm$^2$; and the one reported value for cobalt in bulk samples of work materials was 0.08% (Beaucham *et al.* 2015, Daniels *et al.* 1986, Decker 1991, Deitchman *et al.* 1994, Deng *et al.* 1990, Hervin and Reifschneider 1973, Kiefer *et al.* 1994, Marsh and Esmen 2007, McCleery *et al.* 2001, NIOSH 1972).

#### 2.5.4 Chemicals and pigments

Cobalt concentrations in workplace air at Danish porcelain factories using cobalt-aluminate spinel or cobalt silicate dyes have been reported to exceed the Danish hygienic standard by 1.3- to 172-fold (Tüchsen *et al.* 1996) (see Section 4). Due to improvements made to workplace conditions in the 1982 to 1992 time period, concentrations of cobalt in workplace air decreased from 1,356 nmol/m$^3$ [80 µg/m$^3$] to 454 nmol/m$^3$ [26 µg/m$^3$] and worker urinary cobalt decreased from 100-fold to 10-fold above median concentration of controls (IARC 2006, 1991).

U.S. cobalt occupational exposure level data available from NIOSH HETA surveys for chemicals and pigments indicate the following: workplace air levels range from not detected to 21 µg/m$^3$; surface wipe levels range from not detected to 250 µg/100 cm$^2$; and cobalt in bulk samples of work materials ranges from less than 0.01% to 0.03% (Almaguer 1987, Apol 1976, Burr *et al.* 2005, Chen *et al.* 2008, Durgam and Aristeguieta 2010, Hall 2003, Kawamoto *et al.* 1999, Rosensteel and Meyer 1977, Zey 1985).

#### 2.5.5 Electronics, "green" energy, and recycling of electronic and electrical waste

Recycling can be classified as either informal or formal. Informal e-waste recycling which is dismantling of end-of-life electronics by primitive techniques (e.g., mechanical shredding and open burning) can result in the release of cobalt and other toxic chemicals and generally occurs in developing countries such as China, India, Pakistan, Vietnam, Ghana, and Nigeria (Asante *et al.* 2012, Grant *et al.* 2013, Wang *et al.* 2009. Biomonitoring data from an informal e-waste recycling site in Ghana showed a geometric mean urinary cobalt level of 1.6 µg/L for e-waste recycling workers (Asante *et al.* 2012). Formal e-waste recycling involves the use of properly designed equipment to safely remove recoverable materials from obsolete electronics while protecting workers and the environment. Personal breathing zone (PBZ), blood, and urinary cobalt have been reported for three formal e-waste recycling sites in Sweden (Julander *et al.* 2014). PBZ data showed a geometric mean cobalt concentration of 0.066 µg/m$^3$ in the collected

inhalable fraction and 0.041 μg/m$^3$ in the total dust fraction. Median blood cobalt reported for two sampling occasions were 0.081 μg/L (first occasion) and 0.073 μg/L (second occasion, significantly higher than in office workers, $P \leq 0.05$). Median urinary cobalt reported for two sampling occasions were 0.25 μg/L and 0.21 μg/L.

U.S. cobalt occupational exposure level data available from NIOSH HETA surveys for electronics, "green" energy, and recycling indicate the following: workplace air levels range from not detected to 1.17 μg/m$^3$; the one reported surface wipe level was reported as "detected" (level of detection = 0.02 μg/sample); and the one reported skin (i.e., hand or neck) wipe level was reported as "detected" (level of detection = 0.04 μg/sample) (Beaucham *et al.* 2014, Thoburn and Larsen 1976).

### 2.6 Surgical implants

Surgical implantation (e.g., orthopedic joint replacements, spinal system, dental implants, etc.) can result in exposure to cobalt. The total number of hip replacements in the United States has been variously reported as 120,000 per year (Polyzois *et al.* 2012) or 400,000 per year (Devlin *et al.* 2013, Frank 2012). Most, but not all, hip, knee, and shoulder replacements have at least one articular bearing surface composed of CoCrMo alloy. If the bearing surface(s) or modular taper junction(s) of the total joint replacement are composed of CoCrMo alloy, cobalt ions may be released into the body throughout the lifetime of the device. Blood cobalt ion concentrations generally increase by 5- to 10-fold from preoperative to postoperative levels (Polyzois *et al.* 2012) (see Table B-2 for cobalt levels in blood from individuals with implants). Metal-on-metal (MoM) hip implants include two CoCrMo alloy bearing surfaces articulating against each other and may release more cobalt than joint replacement devices with a single CoCrMo alloy bearing surface and are generally associated with mean or median blood or serum cobalt of 1.89 to 4.97 μg/L and mean or median urine cobalt of 3.8 to 24.0 μg/L (see Table B-2).

One in eight total hip implants requires revision within 10 years, and 60% of those are due to wear-related complications (Bradberry *et al.* 2014). All hip implants that contain metal components contain cobalt as part of cobalt-chromium-molybdenum alloys (Devlin *et al.* 2013, Sampson and Hart 2012). Release of metal from implants results from both wear and corrosion, which is caused by body fluids contacting the metal surfaces or by formation of an electrochemical couple between different metal components (Sampson and Hart 2012). Implants that have failed because of excessive wear or corrosion have been associated with systemic cobalt toxicity in some cases, and cobalt levels in some of these individuals have been reported. Blood levels associated with toxicity may be related to the type of implant; levels were higher among 10 patients with failed ceramic prosthesis (median blood concentration = 506 μg/L; range = 353 to 6,521) compared with eight patients with toxicity from implanted MoM devices (median 34.5 μg/L range = 13.6 to 398.6) (Bradberry *et al.* (2014)). Peak blood cobalt concentrations were > 250 μg/L. Removal of a joint replacement device that is associated with high cobalt ion levels generally results in decreased cobalt ion levels The Medicines and Healthcare Products Regulatory Agency (MHRA) in the United Kingdom issued a safety alert that proposed a level of 7 μg/L cobalt as an action level for further clinical investigation and action (MHRA 2012) and 10 μg/L was proposed by the Mayo Clinic in the United States (Mayo Clinic 2015).

### 2.7 Other sources of exposure: Food, consumer and other medical products and tobacco

Exposure to cobalt in the general population also occurs via inhalation of ambient air and ingestion of drinking water; however, food has been reported to be the largest source of cobalt exposure to the general population (ATSDR 2004). ATSDR reported an average daily dietary intake of cobalt in Canada of 11 µg/day. The food groups with the largest contributions to this intake were bakery goods and cereals (29.8%) and vegetables (21.9%). No estimate for an average dietary intake of cobalt in the United States was identified. Reported values for cobalt content of foods can vary due to differences in environmental cobalt levels, analytical difficulties, and inadequate analytical techniques.

A past use of cobalt (as cobalt sulfate) was as an additive in some beers (NTP 1998), which was based on a U.S patent (USPTO 1958) for the use of cobaltous nitrate or cobaltous chloride to reduce the tendency for beer to gush or overfoam and to increase its foam stability. However, in 1963 to 1964 a form of cardiomyopathy was linked with consumption of beer containing cobalt (Alexander 1969), and in 1966 the FDA prohibited addition of cobaltous compounds to any human food, including beer, in the United States (see Regulations and Guidelines).

Higher cobalt intake may result from consumption of over-the-counter or prescription vitamin and mineral preparations (e.g., cobalt chloride or vitamin $B_{12}$ formulations). In the 1970s, oral intake of cobalt chloride was used to increase red blood cell counts in anemic patients (but discontinued when enlarged thyroids and goiters were observed at higher doses). In the last decade, oral administration of cobalt chloride has been used to correct excessive estrogen production during female hormone replacement therapy (Tvermoes *et al.* 2013, Unice *et al.* 2012, Lippi *et al.* 2005).

Cobalt is present in consumer products including cleaners, detergents, and soaps (ATSDR 2004). The NLM Household Products Database listed 6 products containing cobalt as an ingredient: 1 nickel metal hydride battery (5% to 10% cobalt), 4 dishwasher detergents (2 powders and 2 semi-solid pouches containing powder), and 1 spray car wax product (HPD 2014).

Different brands of tobacco have been reported to contain cobalt ranging from < 0.3 to 2.3 µg/g dry weight; 0.5% of the cobalt content is transferred to mainstream smoke (WHO 2006). Smokers with no occupational exposure have been reported to have a significantly higher mean urinary cobalt concentration (0.6 µg/L, SD = 0.6) than non-smokers (0.3 µg/L, SD = 0.1); cobalt concentrations in blood were the same (Alexandersson 1988, as cited in IARC 1991). However, examination of urinary cobalt levels between cigarette smoke-exposed and unexposed NHANES participants for survey years 1999 to 2004 indicates that there was no significant difference in urinary cobalt levels for smokers and non-smokers (unadjusted for creatinine) (Richter *et al.* 2009). Richter *et al.* noted that while cobalt deficiencies were not reported, smoking does interfere with vitamin $B_{12}$ absorption.

### 2.8 Potential for environmental exposure

Information on potential for environmental exposure discussed below includes data for releases (Section 2.8.1), occurrence (Section 2.8.2), and exposure (Section 2.8.3).

### 2.8.1 Releases

Approximately 75,000 metric tons of cobalt enters the global environment annually (CDI 2006, Shedd 1993). Cobalt is released through the natural processes of rock weathering and biological extraction (i.e., biochemical processes of bacteria and other microorganisms that extract cobalt from rocks and soils). Figure 2-3 shows cobalt released from anthropogenic processes (i.e., burning of fossil fuels, metal production and use). Similar amounts come from natural (40,000 metric tons) and anthropogenic (35,000 metric tons) sources; the majority of the natural source contribution is from biochemical processes and the majority of the anthropogenic contribution is from metal production and use.

Cobalt's widespread use in numerous commercial, industrial (e.g., mining and extraction from ores), and military applications results in releases to the environment through various waste streams. According to the TRI, total reported on- and offsite release of cobalt and cobalt compounds was approximately 5.5 million pounds from 723 facilities in 2013 (TRI 2014c, 2014b, 2014a). Calculations based on media-specific release data from TRI indicate that releases to land accounted for 82% of total releases, offsite disposal for 15%, and underground injection, air, and water for 1% each in 2013. The scenarios that generally contribute most to U.S. releases of cobalt and cobalt compounds as reported to EPA (TRI 2014d) include gold, copper, and nickel ore mining, hazardous waste treatment and disposal, non-ferrous metal smelting and refining, fossil fuel electric power generation, and chemical operations (e.g., petrochemical manufacturing and synthetic dye and pigment manufacturing). Recycling of e-waste can result in releases to the environment (particularly from informal e-waste recycling; see Section 2.5.5). Other potential exposure scenarios (e.g., copper smelting) exist, but no air data were identified.

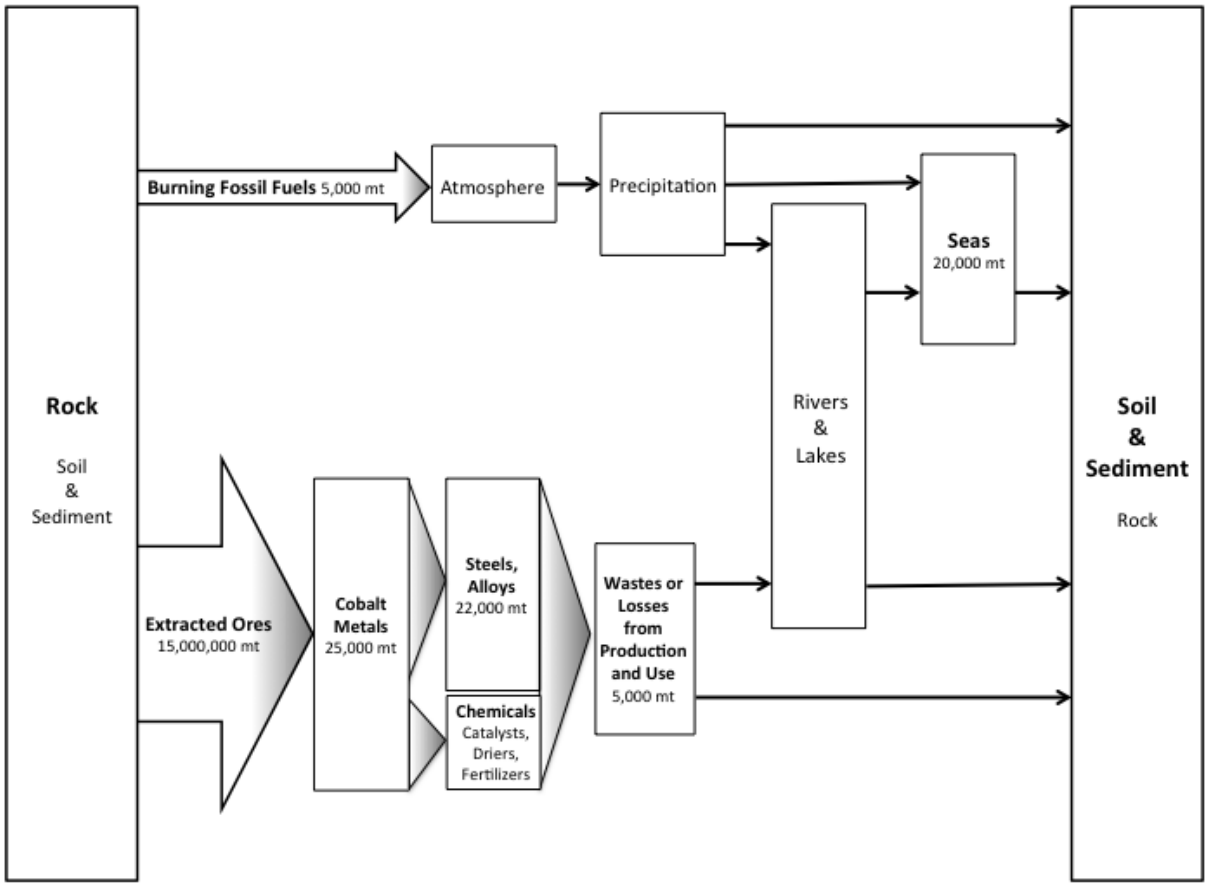


**Figure 2-3. Flow of cobalt released from anthropogenic processes**

Adapted from (CDI 2006, Shedd 1993).

### 2.8.2 Occurrence

The average concentration of cobalt in ambient air in the United States has been reported to be approximately 0.4 ng/m$^3$ (ATSDR 2004). Levels can be orders of magnitude higher near source areas (e.g., near facilities processing cobalt-containing alloys, compounds, etc.). Sources of cobalt in the atmosphere can be natural (e.g., wind-blown continental dust, seawater spray, volcanoes, forest fires, and marine biogenic emissions), and anthropogenic (e.g., burning of fossil fuels, mining and smelting of cobalt-containing ores, hazardous waste treatment and disposal, etc.) (TRI 2014a, EPA 2012, ATSDR 2004).

Median cobalt concentration in U.S. drinking water has been reported to be < 2.0 µg/L; however, levels as high as 107 µg/L have been reported. It is unclear whether higher levels could indicate cobalt being picked up in distribution systems (ATSDR 2004). Cobalt concentrations have been reported to range from 0.01 to 4 µg/L in seawater and from 0.1 to 10 µg/L in freshwater and groundwater (IARC 2006).

Studies have reported cobalt soil concentrations ranging from 0.1 to 50 ppm. However, soils near ore deposits, phosphate rock, ore smelting facilities, soils contaminated by airport or highway

traffic, or other source areas may contain higher concentrations (e.g., soil cobalt concentrations as high as 12,700 ppm reported near hard-metal facilities) (IARC 2006). The soil concentration of cobalt available to be taken up by plants has been reported to range from 0.1 to 2 ppm (IARC 2006).

### 2.8.3 Exposure

Information on exposures to cobalt from environmental releases is limited, and no data for U.S. exposures were identified. Biomonitoring research has confirmed general public exposure to cobalt in scenarios including non-ferrous metal mining (see Figure 2-1). A study of metal exposure from mining and processing of non-ferrous metals in Katanga, Democratic Republic of Congo found that geometric mean urinary cobalt concentrations were 4.5-fold higher for adults and 6.6-fold higher for children in urban and rural communities near mines and metal smelters than in rural communities without mining or industrial activities (Cheyns *et al.* 2014).

## 2.9 Summary and synthesis

Several lines of evidence indicate that a significant number of people living in the United States are exposed to cobalt and cobalt compounds. This evidence includes cobalt and several cobalt compounds being high-production-volume chemicals, widespread use in numerous commercial, industrial, and military applications, and biological monitoring data (i.e., urine, blood, hair, and nails) demonstrating exposure in occupationally and non-occupationally exposed populations. TRI data indicate that production- and use-related releases of cobalt and cobalt compounds have occurred at numerous industrial facilities in the United States.

Biomonitoring studies measuring cobalt in the urine of people exposed to cobalt from different sources indicate that the highest levels were generally seen for occupational exposures and unstable hip implants; lower cobalt levels were due to exposure from stable hip implants or the environment, or in the general public (source of exposure unknown). In general, levels of cobalt in blood (including whole blood, plasma, and serum), in hair, and in nails show a similar pattern to those for urinary cobalt levels.

The primary route of occupational exposure to cobalt is via inhalation of dust, fumes, mists containing cobalt, or gaseous cobalt carbonyl. Dermal contact with hard metal and cobalt salts can result in systemic uptake. Occupational exposure to cobalt occurs during (1) the refining of cobalt, (2) the production of cobalt powders, (3) use in the hard metal, diamond tool and alloy industries (including the production and use of these cobalt-containing products), use to make chemicals, pigments and electronics, and (4) in the recycling of electronics (more of a global than U.S. concern). Workers regenerating spent catalysts may also be exposed to cobalt sulfides. Occupational exposure has been documented by measurements of cobalt in ambient workplace air, worker blood and urine, and deceased worker lung tissue. U.S. occupational exposure data are available for the following industries: metallurgical; cemented carbides and bonded diamonds; chemicals and pigments; and electronics, “green” energy, and recycling.

Some of the highest levels of cobalt reported in blood or urine have been associated with failed medical devices (such as metallic hip implants containing cobalt alloys). Levels of cobalt reported in blood or urine from stable hip implants are generally less than those reported for

unstable hip implants and occupational exposures but more than those reported for exposures from the environment or in the general public.

Although exposure to cobalt in the general public can occur via inhalation of ambient air and ingestion of drinking water, however, food has been reported to be the largest source of cobalt exposure to the general public. Higher cobalt intake may result from consumption of over-the-counter or prescription mineral preparations. Other sources of exposure to cobalt and cobalt compounds include some household consumer products, primarily dishwasher detergents and nickel metal hydride batteries.

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# 3 Disposition and Toxicokinetics

Disposition and toxicokinetics refer to how a chemical can enter and leave the body, what happens to it once it is in the body, and the rates of these processes. Section 3.1 discusses the disposition of cobalt and cobalt compounds in humans and experimental animals, and toxicokinetic data are presented in Section 3.2. Disposition and toxicokinetic data are important because they describe various factors that affect the toxicity of a chemical. These factors include routes and rates of absorption, distribution, and retention; routes of elimination; and gender and/or species differences in these factors. The mechanistic implications of these data are discussed in Section 7.

## 3.1 Disposition

Disposition includes absorption, deposition, distribution, metabolism, retention, and excretion. The disposition of cobalt is affected by several factors including the chemical form, solubility, dose, particle size, route of exposure, nutritional status, and age of the species exposed. The primary exposure, distribution, and excretion pathways of cobalt are illustrated in Figure 3-1. Data derived from studies in humans are discussed in Section 3.1.1 while studies in experimental animals are discussed in Section 3.1.2.

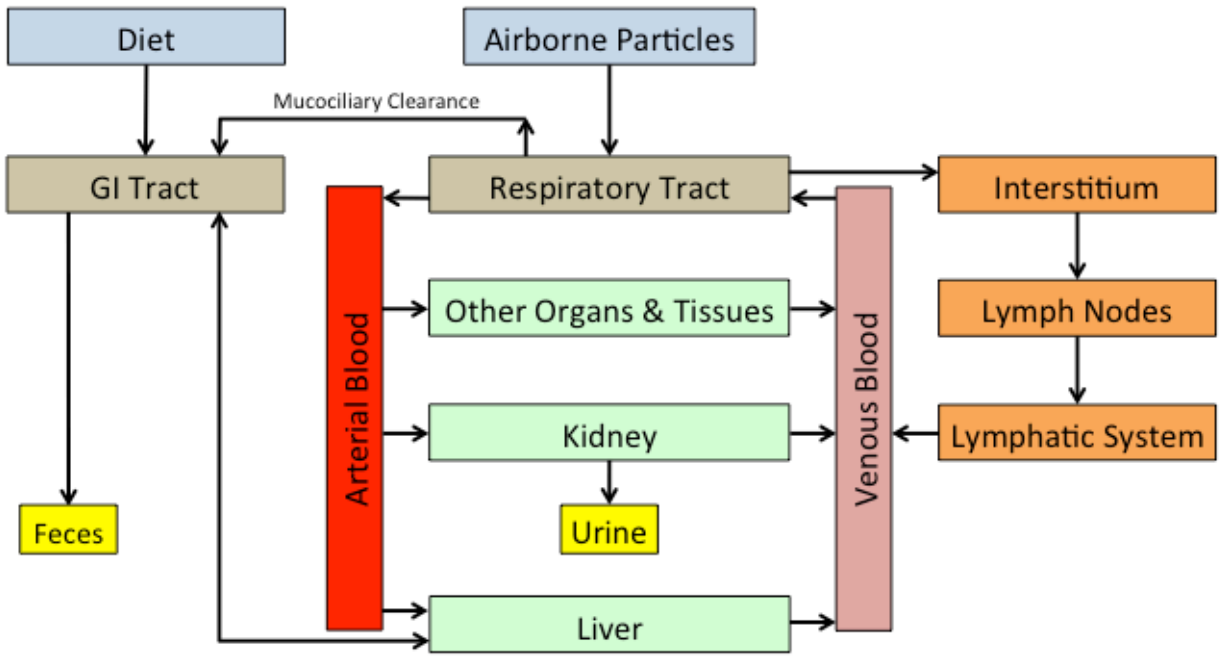


**Figure 3-1. Cobalt disposition**

Source: Adapted from (Keegan *et al.* 2008).

### 3.1.1 Humans

Dietary intake of cobalt has been reported as the largest source of exposure for the general population; an average daily intake of cobalt in Canada was reported as 11 ug/day (ATSDR

2004) (see Section 2.7). Most of the cobalt in the diet is inorganic with a very small fraction from vitamin $B_{12}$ (Lison 2015). The normal range of cobalt concentrations (nonoccupational exposure) in the blood and urine are about 0.1 to 0.5 μg/L and < 2 μg/L, respectively (Paustenbach *et al.* 2013, IARC 2006) (see Section 2). About 90% to 95% of cobalt in blood is bound to serum albumin while the concentration of free cobalt is about 5% to 12% of the total cobalt concentration (Paustenbach *et al.* 2013, Simonsen *et al.* 2012). Letourneau *et al.* (1972) showed that a dose of vitamin $B_{12}$ had no impact on retention of inorganic cobalt in humans. The total body burden of cobalt in humans is estimated as 1.1 to 1.5 mg with about 85% present in the vitamin $B_{12}$ organometallic complex (Paustenbach *et al.* 2013, WHO 2006).

#### Absorption

Cobalt absorption from the gastrointestinal (GI) tract is highly variable, with reported values ranging from < 5% to 97% (Holstein *et al.* 2015, NTP 2014b, Paustenbach *et al.* 2013, IARC 2006, WHO 2006, Smith *et al.* 1972). Unice *et al.* (2012) suggested a central tendency value of 25% for GI absorption of soluble inorganic cobalt while Unice *et al.* (2014) assumed GI absorption of 20% to 45% for aqueous forms and 10% to 25% for solid forms. Cobalt concentrations in whole blood increased 9 to 36 times above normal background concentrations in volunteers who ingested a liquid dietary supplement that contained cobalt chloride for up to 16 days (Tvermoes *et al.* 2013). Soluble cobalt compounds are better absorbed than insoluble forms (Christensen and Poulsen 1994, Christensen *et al.* 1993a). For example, men and women volunteers who ingested tablets containing soluble cobalt chloride ($CoCl_2$) had approximately 10-fold higher concentrations of cobalt in blood and 50- to 90-fold higher concentrations in urine than when they ingested tablets containing insoluble cobalt oxide ($Co_3O_4$) (Christensen *et al.* 1993a). Controlled studies in human volunteers also indicate that GI uptake is higher in women than in men with adjusted mean whole blood concentrations about two-fold higher in women (Finley *et al.* 2013, Christensen *et al.* 1993a). The higher cobalt uptake in women may be due to a higher incidence of iron deficiency since cobalt absorption efficiency is higher in individuals with iron deficiency (31% to 71% compared to 18% to 44% in control subjects) (Sorbie *et al.* 1971, Valberg *et al.* 1969). Meltzer *et al.* (2010) reported that cobalt whole blood concentrations were significantly elevated in women with low serum ferritin concentrations compared to women with higher serum ferritin concentrations and in women with mild to moderate anemia compared to women with only slightly reduced hemoglobin. Low iron status was a prerequisite for high blood concentrations of cobalt; however, not everyone with low iron status had increased blood levels of cobalt. These data suggest that cobalt and iron may share a common gastrointestinal uptake mechanism that may be upregulated with anemia or iron deficiency (Paustenbach *et al.* 2013). Other nutritional factors may affect cobalt absorption due to the formation of complexes with certain organic anions (e.g., amino acids) present in foods.

Studies describing absorption of cobalt from the respiratory tract in humans are limited. Cobalt levels in blood and urine of workers generally increase in proportion to inhalation exposure levels to airborne cobalt dust and fumes, especially when workers were exposed to soluble cobalt-containing particles (NTP 2014b, IARC 2006). The pattern of urinary excretion of cobalt in workers exposed to less soluble cobalt oxide particles indicated a lower absorption rate and longer retention time in the lungs. Deposition in the respiratory tract primarily depends on particle size and breathing pattern (WHO 2006, ATSDR 2004). In general, particles larger than 2 μm tend to deposit in the upper respiratory tract due to higher airstream velocities and inertial

impaction. These particles are readily cleared through mucociliary action and swallowed. Smaller particles escape inertial impaction and deposit in the bronchiolar or alveolar regions via sedimentation and diffusion. Particles deposited in the respiratory tract may dissolve and be absorbed into the blood or undergo phagocytosis or endocytosis by macrophages. In addition, some nanoparticles can translocate rapidly from the lungs to the mediastinal lymph nodes and bloodstream (Luyts *et al.* 2013). Recent *in vitro* studies with human lung cells show that insoluble cobalt oxide particles (CoO or $Co_3O_4$) are readily taken up through endocytosis and are partially solubilized at the low pH within lysosomes while soluble cobalt salts utilize cellular transporters such as calcium channels or the divalent metal ion transporter to enter cells (Ortega *et al.* 2014, Sabbioni *et al.* 2014, Smith *et al.* 2014, Papis *et al.* 2009). Controlled aerosol studies using human volunteers show that about half of the initial lung burden of inhaled cobalt oxide ($Co_3O_4$) particles may remain in the respiratory tract after six months (Bailey *et al.* 1989, Foster *et al.* 1989).

Dermal absorption of cobalt was demonstrated in two studies that measured increased cobalt concentrations in the urine of volunteers who immersed their hands in hard metal dust containing 5% to 15% cobalt for 90 minutes (Scansetti *et al.* 1994) or in a used coolant solution containing 1,600 mg/L cobalt for one hour (Linnainmaa and Kiilunen 1997). Cobalt also accumulated in the fingernails of three cobalt-sensitive patients after immersing a finger in a cobalt salt solution for 10 minutes/day for 2 weeks (Nielsen *et al.* 2000). *In vitro* percutaneous absorption studies were conducted with cobalt powder dispersed in synthetic sweat and applied to human skin mounted on Franz diffusion cells (Larese Filon *et al.* 2009, 2007, 2004). The mean permeation flux was 0.0123 $\mu g/cm^2/hr$, the lag time was 1.55 hr, and the permeation coefficient was 0.00037 cm/hr. Median cobalt concentrations in the receiving phase indicated that significantly more (~400 fold) cobalt penetrated damaged skin compared with intact skin (Larese Filon *et al.* 2009). Cobalt was detected in its ionic form in both the donor and the receiving phase. Significant amounts of cobalt also remained within the skin. These experiments showed that skin absorption was closely related to the capacity of synthetic sweat to oxidize metallic cobalt powder to soluble cobalt ions. No significant dermal absorption occurred when cobalt was dispersed in a saline solution (Larese Filon *et al.* 2004).

#### Distribution and excretion

Cobalt occurs in most tissues of non-occupationally exposed people because it is a component of vitamin $B_{12}$. In humans, inorganic cobalt is distributed to liver, kidney, heart, and spleen with lower concentrations found in bone, hair, lymph, brain, and pancreas (Paustenbach *et al.* 2013, WHO 2006). Cobalt levels measured in blood and urine from various exposed populations compared to control populations are discussed in Section 2.3 and summarized in Figure 2-1 and Table B-2 In addition, several case-referent studies compared cobalt tissue levels in patients dying from cancer with patients dying from other causes (see Appendix B). Cobalt chloride administered intravenously (i.v.) or orally to human volunteers was distributed primarily to the liver (Jansen *et al.* 1996, Smith *et al.* 1972). Whole body radioisotope scans (measured at various times up to 1,000 days) following i.v. administration of inorganic cobalt indicated that 10% to 30% (mean 20%) was found in the liver (Smith *et al.* 1972). Cobalt levels in plasma declined rapidly in this study due to rapid distribution to tissues and renal excretion; however, about 9% to 16% of the administered dose was retained with a half-life of about 800 days. Measurements of cobalt retention for up to 1,018 days indicated that about one fifth of the total body content

was present in the liver. Cobalt can also transfer to human milk and across the placenta (Rudge *et al.* 2009, Wappelhorst *et al.* 2002). Most of the cobalt in plasma is bound to leukocytes or plasma proteins with a maximum free fraction of 12%. Free cobalt is also taken up by red blood cells via a membrane transport pathway shared with calcium (Simonsen *et al.* 2012, Simonsen *et al.* 2011). Uptake of cobalt by red blood cells is practically irreversible because the ions bind to hemoglobin and are not extruded by the calcium pump. Thus, it has been speculated that cobalt partitions primarily into tissues with high calcium turnover and accumulates in tissues with slow turnover of cells. Although elevated concentrations of cobalt have been reported in the liver and kidney (oral or parental exposure) or lung (inhalation of insoluble particles), cobalt levels in the body do not appear to increase in any specific organ with age (Lison 2015, Paustenbach *et al.* 2013, IARC 2006).

Renal excretion of absorbed cobalt is rapid over the first days following exposure but is followed by a second, slower phase that lasts several weeks (Simonsen *et al.* 2012, IARC 2006). However, a small proportion (~10%) is retained in the tissues with a biological half-life of 2 to 15 years. Controlled experimental studies in humans indicate that 3% to 99% of an orally administered dose of cobalt is excreted in the feces and primarily represents unabsorbed cobalt (WHO 2006). Fecal elimination decreases as cobalt solubility increases. Following i.v. administration of cobalt chloride to 6 volunteers, fecal elimination accounted for about 2% to 12% of the administered dose while about 28% to 56% was eliminated in the urine after 8 days (Smith *et al.* 1972). Valberg *et al.* (1969) reported similar results in subjects administered cobalt by intramuscular injections and followed for 10 days (~6% excreted in feces and 58% in urine). Solubility and particle size affect elimination following inhalation exposure (WHO 2006). Clearance of cobalt particles from the lungs has been reported to follow three-phase kinetics (see Section 3.2.1). Large particles are rapidly cleared from the upper airways via the mucociliary pathway, swallowed, and eliminated in the feces. Urinary excretion of inhaled cobalt particles increases with time. Foster *et al.* (1989) reported that following inhalation of cobalt oxide ($Co_3O_4$) particles, about 17% was cleared mechanically to the gastrointestinal tract and eliminated in the feces within the first week. After 6 months, about 33% of the initial lung burden was eliminated in the urine and about 28% was eliminated in the feces.

### 3.1.2 Experimental animals

The disposition of cobalt has been investigated in mice, rats, hamsters, guinea pigs, rabbits, dogs, miniature swine, and baboons and show some similarities with human studies. These data are briefly reviewed below. As in humans, cobalt as part of vitamin $B_{12}$ is an essential micronutrient in experimental animals. However, cobalt deficiency has been described in ruminants (e.g., sheep, goats, and cattle) raised in areas with very low cobalt (Yamada 2013). Cobalt supplements were beneficial in these cases because cobalamin can be synthesized by gut bacteria and absorbed.

#### Absorption

Cobalt absorption in experimental animals is highly variable and depends on the chemical form of the compound, age of the animal, species, and nutritional status (NTP 2014b, WHO 2006, Ayala-Fierro *et al.* 1999). In rats, cobalt chloride was absorbed more efficiently from the gastrointestinal tract than insoluble cobalt oxide ($Co_3O_4$) (13% to 34% compared to 1% to 3%) (NTP 2014b). Gastrointestinal absorption of soluble cobalt compounds was much lower in cows

(1% to 2%) and guinea pigs (4% to 5%) compared with rats. Cobalt absorption was 3% to 15% greater in young rats and guinea pigs than in adults (Naylor and Harrison 1995). As observed in humans, cobalt absorption was increased in iron-deficient rats (Thomson *et al.* 1971).

Inhalation studies of cobalt metal, cobalt oxides, or soluble cobalt salts in experimental animals show that dissolved cobalt is absorbed rapidly from the lungs while a small percentage is absorbed over several months (NTP 2014b, Leggett 2008, IARC 2006, NTP 1998, Kyono *et al.* 1992, IARC 1991). Cobalt particles are mechanically cleared by mucociliary action and swallowed or phagocytized by macrophages. The fraction of the remaining lung content of cobalt oxide ($Co_3O_4$) translocated to blood per day (i.e., dissolution of particles and absorption into the blood) varied according to particle size, particle surface area, species, and time (Kreyling *et al.* 1991a, Andre *et al.* 1989, Bailey *et al.* 1989, Collier *et al.* 1989, Patrick *et al.* 1989). Initially, translocation of the smaller particles (0.8 μm) ranged from about 0.4%/day in baboons to about 1.4%/day in HMT (inbred strain) rats. Initial translocation rates for the larger particles (1.7 μm) were lower in all species and ranged from about 0.2%/day in baboons to 0.6%/day in HMT rats (Bailey *et al.* 1989). Translocation rates for higher density $Co_3O_4$ particles were about a factor of 3 slower than for less dense particles (Kreyling *et al.* 1991a, Bailey *et al.* 1989). Translocation rates reported by Bailey *et al.* (1989) showed a variety of different forms with time, particularly for the smaller particles; this is discussed further in the following section (Figure 3-2). Translocation of cobalt from the lung to the blood also was significantly faster in younger rats compared with older rats (Collier *et al.* 1991).

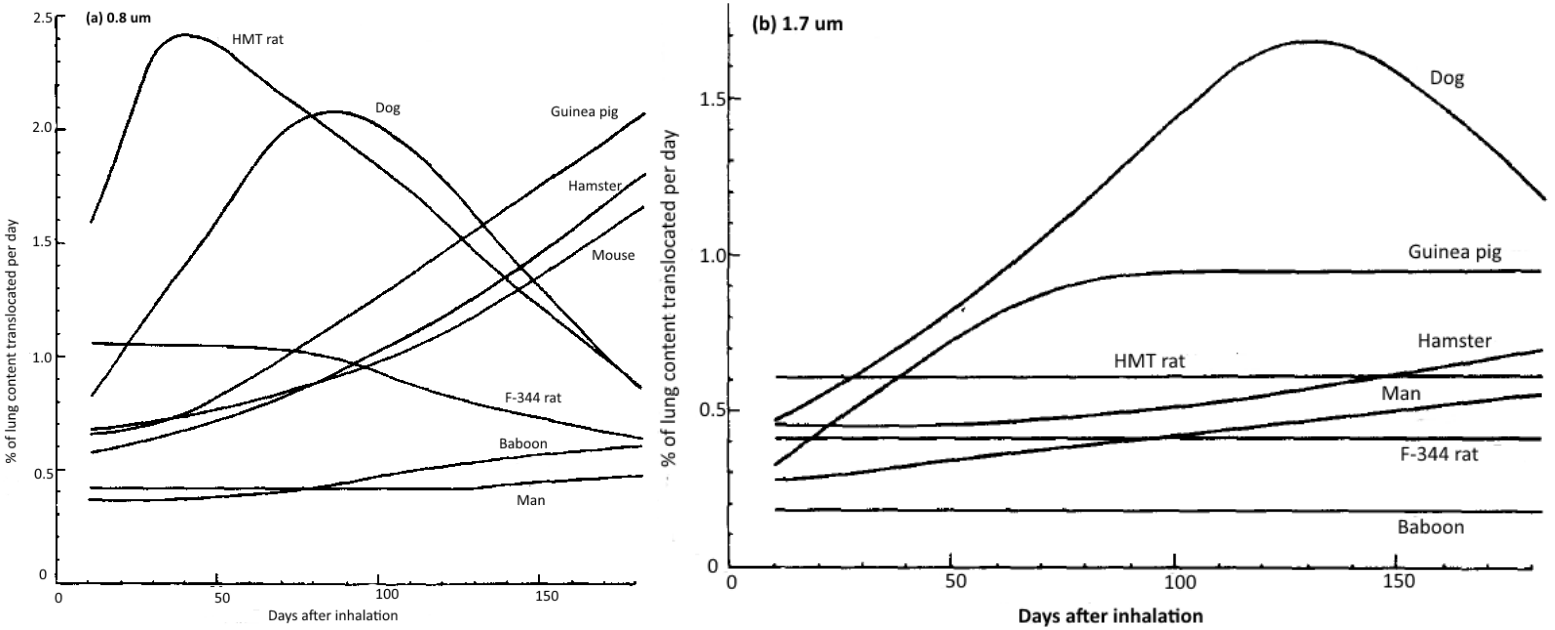


**Figure 3-2. Rate of translocation of cobalt from lung to blood following inhalation of cobalt oxide particles**

Source: (Bailey *et al.* 1989). Used with permission.

Dermal absorption of cobalt (applied as cobalt chloride) has been investigated in mice, guinea pigs, and hamsters (Lacy *et al.* 1996, Kusama *et al.* 1986, Inaba and Suzuki-Yasumoto 1979). Dermal absorption of cobalt applied to intact or acid-burned skin of mice was about 0.1% after one hour but increased to 25% to 50% when applied to skin damaged by incision, abrasion, or punctures (Kusama *et al.* 1986). In a similar study in guinea pigs, absorption of cobalt through intact skin was less than 1% while absorption through abraded skin was about 80% 3 hours after exposure (Inaba and Suzuki-Yasumoto 1979). Lacy *et al.* (1996) did not report the amount of cobalt absorbed through the intact skin of hamsters but reported that small amounts of cobalt were detected in urine 24 to 48 hours after application and that much of the metal was retained in the skin after 48 hours. These authors also reported that uptake of cobalt by keratinocytes exposed *in vitro* was about 5% of the dose.

#### Distribution and excretion

Absorbed cobalt is distributed rapidly to all tissues in experimental animals and is similar to that in humans (NTP 2014b, WHO 2006). Edel *et al.* (1994) reported that tissue distribution depended on dose, route of administration (oral versus parenteral), and time. Following oral administration of cobalt compounds, the highest tissue concentrations generally occur in the liver and kidney with lower amounts in the heart, spleen, muscle, bone, brain, pancreas, lung, and gonads (Ayala-Fierro *et al.* 1999, Clyne *et al.* 1988, Gregus and Klaassen 1986, Bourg *et al.* 1985, Thomas *et al.* 1976, Hollins and McCullough 1971). Following single-dose parenteral administration, some studies reported that concentrations were initially highest in the liver and kidney but declined rapidly (Thomas *et al.* 1976, Hollins and McCullough 1971). However, Edel *et al.* (1994) reported higher concentrations in the lung, large intestine, kidney, liver, and spleen 24 hours after a single i.v. injection of cobalt chloride. One hundred days after a single i.p. injection, tissue distribution was affected by dose with higher concentrations in the spleen, pancreas, and bone following the lower dose but mainly in bone following higher doses with some accumulation in the heart.

Distribution of cobalt following inhalation exposure is similar to that observed for other routes with the exception of greater retention in the lung for both soluble and insoluble cobalt (NTP 2014b, Patrick *et al.* 1994, Kyono *et al.* 1992, Collier *et al.* 1991, Bucher *et al.* 1990, Bailey *et al.* 1989, Patrick *et al.* 1989, Kreyling *et al.* 1986, Kerfoot *et al.* 1975, Wehner and Craig 1972). Long-term retention of insoluble cobalt particles and soluble cobalt salts deposited in the lung shows wide interspecies variation and represents a potential continuing source of cobalt ion release (Patrick *et al.* 1994, Kreyling *et al.* 1991a, Bailey *et al.* 1989). In addition, some particles can translocate to the pulmonary interstitium where they are cleared from the lungs through the lymphatic system (Pauluhn 2009). Nanoparticles also may penetrate the alveolar membrane and distribute to extrapulmonary tissues via the circulation (Mo *et al.* 2008). The average size of the long-term retention component in humans is greater than in experimental animals (Leggett 2008, Bailey *et al.* 1989). Retention of insoluble cobalt oxide ($Co_3O_4$) particles (0.8 μm and 1.7 μm) after 90 and 180 days are shown in Table 3-1. These data show that lung retention is generally greater for larger particles than smaller particles and suggests temporal interspecies differences in the rate of particle dissolution and absorption. However, the percentage of total body cobalt content found in the lungs 30 and 180 days after exposure generally exceeded 90% in all species

for both particle sizes. In spite of considerable clearance from the lung, very little accumulated in other tissues.

**Table 3-1. Interspecies comparison of lung retention of cobalt oxide ($Co_3O_4$)**

| | Lung retention (%)[a] | | | |
|---|---|---|---|---|
| | 90 days | | 180 days | |
| Species/strain | 0.8 μm | 1.7 μm | 0.8 μm | 1.7 μm |
| Human | 64 | 75 | 45 | 56 |
| Baboon | 55 | 55 | 26 | 37 |
| Dog, beagle | 27 | 45 | 5.5 | 12 |
| Guinea pig | 49 | 46 | 8.3 | 15 |
| Rat, HMT (1985) | 5.2 | 20 | 1.3 | 8.0 |
| Rat, HMT (1986) | 5.3 | 18 | 1.2 | 7.2 |
| Rat, F-344 | 14 | 25 | 4.7 | 9.2 |
| Rat, Sprague-Dawley | 8 | 39 | 1.0 | 15 |
| Hamster, Syrian golden | 21 | 35 | 3.4 | 12 |
| Mouse, CBA/H | 15 | nd | 2.8 | Nd |

Source: (Bailey *et al.* 1989).
nd = no data.
[a]Calculated as the fraction of lung content (measured as activity of $^{57}Co$) at 90 and 180 days relative to the lung activity at three days after inhalation. The amount retained after three days was thought to be representative of the amount deposited in long-term lung retention sites because, by this time, the rapid phase of mucociliary clearance should be complete.

Kreyling *et al.* (1991a) conducted a lung clearance study in baboons, dogs, and HMT rats using $Co_3O_4$ particles (0.9 μm diameter) that were chemically similar to those used by Bailey *et al.* but had a higher density (i.e., less porous) and a smaller specific surface area. In each species tested, the denser 0.9 μm particles had higher lung retention after 90 and 180 days than the more porous 0.8 μm particles.

Bailey *et al.* (1989) and Kreyling *et al.* (1991a) also applied a simple dissolution model to predict the diverse shapes of the time-dependent rate of cobalt translocation to blood from $Co_3O_4$ particles deposited in the lungs. This model was based on the assumption that the dissolution rate is proportional to the specific surface area of the particle (surface area per unit mass). Since the specific surface area increases as the particles dissolve, a high initial dissolution rate results in a rapid increase in specific surface area and, in turn, causes an increase in the dissolution rate with time. Thus, translocation will peak when another slow clearance mechanism is superimposed on particle dissolution. A small fraction of the dissolved cobalt will not immediately translocate to the blood but will be retained in the lungs and slowly released. The translocation rate was defined in terms of two parameters: (1) the initial fractional absorption rate and (2) the fraction of dissolved cobalt that is retained long-term in tissues (predicted as 1% to 10%). Although there were some discrepancies between the curves predicted by the model and the observed translocation rates (see Figure 3-2), overall, the model accounted remarkably well for the different forms of translocation rates by varying the fractional dissolution rate and the long-term retention fraction and suggested marked species differences in these parameters. The rate-determining step for translocation was intracellular particle dissolution.

In an attempt to better understand the basis for the interspecies differences in the rate of $Co_3O_4$ absorption, species differences in lung retention and translocation (absorption) of soluble cobalt chloride also was investigated (Patrick *et al.* 1994). The mean fraction of cobalt retained in the lungs in the various test species administered cobalt chloride or cobalt nitrate (dog only) (expressed as percent of initial body content) ranged from about 0.13% (hamster) to 1.2% (dog, estimated value) after 100 days while the fraction retained in the whole body ranged from 0.35% (hamster) to 3.2% (dog). Lung retention by species declined in the following order: dog > HMT rat > guinea pig > baboon > F344 rat > hamster. These long-term retention values were lower than the predicted values of 1% to 10% used in the model (see previous paragraph). The mean fraction of cobalt retained in the lungs after 100 days in the various test species (expressed as percent of cobalt remaining in the body after 100 days) ranged from 11.8% (baboon) to 60% (HMT rat) with no significant accumulation in other organs with the exception of the trachea. However, relative concentrations in the trachea showed no significant interspecies differences. During the first week, 90% or more of the administered dose was cleared from the lung and was similar to the pattern observed for i.v.-injected $Co(NO_3)_2$ in the same species (Patrick *et al.* 1994, Bailey *et al.* 1989). These data suggest that interspecies differences in the time-dependent absorption rates (i.e., translocation of dissolved cobalt from the lung to the blood) for inhaled $Co_3O_4$ particles were not explained by differences in the fraction of dissolved cobalt retained long-term in lung tissue. Kreyling *et al.* (1991b) also found little interspecies variation in pH within alveolar macrophages; therefore, interspecies differences in translocation rates were not explained by differences in phagolysosomal pH. Alternative explanations for these interspecies differences could include a second long-term phase of lung retention as particles or as particle fragments (Patrick *et al.* 1994).

A recent inhalation study with rats and mice exposed to cobalt metal showed that cobalt concentrations increased with increasing exposure in all tissues examined; however, tissue burdens normalized to exposure levels did not increase with increasing exposure, with the exception of the liver (NTP 2014b). Cobalt tissue concentrations (μg Co/g tissue) in male and female rats showed the following order: lung > liver > kidney > femur > heart > serum > blood (NTP 2014b). Tissue cobalt burdens (μg Co/tissue) showed a similar order with the exceptions that liver accumulated more cobalt than the lung, and the heart accumulated more cobalt than the femur. At three weeks post-exposure in female rats, cobalt concentrations were markedly reduced in blood, serum, and lung (no data were available for other tissues). Tissue distribution in mice was similar to that observed in rats but concentrations in the femur and heart were similar to concentrations in blood and serum. These data from rodents exposed to cobalt by inhalation indicated that tissues tended to accumulate cobalt at concentrations greater than levels found in the blood and serum and that cobalt was distributed to extra-pulmonary tissues.

Cobalt excretion occurs rapidly with the majority of the administered dose eliminated within hours to a few days after exposure ceases (Paustenbach *et al.* 2013, Gregus and Klaassen 1986). Cobalt is excreted in the urine, feces, and bile with similar excretion patterns reported for all species studied (NTP 2014b, WHO 2006, ATSDR 2004). Most of the i.v.-injected dose of cobalt chloride (~73% to 75%) was eliminated in the urine while smaller amounts were excreted in the bile (2% to 5%) and feces (10% to 15%) (Ayala-Fierro *et al.* 1999, Gregus and Klaassen 1986). Soluble cobalt compounds are cleared from the lungs at a faster rate than less soluble compounds. The rate of urinary excretion correlates with the rate of translocation of cobalt from the lungs to the blood while fecal excretion rates correlate with the rate of mechanical clearance

of cobalt particles from the lung (WHO 2006, ATSDR 2004). Following oral exposure, cobalt is primarily excreted in the feces but the rate decreases as cobalt particle solubility increases (WHO 2006). However, species and sex differences in cobalt excretion rates have been reported. Cobalt urinary excretion rates (μg/16 hr) in male rats were about two-fold higher than in females exposed to various concentrations of cobalt sulfate for 13 weeks (Bucher *et al.* 1990). In another study, mean urinary excretion rates of cobalt (administered as $CoCl_2$ solution to the lungs or inhaled as an aerosol) ranged from 0.002% of the initial body content per day in HMT rats to 0.026% per day in dogs (Patrick *et al.* 1994). Mean daily fecal excretion rates ranged from 0.0009% (dog) to 0.004% (HMT rat).

### 3.2 Toxicokinetics

Various toxicokinetic parameters of inorganic cobalt have been measured, and several pharmacokinetic models have been developed that describe cobalt disposition in the body (Unice *et al.* 2014, Paustenbach *et al.* 2013, Unice *et al.* 2012, Leggett 2008, ATSDR 2004). This section provides a brief review of toxicokinetic data in humans (Section 3.2.1) and laboratory animals (Section 3.2.2).

#### 3.2.1 Humans

The kinetics of inhaled cobalt are determined by mechanical (mucociliary) clearance and by translocation to blood and the lymphatic system (Figure 3-1) (ATSDR 2004). Foster *et al.* (1989) calculated average translocation and mechanical clearance rates of inhaled cobalt oxide ($Co_3O_4$) particles in four human volunteers. The ratio of translocation to mechanical clearance was about 5:1 for particle sizes of 0.8 and 1.7 μm. Inhalation studies in workers and volunteers exposed to cobalt have shown that the elimination of poorly soluble cobalt metal or cobalt oxides (CoO or $Co_3O_4$) from the lungs is multiphasic with reported half-lives for the phases of 2 to 44 hours, 10 to 78 days, and years (NTP 2014b, WHO 2006, Mosconi *et al.* 1994a, Apostoli *et al.* 1994, Beleznay and Osvay 1994, Newton and Rundo 1971). The elimination pattern was independent of the degree of exposure. About 17% of the initial lung burden was eliminated within the first week while about 40% was retained at 6 months after exposure (WHO 2006, Foster *et al.* 1989). These elimination phases likely involve mucociliary clearance of cobalt particles from the tracheobronchial region, macrophage-mediated clearance of cobalt particles from the lungs, and long-term retention and clearance from the lung. The slower clearance with time likely reflects cobalt that is bound to cellular components in the lung (WHO 2006, ATSDR 2004, Foster *et al.* 1989, Kreyling *et al.* 1986). Studies in human volunteers administered cobalt chloride by i.v. injection also showed a multiphasic elimination pattern (Holstein *et al.* 2015, Jansen *et al.* 1996, Letourneau *et al.* 1972, Smith *et al.* 1972). These studies showed that 36% to 44% of the administered dose is cleared with a biological half-life of 6 to 12 hours, 45% to 56% is cleared with a biological half-life of 2 days to 60 days, and 9% to 11% is cleared with a biological half-life of 600 to 800 days (Paustenbach *et al.* 2013). Jansen *et al.* (1996) reported an apparent volume of distribution at steady state of 48 L that likely reflected initial accumulation in the liver (~50% of the administered dose).

Leggett (2008) developed a biokinetic model for inorganic cobalt that depicts recycling of cobalt between blood and four systemic tissues (liver, kidneys, skeleton, and other soft tissues) and transfer from blood to excretion pathways. The model assumes first-order kinetics, and parameter values are expressed as transfer coefficients (fractional transfers per day) that were

largely derived from controlled human studies. Unice *et al.* (2014, 2012) further refined this model by incorporating different gastrointestinal absorption rates, adding compartments to account for albumin-bound cobalt in intravascular and extravascular fluid, and accounting for additional parameters such as total blood volume, red blood cell age, and urinary excretion rates. The model was a reasonably good predictor of cobalt blood and urine concentrations measured in male and female volunteers who ingested a cobalt supplement for 16 days to 3 months (Tvermoes *et al.* 2014, Unice *et al.* 2014, Tvermoes *et al.* 2013).

### 3.2.2 Experimental animals

Lung clearance kinetics of cobalt particles include both mechanical transport and translocation (Kreyling *et al.* 1991a, Bailey *et al.* 1989). Lung clearance of inhaled cobalt metal particles in rats and mice showed a well-defined two-phase elimination profile following 3-month or 2-year studies (NTP 2014b). The majority (> 95% in rats and > 82% in mice) of the deposited cobalt was cleared rapidly (half-life of 1 to 5 days) while the remainder was cleared more slowly (half-lives of ~20 to > 400 days) depending on the concentration and study duration. Lung steady-state burdens were reached after approximately 6 months and were similar in rats and mice. Lung cobalt burdens were well below the levels that would cause lung overload. Other studies showed that interspecies differences in clearance patterns associated with mechanical transport and translocation were not correlated. Initial mechanical clearance rates were typically 10- to 20-fold greater in rodents than in other species, decreased monotonically with time, and were similar for different particle sizes. In contrast, interspecies differences in translocation rates varied by 3- to 10-fold, remained constant or increased and then decreased with time, and were affected by particle size (see Figure 3-2). Thus, in HMT rats, both rates were initially high, while in baboons and humans both rates were low. Mice, hamsters, and F344 rats had high rates of mechanical clearance but low to moderate rates of translocation while dogs had slow mechanical transport but rapid translocation.

Thomas *et al.* (1976) reported that the whole-body half-life of $^{60}CoCl_2$ administered by i.v. injection was longer in the mouse (495 days) than in the rat (309 days), monkey (183 days), or dog (180 days), but all were lower than values reported in humans (see Section 3.2.1). Other studies in rats and dogs showed multiphasic first-order elimination kinetics following oral, inhalation, or i.v. exposure (Table 3-2). These data indicate that soluble cobalt compounds are cleared faster than cobalt metal in rats and that the cobalt oxide particle clearance in dogs during the intermediate phase was proportional to particle size. Elimination of cobalt from the blood in the recent NTP (2014b) study also indicated rapid and slow clearance phases; however, it was not possible to fit the blood data to a two-compartment model due to the lack of early sampling times. However, cobalt elimination half-lives estimated from blood concentrations on the last day of exposure (2-week studies) and 3 weeks post-exposure were 9.2 to 11.1 days in female rats and 4.1 to 7.3 days in female mice.

**Table 3-2. Elimination half-lives for cobalt administered to experimental animals**

| | | | Elimination T½ | | |
|---|---|---|---|---|---|
| **Reference** | **Species: exposure route** | **Compound(s)** | **Phase 1** | **Phase 2** | **Phase 3** |
| (Ayala-Fierro *et al.* 1999) | Male F344 rats: i.v. | $CoCl_2$ | 1.3 hr | 4.3 hr | 19 hr |

| | | | | | |
|---|---|---|---|---|---|
| (Ayala-Fierro *et al.* 1999) | Male F344 rats: oral | $CoCl_2$ | 0.9[a] hr | 4.6 hr | 22.9 hr |
| (Menzel *et al.* 1989) | Male SD rats: inhalation | $CoCl_2$ | 1.8 hr | 3.7–8.7[b] hr | − |
| (Kyono *et al.* 1992) | Male SD rats: inhalation | Co metal | 52.8[c] hr<br>52.8[d] hr | 156[c] hr<br>172.8[d] hr | − |
| (Kreyling *et al.* 1986) | Male beagles: inhalation (endotracheal tube) | $Co_3O_4$<br>$Co_3O_4$ + CoO<br>$Co(NO_3)_2$ | 0.5 d<br>1−4 d<br>0.8 d | 6–80[e] d<br>20−86[e] d<br>27 d | 300–380 d<br>340–440 d<br>400 d |

− = No data.
[a]Absorption half-life.
[b]Calculated from elimination rate constants of 0.188 $h^{-1}$ (single exposure) and 0.08 $h^{-1}$ (repeat exposure).
[c]Lung.
[d]Blood.
[e]Half-lives were proportional to particle size.

### 3.3 Synthesis

Cobalt is absorbed from the GI tract, lungs, and skin and rapidly distributed throughout the body. Absorption from the gastrointestinal tract is highly variable and is affected by the chemical form, dose, age, formation of complexes with organic ions, and nutritional status. Soluble compounds are absorbed to a greater extent than poorly soluble forms. Current biokinetic models assume GI absorption of 20% to 45% for aqueous forms and 10% to 25% for solid forms. Studies in experimental animals indicate higher absorption in young rats and guinea pigs than in adults while studies in human volunteers indicate higher GI absorption in women than in men and may reflect iron status. Cobalt absorption from the GI tract is higher in iron deficient humans and experimental animals and suggests that cobalt and iron share a common uptake mechanism. Cobalt levels in blood and urine of workers generally increase in proportion to airborne concentrations. Although absorbed cobalt is distributed systemically, it does not accumulate in any specific organ with age. Translocation rates of cobalt from the lung to the blood show considerable interspecies variation with time and particle size with humans and baboons generally having lower rates than dogs or rodents, and the whole-body half-life of cobalt was longer in humans than in mouse, rat, monkey, or dog.

Cobalt excretion occurs rapidly with the majority of the administered dose eliminated within hours to a few days after exposure ceases. Cobalt is excreted in the urine, feces, and bile with similar excretion patterns reported for all species studied. Elimination in the feces primarily represents unabsorbed cobalt while absorbed cobalt is eliminated in the urine. Toxicokinetic studies indicate multiphasic elimination following inhalation of cobalt particles or i.v. injection of cobalt chloride and generally show shorter elimination half-lives in experimental animals compared to humans. Elimination half-lives reported for poorly soluble cobalt metal or cobalt oxide particles from human lung ranged from 2 to 44 hours, 10 to 78 days, and years. These elimination phases likely represent an initial rapid elimination from the tracheobronchial region via mucociliary clearance, macrophage-mediated clearance, and long-term retention and clearance. A similar pattern was reported in human volunteers given an i.v. injection of cobalt chloride with about 40% cleared with a half-life of 6 to 12 hours, 50% cleared with a half-life of 2 to 60 days, and 10% cleared with a half-life of 600 to 800 days.

# 4 Human Cancer Studies

## Introduction

The objective of the cancer hazard evaluation of cobalt and cobalt compounds that release cobalt ions *in vivo* (hereinafter referred to as cobalt) is to reach a preliminary level of evidence conclusion (sufficient, limited, or inadequate) for the carcinogenicity of cobalt from studies in humans by applying the RoC listing criteria to the body of evidence.

In general, most of the human studies do not provide information on the type(s) of cobalt compounds to which the subjects were exposed.

The steps in the cancer hazard evaluation, including the location of the discussion of these steps in the document, are listed below.

1. Selection of the relevant literature included in the cancer evaluation (Section 4.1 and Cobalt Protocol [NTP 2014c]).
2. Description of the study methods and characteristics (Appendix C.1, Tables C-1a-i) and evaluation of study quality and other elements related to the utility of the studies to inform the cancer hazard evaluation: Section 4.2 (cohort studies of lung cancer), Section 4.3 (case-control studies of esophageal, and other aerodigestive cancers (i.e., oral cavity, laryngeal, and pharyngeal cancers), and Appendix C.2, Tables C-2a to C-2c.
3. Cancer assessment: Lung (Section 4.2.3), esophagus (Section 4.3.3), and other cancers (Section 4.4).
4. Preliminary recommendation for the level of evidence of carcinogenicity (sufficient, limited, or inadequate) of cobalt from human studies (Section 4.5).

The cancer hazard evaluation of cobalt primarily focuses on cancers of the lung, the esophagus, and other aerodigestive cancers (i.e., oral cavity, laryngeal, and pharyngeal cancers) since these are the only tissue sites evaluated in multiple studies. (For rationale, see Protocol: Methods for Preparing the Draft Report on Carcinogens Monograph on Cobalt ["Cobalt Protocol"; NTP 2014c] and Tables 4-1 and 4-4). Because the occupational cohort studies primarily reported on lung cancer and the case-control studies reported on esophageal cancers and other aerodigestive cancers, this section is organized by study design (following the selection of literature): cohort studies and lung cancer are discussed in Section 4.2, case-control studies and esophageal cancer in Section 4.3, and aerodigestive and other cancers (reported in both case-control and cohort studies) in Section 4.4.

### 4.1 Selection of the relevant literature

Details of the procedures (such as the databases and literature search terms and screening methods) used to identify and select the primary studies and supporting literature for the human cancer evaluation are detailed in Appendix A and the cobalt protocol.

Primary epidemiologic studies were considered for the cancer evaluation if the study was (1) peer reviewed; (2) provided risk estimates (or sufficient information to calculate risk estimates) for cobalt and human cancer, and (3) provided exposure-specific analyses for cobalt at an

individual level, or based on the authors' report, cobalt exposure was probable or predominant in the population, job, or occupation under study.

Because cobalt can be released from hip and other joint implants, a preliminary literature search was also conducted to identify case reports and cohort studies of joint replacements or prosthetic devices. The case reports included at least 15 cases of malignant fibrous histocytoma (12 cases reviewed by Visuri *et al*. 2006, Hughes 1987, Lucas *et al.* 2001, Min 2007), at least 5 cases of osteosarcoma (4 reviewed by Visuri *et al.* 2006, Malcom 1984), at least 6 cases of other types of sarcoma (4 reviewed by Visuri *et al.* 2006, Tayton 1980, Van der list 1988), and at least 3 cases of non-Hodgkin or B-cell lymphoma (Dodion 1982, McDonald 1881, Cheuk *et al.* 2005) occurring at the site of implantation of joint prosthetic devices (e.g., hip, knee, screws) containing cobalt alloys (primary cobalt-chromium). Case-reports of these types of cancer were also found among non-cobalt containing implants (reviewed by Visuri *et al.* 2006). The cohort studies (at least 16) were primarily record linkage studies conducted in Nordic countries, the United Kingdom, Austria and the United States, the majority of which did not provide information on the type of implants and most likely included patients with cobalt- and non-cobalt-containing implants. Two cohort studies (Visuri *et al.* 1996, 2010) and patient series study (Visuri *et al.* 1996) reported on cancer risk among patients with McKee-Farrar implants, which contain a cobalt-chromium-molybdenum alloy. Overall, these studies were considered to be uninformative for evaluating effects due to cobalt because of study design (case reports have no comparison group), lack of specificity to cobalt (other types or implants or metals in cobalt implants) and inadequate information on the extent of exposure to cobalt, and thus were excluded from the cancer assessment.

Studies of radioactive cobalt were also excluded, because of potential confounding from radioactivity. In general, cohort or case-control studies of populations with jobs, workplaces, or environmental exposures in which cobalt exposure may have occurred (e.g., studies of hard-metal workers) were excluded if a specific risk estimate for potential cobalt exposure alone was not reported.

Biomarker studies of cobalt and cancer were included if they were conducted within defined populations and provided risk estimates for cobalt levels and cancer. A series of clinical studies that compared cobalt and other metal levels in target tissues (such as tumors of different stages or normal tissue) or surrogates (e.g., hair, nails, blood) from cancer patients with a referent group (e.g., healthy humans, patients with cancer, other diseases) were identified and are summarized in Appendix B, Tables B-2 (hair) and B-3 (tissues). For most studies, the source of the exposure was unknown and it could not be distinguished whether metal levels could be a cause of cancer or whether the cancer process itself affected accumulation of cobalt in the tissue. Because these studies did not provide information to calculate an effect estimate, and most did not have defined methods for selecting the subjects, they are not included in the cancer hazard evaluation.

Environmental studies of cobalt and cancer were included if they were conducted within defined populations and provided risk estimates for cobalt levels and cancer. A total of four studies was identified, two of which investigated the relationship between cobalt in air to breast (Coyle *et al.* 2006) and lung (Coyle *et al.* 2005) cancer. The other two studies investigated the relationship between soil levels of cobalt and cancer (McKinley *et al.* 2013, Kibblewhite *et al.* 1984). None of the studies moved forward into the cancer hazard evaluation because they did not provide a

risk estimate (or sufficient information to calculate one) or exposure-specific analyses at the individual level.

### 4.2 Cohort studies and nested case-control studies reporting on lung cancer

This section provides an overview of the cohort and nested case-control studies (Section 4.2.1), an overview of the adequacy of the studies to inform the cancer hazard evaluation (Section 4.2.2) and an assessment of the evidence from the studies on the association between cobalt exposure and lung cancer risk (Section 4.2.3).

#### 4.2.1 Overview of the methodologies and study characteristics

For each of the reviewed cohort studies, detailed data on study design, methods, and findings were systematically extracted from relevant publications, as described in the study protocol, and into Table 4-1, Tables C-1a-g in Appendix C, and Table 4-2 in Section 4.2.2.

The available epidemiological studies that satisfy the criteria for consideration in the cancer evaluation consist of a series of occupational cohort or nested case-control studies conducted in five independent populations. These include a cohort of female Danish porcelain painters; a cohort of French electrochemical workers; and French cohorts of hard-metal workers, and stainless and alloyed steel workers; and Norwegian nickel refinery workers.

Tüchsen *et al.* (1996) reported on cancer incidence at multiple tissue sites among 1,394 female porcelain painters employed in underglazing departments of two porcelain plate factories in Denmark where cobalt-aluminate spinel and/or cobalt silicate was used, compared with top glaze decorators in a department in one of the factories without cobalt exposure.

Studies on the French electrochemical workers producing cobalt were reported in two publications. The first publication was on a historical mortality cohort and nested case-control study of lung cancer among 1,143 cobalt production workers in a French electrochemical plant (Mur *et al.* 1987). This study included workers who had been employed for at least one year between 1950 and 1980. At this plant, cobalt was produced from a cobalt chloride solution by etching roasted ore, neutralization, filtration, and electrolysis. The manufacturing process also included production of cobalt salts and oxides. The second publication was a re-analysis of the cohort (N = 1,148), incorporating revised case-ascertainment and an extended period of follow-up (Moulin *et al.* 1993). The electrochemical worker cohort analyses reported findings for trachea/bronchus/lung cancer, buccal cavity/pharynx, and larynx cancers (Mur *et al.* 1987); and bronchus/lung, buccal-cavity/pharynx, larynx, esophagus, and brain cancers (Moulin *et al.* 1993). Although both studied the same population, the original cohort is discussed because it contains additional information (e.g., a nested case-control analysis) not included in the update.

Two publications reported on overlapping populations of hard-metal workers. The first was a historical mortality cohort and nested case-control study of lung cancer among 7,459 workers at 10 hard-metal producing factories in France (Moulin *et al.* 1998) where activities also included powder metallurgy processes. The second was a sub-study of lung cancer among 2,860 workers in the largest hard-metal producing factory in France (the factory was included in the Moulin *et al.* [1998] study, with an additional year of follow-up included) which also produced magnets and stainless steel with cobalt, and cobalt powders by calcination and reduction of cobalt hydroxide (Wild *et al.* 2000). This study also provided complete job histories.

A historical cohort and nested case-control study of stainless and alloyed steel workers and lung cancer conducted in one factory in France (N = 4,897), which produced and cast stainless and alloyed steel from cobalt, was also identified. Lastly, an incident nested case-control study of 213 cases of lung cancer among Norwegian nickel refinery workers was conducted to evaluate whether exposure to cobalt (and other metals) could explain the elevated risk of lung cancer in nickel workers.

In the two studies of electrochemical workers (Moulin *et al.* 1993, Mur *et al.* 1987), exposure was assessed based on company records, which grouped workers into general service, maintenance, and sodium production or cobalt production areas. Analysis was conducted for "ever employment" in the cobalt production workshop, or for exclusive employment in this area. Similarly, in the porcelain factories, exposure was based on company records, which grouped workers into those who worked in departments with and without cobalt exposure (Tüchsen *et al.* 1996). Exposure to cobalt in the hard-metal factories, and the stainless and alloyed steel factory was classified using a semi-quantitative job-exposure matrix (JEM) developed by experts; the nickel refinery workers were classified using this JEM which incorporated quantitative personal measurements from the breathing zone.

All of the cohort and nested case-control studies reported on lung cancer alone, or lung cancer and aerodigestive cancers, with only one of these reporting specifically about aerodigestive cancers (i.e., buccal cavity/pharynx, and larynx cancers) (Mur *et al.* 1987) in relation to cobalt exposure. Only one study reported on multiple sites in relation to cobalt (i.e., cervix, ovary, breast, and skin) (Tüchsen *et al.* 1996); thus, lung cancer is the only site with an adequate database to contribute to the cobalt and cancer assessment.

The description of study methods and characteristics of each study is included in Appendix C, Tables C-1a-g.

**Table 4-1. Cohort and nested case-control studies of exposure to cobalt**

| Reference | Population | Design and outcome (cancer sites) | Exposure: Cobalt compounds, assessment, metrics |
|---|---|---|---|
| (Tüchsen *et al.* 1996) | **Danish porcelain painters**<br>1943–1992<br>N = 1,394 female workers<br>874 exposed<br>520 unexposed | Cancer incidence cohort study (SIR); Danish cancer registry<br>ICD-7: Lung (162.0, 162.1) and 16 other tissue/organ sites | Cobalt-aluminate spinel; cobalt silicate<br>Company records<br>Exposed: Ever employed in two plate underglazing factories<br>Unexposed: workers employed in a cobalt-free department in one factory |
| (Mur *et al.* 1987)<br>(Moulin *et al.* 1993) (follow-up) | **French electrochemical workers**<br>*Mur* et al. *1987*<br>1950–1980<br>N = 1,143 males<br>*Moulin* et al. *1993*<br>1950–1988 | Historical mortality cohort study (SMR) and nested case-control analysis (OR)<br>*Mur* et al. *1987*<br>ICD-8: All causes; trachea, bronchus, and lung (162); buccal cavity/pharynx/larynx (140–149, 161)<br>*Moulin* et al. *1993* | Production of cobalt, cobalt salts and oxides. Company records classified workers exclusively employed in one of four work groups including cobalt production workshop<br>*Mur* et al. *1987*<br>Cohort analysis: Only or never employed in cobalt production<br>Nested case-control analysis: |

| Reference | Population | Design and outcome (cancer sites) | Exposure: Cobalt compounds, assessment, metrics |
|---|---|---|---|
| | N = 1,148<br>Number of cobalt production workers NR | ICD-8: All causes; bronchus, lung (162); brain (191) | Ever/never employed in cobalt production<br>*Moulin* et al. *1993*<br>Mortality SMR analysis<br>Only vs. never employed in cobalt production |
| (Moulin *et al.* 1998) (multi-plant)<br>(Wild *et al.* 2000) (sub-study of largest plant) | **French hard-metal workers**<br>*Moulin* et al. *1998*<br>1945–1991<br>N = 7,459 men and women; 68 cases and 180 controls<br>*Wild* et al. *2000*<br>1950–1992<br>N = 2,860 men and women<br>Number of workers employed in cobalt production only NR | Nested case-control analysis (OR) and historical mortality cohort study (SMR)<br>*Moulin* et al. *1998*<br>ICD-8: Lung (162)<br>*Wild* et al. *2000*<br>ICD-8: Lung (162) | Production of magnets, stainless steel, and cobalt powders<br>"Other" cobalt exposure may have included metallic and ionized cobalt<br>Semi-quantitative JEM<br>*Moulin* et al. *1998*<br>Duration, intensity and cumulative exposure<br>*Wild* et al. *2000*<br>Ever exposed |
| (Moulin *et al.* 2000a) | **French stainless and alloyed steel worker cohort**<br>1968–1991<br>N = 4,897; 54 cases and 160 controls | Nested case-control analysis (OR) within a historical mortality cohort study<br>ICD-8: Lung (162) | Steel production and casting of stainless steel, nickel, ferro-chromium, and other ferroalloys in which iron, chromium, nickel, and cobalt compounds are used<br>Powder manufacture of metallic powders<br>Semi-quantitative JEM<br>Duration, intensity, and cumulative exposure |
| (Grimsrud *et al.* 2005) (methods described in Grimsrud *et al.* 2003, Grimsrud *et al.* 2002) | **Nickel refinery worker cohort**<br>1952–1995<br>N = 5,389; 213 cases and 524 controls | Nested case-control analysis (OR) within an incidence cohort study; Norwegian Cancer Registry<br>ICD NR: Lung | Cobalt present in raw materials and intermediates in refinery and produced electrolytically in an electrowinning process<br>Breathing zone personal samples for cobalt and nickel JEM<br>Quantitative cumulative exposure |

### 4.2.2 Study quality and utility evaluation

This section provides an overview of the adequacy of the cohort and nested case-control studies to inform the cancer hazard evaluation (see Appendix C for details on the assessment). This assessment considers factors related to study quality (potential for selection and attrition bias, information bias regarding exposure and outcome, and concern for inadequate analytical methods, selected reporting, and inadequate methods or information to evaluate confounding)

and study sensitivity (e.g., such as adequate numbers of individuals exposed to substantial levels of cobalt). The ratings for each of these factors are provided in Table 4-2 and a detailed description of the rationale for the rating is provided in Appendix C.

No critical concerns for the potential for any of the biases (domains) were identified in the available studies; thus, each may have some utility for evaluating potential cancer hazards. All of the reported cohorts are relatively small or moderate sized and are, consequently, underpowered due to few exposed cases or deaths. With one exception (Grimsrud *et al.* 2005), the cohort or nested case-control studies included only very few cases exposed to cobalt alone, limiting their statistical power to evaluate a modest risk of lung cancer (if it exists) from cobalt. In addition, the level of exposure to cobalt alone in the cohort and nested studies was not defined with enough detail (excepting Grimsrud *et al.* 2005) to explore exposure-response relationships. Table 4-2 depicts the overall assessment of the ability to inform the cancer evaluation based on the overall utility of the studies, including potential for biases and study sensitivity.

The study of nickel refinery workers (Grimsrud *et al.* 2005) was considered to have the highest quality because it had adequate numbers of exposed cases, evaluated cancer incidence, incorporated quantitative assessments of exposure to cobalt, and had sufficient information on potential confounders and co-exposures to incorporate these factors into analyses. However, exposure to cobalt was highly correlated with nickel, which compromises the ability of the statistical models to disentangle effects from the two exposures.

The remaining studies were also considered to have low/moderate ability to inform the cancer hazard evaluation primarily because of more limited (semi-quantitative or qualitative) exposure assessments, potential bias, and/or lower sensitivity. The major concern in the studies of hard-metal workers (Moulin *et al.* 1998, Wild *et al.* 2000) and stainless steel workers was potential confounding from potential co-exposure to other lung carcinogens; this was also the case, but to a lesser extent, for the electrochemical workers cohort. In the porcelain worker study (Tüchsen *et al.* 1996), subcohorts of workers employed prior to 1981 when biomonitoring began and exposure levels began to fall, would have contributed information about high exposures; however, only estimates for the entire cohort were reported, potentially diluting the effect. No relationship with duration of employment was found, but this was not reported by calendar period. In the electrochemical workers cohort, concerns arose about the changing source of outcome information from the first analysis (Mur *et al.* 1987) to the updated analysis (Moulin *et al.* 1993). The change from use of medical records to death certificates, in combination with a restriction to account for loss to follow-up in the foreign-born workers, reduced the estimate of the risk in the follow-up study. In general, potential bias from these studies was in the direction of the null, and they had limited sensitivity to detect an effect due to their small size or inadequate information regarding level of exposure.

**Table 4-2. Bias and quality summary for cohort and nested case-control studies**

| Citation | Bias | | | | | | Quality[a] | Utility[b] |
|---|---|---|---|---|---|---|---|---|
| | Selection | Exposure | Outcome | Confounding methods | Adequacy of analysis | Selective reporting | Sensitivity | Integration |
| **Porcelain painters** Tüchsen *et al.* (1996) | ++ | ++ | +++ | ++ | ++ | +++ | + | ++ |
| **Electrochemical workers** Moulin *et al.* (1993) (with Mur *et al.* 1987) | ++ | ++ | ++ | + | +++ | +++ | + | + |
| **Hard-metal workers** Moulin *et al.* (1998) | ++ | ++/+++ | +++ | + | +++ | +++ | ++ | ++ |
| Wild *et al.* (2000) | ++ | ++/+++ | +++ | + | ++ | +++ | ++ | ++ |
| **Stainless and alloyed steel workers** Moulin *et al.* (2000a) | +++ | ++ | +++ | + | +++ | +++ | ++ | ++ |
| **Nickel refinery workers** Grimsrud *et al.* (2005) | +++ | +++ | +++ | ++ | +++ | +++ | +++ | +++ |

[a]Levels of concern for bias and for study quality rating – Equal column width for types of bias does not imply they have equal weight (see appendix for description of terms): Scoring system: +++: low/minimal concern or high quality; ++: some concern or medium quality; +: major concern or low quality; 0: critical concern.
[b]Utility of the study to inform the hazard evaluation (see Appendix C for description of terms) scoring system: ++++: high utility; +++: moderate utility; ++: moderate/low utility; +: low utility; 0: inadequate utility.

### 4.2.3 Cancer assessment: Lung

The goal of the cancer assessment is to evaluate the evidence for the carcinogenicity of cobalt for lung cancer. The conclusions regarding the assessment of study utility are brought forward, and these are considered together with the evidence from the individual studies. Next, the evidence is integrated across studies to reach a preliminary level of evidence conclusion to determine whether there is credible evidence of an association between cobalt and lung cancer, and whether such an observed association could be explained by chance, bias, or confounding.

Several of the guidelines developed by Austin Bradford Hill (Hill 1965) are relevant to the evaluation of the level of evidence for this assessment, including the magnitude (strength) and consistency of any observed associations across studies, evidence of an exposure-response gradient, and temporality of exposure. The preliminary listing recommendation is provided in Section 4.5.

#### Background information

Lung cancer is the third most common cancer in the United States, making up 13.5% of all new cancers. The age-adjusted annual lung cancer rates (including trachea and bronchus) (per 100,000 males or females) in the United States from 2007 to 2011 (SEER 2015a) were approximately 72.2 (male) and 51.1 (female) for incidence; and 61.6 (male) and 38.5 (female)

for mortality, with a 5-year survival rate of 16.8%. These data suggest that mortality and incidence data are approximately comparable for informing the cancer assessment. Rates for new lung and bronchus cancer cases have decreased on average 1.5% each year over the last 10 years; and death rates have decreased on average 1.8% each year from 2002 to 2011. Incidence trends and rates in European countries where all of the cohort studies were conducted are broadly similar (Ferlay *et al.* 2013). For example, in the European Union, lung cancer incidence per 100,000 males is 66.3, and mortality is 56.4.

Latencies for solid tumors such as lung cancer are generally estimated to exceed approximately 20 years, but may vary considerably. Incidence rates of lung cancer generally increase after 50 years of age, and this cancer is most frequently diagnosed among people aged 65 to 74; the median age at diagnosis is 70. None of the studies of cobalt and lung cancer included in this review have indicated the sub-type(s) of lung cancer included in their analyses.

The single most important non-occupational risk factor for the development of lung cancer is smoking. Other risk factors of concern include exposure to arsenic, asbestos, cadmium, silica, chromates, nickel compounds, and polycyclic aromatic hydrocarbons, all of which are found in cobalt manufacturing processes.

#### Evidence from individual studies

Based on the study quality evaluation, all six cohort and/or nested case-control studies reporting on lung cancer and cobalt exposure were considered to have some utility for inclusion in the cancer assessment. The findings from the individual studies are discussed below and presented in Table 4-3. The available cohort and nested case-control studies of cobalt and lung cancer include a cohort of Danish female porcelain painters, a cohort of French electrochemical workers, a French multi-centric cohort of hard-metal factory workers, a related cohort of workers from the largest factory in the multi-centric French hard-metal factory cohort, a cohort of French stainless and alloyed steel workers, and a cohort of Norwegian nickel-refinery workers.

**Table 4-3. Evidence from cohort and case-control studies on lung cancer and exposure to cobalt**

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| (Tüchsen *et al.* 1996)<br>Cohort<br>Copenhagen, Denmark<br>Factory 1: 1943–1992; Factory 2: 1962–1992 | Danish porcelain painters.<br>1,394 total; 874 cobalt-exposed workers, 520 unexposed workers.<br>Exposure assessment method**:** company records | **Lung (162 and 162.1)** | | | | Employment in factories/departments with or without cobalt.<br>**Confounding:** No control for smoking; however, smoking data on subset of workers suggests that smoking was not associated with exposure.<br>**Strengths:** Population exposed primarily to cobalt compounds alone; only female population with data on cobalt.<br>**Limitations:** Small number of exposed cases. Differential selection out of the cohort could have occurred as the authors mentioned that records of ill persons may have been removed potentially resulting in an underestimate of the true incidence of cancer. |
| | | All exposed | 8 | SIR 2.35 (1.09–4.45) | Age, calendar year | |
| | | Factory 1 exposed to cobalt silicate from 1972 | 3 | 1.6 (0.41–4.37) | | |
| | | Factory 2 exposed to cobalt-aluminate spinel dye thru 1988 | 5 | 3.25 (1.19–7.2) | | |
| | | Referents | 7 | 1.99 (0.87–3.94) | | |
| (Mur *et al.* 1987)<br>Cohort<br>France<br>1950–1980 | Electrochemical workers<br>N = 1,143; number of cobalt production workers NR ~ 25% of current staff at time of publication<br>Exposure assessment method: company records | **Lung (162)** | | | | **Exposure duration:** 60% worked greater than 10 years; 75% hired before 1975.<br>**Confounding:** Likely inadequate control for smoking; however, likely co-exposure to nickel and arsenic with no control for co-exposures.<br>**Strengths:** Cobalt production workers exposed primarily to cobalt compounds.<br>**Limitations:** Small number of exposed cases; high loss to follow-up (20%); potential for selection bias due to left-truncation |
| | | Only employed in cobalt production | 4 | SMR 4.66 (1.46–10.64) | Age, year of death | |

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| | | | | | | |
| (Mur *et al.* 1987)<br>Nested case-control<br>France<br>1950–1980 | Electrochemical plant workers<br>Cases: 9; controls: 18<br>Exposure assessment method**:** company records | **Lung (162)** | | | | **Confounding:** Cases (deaths from lung cancer) were matched to controls (deaths from cause other than cancer) for year of birth, age at death, and smoking habits; smoking data on only 30% of the cohort; co-exposures to nickel and arsenic were not controlled.<br>**Strengths:** Nested study reduces concern of potential confounding from life style factors<br>**Limitations:** Small numbers with limited information on exposures (only ever/never employment in cobalt production department); also, 46% of the cohort was hired prior to the start of follow-up which could induce a downward bias in the effect estimate due to over-prevalence of healthier workers (left-truncation). |
| | | Ever worked in cobalt production | 4 | OR [4.0 (0.66–24.4)] | None | |
| (Moulin *et al.* 1993)<br>Cohort<br>France<br>Extended follow-up of the Mur *et al.* 1987 study through 1988 | Electrochemical workers<br>Cohort 1: N = 1,148; Cohort II: N = 870; number of cobalt workers NR<br>Exposure assessment method**:** company records | **Lung (162)** | | | | **Confounding:** No reported control for period effects, duration, or time since first exposure; no consideration of smoking; potential co-exposures to nickel and arsenic from its presence in cobalt ore not controlled.<br>**Strengths:** Cobalt production workers exposed primarily to cobalt compounds.<br>**Limitations:** Small number of exposed cases in overall or sub-cohort; low power to detect an effect; concern about outcome misclassification; potential for selection |
| | | Exclusive employment in cobalt production, Cohort I | 3 | OR 0.85 (0.18–2.5) | Age | |
| | | Exclusive employment in cobalt production, Cohort II | 3 | 1.16 (0.24–3.4) | | |
| | | Ever | 4 | 0.88 (0.24–2.25) | | |

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| | | worked in Cobalt production, Cohort I | | | | bias due to left-truncation |
| | | Ever worked in cobalt production, Cohort II | 4 | 1.18 (0.32–3.03) | | |
| (Moulin *et al.* 1998)<br>Nested case-control<br>France<br>1968–1991 | Workers in all 10 hard-metal factories in France<br>Cases: 61; controls: 180<br>Exposure assessment method: JEM | **Lung (162)** | | | | No information on actual exposure level or average exposure duration for the cohort.<br>**Confounding:** Potential concern for exposure to other lung carcinogens, which were not controlled in the cobalt alone analyses.<br>**Strengths:** Exposure-response analyses with multiple exposure metrics; JEM validated for atmospheric concentrations of cobalt; incident cohort reducing the potential for left truncation; internal analysis reducing the impact of the reported HWE; and lagged analysis.<br>**Limitations:** Potential confounding by co-exposures classified only as "ever/never" in the JEM. |
| | | Exposure level 2 to 9 | 15 | OR 2.21 (0.99–4.9) | Age | |
| | | Exposure intensity trend | 15 | 2.05 (0.94–4.45) | | |
| | | Exposure duration | 15 | 2.2 (0.99–4.87) | | |
| | | Unweighted cumulative exposure | 15 | 1.83 (0.86–3.91) | | |
| | | Frequency weighted cumulative exposure trend | 15 | 2.03 (0.94–4.39) | | |
| (Wild *et al.* 2000)<br>Cohort<br>France | Hard-metal workers - Largest plant in France<br>2,216 men and 644 | **Lung (162)** | | | | No information on actual exposure level or average exposure duration for the cohort<br>**Confounding:** Potential exposure to lung carcinogens which were not controlled in |
| | | Cobalt except in hard metals | 15 | SMR 1.95 (1.09–3.22) | Age, sex | |

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| 1968–1992 | women<br>Exposure assessment method**:** JEM | | | | | cobalt-only analyses.<br>**Strengths:** Incident cohort; lagged analysis.<br>**Limitations:** External analysis only presented; no exposure metrics except for ever/never provided. |
| (Moulin *et al.* 2000a)<br>Nested case-control<br>France<br>1968–1992 | Stainless and alloyed steel workers<br>Cases: 54 (17 cobalt exposed); controls: 162 (67 cobalt exposed)<br>Exposure assessment method: JEM | **Lung (162)** | | | | No information on actual exposure level or average exposure duration for the cohort<br>**Confounding:** Potential confounding from exposure to chromium and/or nickel, and iron; controlled for smoking<br>**Strengths:** Semi-quantitative JEM; exposure metrics including duration and cumulative dose, frequency weighted and unweighted provided; HWE mitigated by use of internal analyses.<br>**Limitations:** Known carcinogens had non-significant ORs < 1.0, indicating that the study had low sensitivity to detect an effect. |
| | | Exposed, Crude | 17 | OR 0.64 (0.33–1.25) | | |
| | | Exposed, known smoking status, Crude | 12 | 0.62 (0.26–1.46) | | |
| | | Exposed, known smoking status, smoking adjusted | 12 | 0.43 (0.16–1.14) | | |
| | | Exposed, known smoking status, PAH, silica, and smoking adjusted | 12 | 0.44 (0.17–1.16) | | |
| (Grimsrud *et al.* 2005)<br>Nested case-control | Nickel refinery workers<br>Cases: 213; controls: | **Lung** | | | | **Exposure levels (**µg/m$^3$): high (144–3,100); medium (29.7–142); low (0.31–29.5).<br>**Confounding:** No multivariate estimates |
| | | Rise in OR per mg/m$^3$ × | NR | OR 1.3 (0.9–1.8) | Smoking | |

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| Norway<br>1910–1995 | 525<br>Exposure assessment method: JEM | years, smoking adjusted | | | | for the categorical variable (low, high, medium exposures) were possible due to collinearity with nickel. Continuous rise in OR controlled for smoking and co-exposures.<br>**Strengths:** Quantitative cobalt levels reported based on measurements from the breathing zone; incident cases; internal analyses; relatively large number of cases compared to other cobalt studies.<br>**Limitations:** Collinearity with nickel. |
| | | Low (0.31–29.5 µg/m$^3$ × years | 49 | 1.5 (0.6–3.8) | | |
| | | Med (29.7–142 µg/m$^3$ × years | 73 | 2.4 (1–5.6) | | |
| | | High (144–3,100 µg/m$^3$ × years | 82 | 2.9 (1.2–6.8) | | |
| | | **Lung** | | | | |
| | | Rise in OR per mg/m$^3$ × years, smoking and co-exposure adjusted | NR | 0.7 (0.3–1.4) | Smoking, nickel, sulfuric acid mists, asbestos, arsenic | |
| | | **Lung** | | | | |
| | | Cobalt electrolysis workshop, 0.03–2.2 yr | 23 | 1.6 (0.8–3) | Smoking, and employment in other workshops | |
| | | Cobalt electrolysis workshop, 2.3–11.8 yr | 44 | 2.8 (1.5–5) | | |

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| | | Cobalt electrolysis workshop 12–48 yr | 62 | 5.1 (2.9–9.1) | | |

HWE = Healthy worker effect; HWSE = Healthy worker survival effect; JEM = job-exposure matrix/ NR = Exposure levels or duration not reported; OR = odds ratio; PAHs = polycyclic aromatic hydrocarbons.

***Porcelain painters***

Tüchsen *et al.* (1996) reported a significantly increased risk of lung cancer in all exposed female workers compared with the Danish female population (SIR = 2.35, 95% CI = 1.01 to 4.62, based on 8 exposed cases). Factory-specific SIRs for lung cancer were also reported, indicating that Factory 1, where cobalt aluminate-spinel was replaced by cobalt silicate in 1972, had a non-significantly elevated SIR of 1.6 based on 3 exposed cases (no CI provided); and that Factory 2, where workers continued to be exposed to cobalt aluminate-spinel until 1989, had a significantly elevated SIR of 3.25 based on 5 exposed cases. In addition, the authors reported an elevated SIR of lung cancer in the referent group (SIR = 1.99, 95% CI = 0.80 to 4.11, 7 cases), similar in magnitude to that found in the exposed group.

This study had low sensitivity to detect an effect because of (1) small numbers of exposed cases in this relatively small cohort and (2) potentially combining workers with high and low exposures together, which could dilute any effect and bias the results towards the null. In addition, no lagged analyses were reported. A concern about differential selection also exists in this study. The authors suggested that removal of records of ill persons was known to take place in Danish manufacturing. The possibility of differential selection out of the cohort could have resulted in an underestimation of the true incidence of lung cancer in this study.

An elevated lung cancer SIR, similar in magnitude to that reported in the exposed group, was also observed in the referents; a comparison of the exposed departments with the reference department gave a relative risk ratio of 1.2 (95% CI = 0.4 to 3.8). The referents were reported to be top glaze decorators employed in a department without cobalt exposure. Data from a previous publication in this factory (Raffn *et al.* 1988) indicated an overlap of cobalt levels in referents and exposed individuals, suggesting that the referents in the Tüchsen *et al*. paper were not completely "unexposed." Limited information regarding smoking and its potential relationship with cobalt exposure was provided from two surveys of subsamples of workers (Prescott *et al.* 1992, Raffn *et al.* 1988). Based on a calculation of the weighted average of exposed and unexposed respondents from both studies taken over the total sample size of the two studies, and disregarding the specific cobalt compound to which workers were exposed, the smoking rate is calculated to be 52% for exposed and 38% for referent women. The rate of smoking among exposed women is close to that of skilled Danish women taken in 1982 (47%) and 1987 (55%); and the rate of smoking in the referent group is similar to, but lower than, the rate in the general population of Danish women (43% and 42% in these two years). This suggests that there may be a non-smoking cause for the increased rate of lung cancer in the referent population, which might be due either to misclassification of cobalt exposure, or to another unmeasured confounder. It is also possible that cobalt-exposed workers are also exposed to the same unmeasured confounder, although data from the substudy indicates that levels of silica, nickel, and dust were very low based on air monitoring done in 1981 (Raffn *et al.* 1988). The porcelain painters cohort provides inconclusive evidence for a carcinogenic effect of cobalt and lung cancer because of the finding of similarly elevated levels of lung cancer among the referents.

The Tüchsen *et al.* (1996) study stands out from others in that it consists entirely of women. Christensen *et al*. (1993a) conducted a cross-over study of oral administration of soluble and insoluble cobalt compounds and found that there are clear differences in biological levels by gender, with significantly higher urinary cobalt (higher uptake) levels and urinary excretion of cobalt in females compared with males.

***Electrochemical workers***

Two publications reported on the same cohort of cobalt production workers in a French electrochemical plant (Moulin *et al.* 1993, Mur *et al.* 1987). Findings from both publications are reported because the methodologies employed in each differ in important ways that shed light on their interpretation; that is, the later paper (Moulin *et al.* 1993) is not simply an update of the earlier paper. The first paper reported a statistically significantly increased SMR for lung cancer among the workers employed in cobalt production only (SMR = 4.66, 95% CI = 1.46 to 10.64, based on 4 observed deaths) (Mur *et al*.). There was large loss to follow-up and clear evidence of a healthy worker effect in the overall cohort (all-cause mortality SMR = 0.77 [95% CI = 0.67 to 0.88]), but not among cobalt production workers. However, in an internal matched analysis (matching variables were year of birth, age at death, and smoking habits), the percent of cases and controls matched on year of birth, age at death and smoking habits ever employed at cobalt production was provided, without estimated odds ratio or confidence interval. An unadjusted calculation computed by NTP = OR of 4.0 (95% CI = 0.7 to 24.4), indicating internal consistency with the reported SMR for those working only in cobalt production.

However, in an extension of the follow-up of the same cohort (Moulin *et al*. 1993) the SMR for lung cancer among French-born workers exclusively employed in cobalt production was 1.16, (95% CI = 0.24 to 3.40), based on 3 observed deaths. (Confidence in the SMR for the entire cohort is lower because of high loss to follow-up and strong healthy worker effect due to 24% foreign-born workers). In addition, Moulin *et al*. reported a discrepancy in the number of observed cases exclusively employed in cobalt production in the two analyses (e.g., Mur *et al.* [N = 4]; Moulin *et al.* [N = 3]) due to differences in the methods used to ascertain cause of death. The Mur *et al.* study used physicians' medical records, whereas Moulin *et al*. (1993) used death certificates for the years when they were available and, in the process, one exposed case was re-classified as non-diseased; furthermore, during the extended follow-up, no additional lung cancer cases were observed.

A further limitation of this study is its very weak consideration of risk factors for lung cancer, particularly smoking status, and possible co-exposures in the cobalt production process to nickel and arsenic. Mur *et al*. initially reported that smoking histories were available for 30% of workers, and the authors reported matching cases and controls on smoking status; however, no explanation was given regarding the methods of matching given the small percentage of workers with information on smoking status. Moulin *et al*. did not address smoking in the analysis, but reported no excess of mortality from circulatory and respiratory diseases, suggesting that smoking is unlikely to be higher in this cohort than in the local French referent population.

Selection bias is somewhat of a concern in this cohort, as 46% of members were hired prior to the start of follow-up, which suggests that the cohort had a high proportion of healthy prevalent workers, which can bias the risk estimate downward (left-truncation) (Applebaum 2011).

The evidence from these electrochemical studies is inconclusive, based on the low sensitivity of the Moulin *et al*. study to detect an effect, the lack of exposure metrics in both studies, potential selection bias from left-truncation, and the inability to control for confounding. The changed outcome classification across the two analyses does not inspire confidence in the methods used in either study. The Mur *et al*. analysis was consistent across the internal and external analyses,

reducing concerns about confounding from the HWE, however, selection bias due to left-truncation remains a concern.

***French hard-metal worker cohorts***

The populations included in the two studies of cobalt exposure and lung cancer among hard-metal workers overlap, and both studies report either statistically significant elevated risks, or borderline statistically significant risks, of lung cancer among those exposed to cobalt without tungsten carbide. Moulin *et al*. (1998) first reported results from the multi-center study of 10 hard-metal factories in France. In the internal nested case-control analysis (Moulin *et al.* 1998), based on 15 exposed cases, a borderline statistically significant increased risk of lung cancer was associated with exposure to "cobalt alone or simultaneously with agents other than tungsten carbide" (levels 2 to 9) compared with little or no exposure (levels 0 or 1) (OR = 2.21, 95% CI = 0.99 to 4.90). Regarding the presence of an exposure-response relationship, Moulin *et al*. reported two-fold elevated trend tests (although not reaching statistical significance) based on 15 cases across levels of exposure (OR = 2.05, 95% CI = 0.94 to 4.45), levels of duration (2.20, 95% CI = 0.99 to 4.87), cumulative weighted (1.83, 95% CI = 0.86 to 3.91), and cumulative un-weighted doses (2.03, 95% CI = 0.94 to 4.39). Numbers of cases and category-specific OR estimates for levels or categories of duration or cumulative dose were not provided. Wild *et al.* (2000) added years of follow-up to the cohort from the largest factory included in the multi-center study and found a statistically significant elevated SMR of lung cancer among those exposed to "cobalt except in hard metals" based on the JEM (SMR = 1.95, 95% CI = 1.09 to 3.22). Wild *et al*., however, did not provide information on exposure-response relationships; and neither study provided an examination of latency.

Moulin *et al*. (1998) and Wild *et al.* (2000) both measured and addressed co-exposures to 9 workplace lung carcinogens and smoking in analyses for cobalt-tungsten carbide. In both studies, the JEM was used to assess exposure to other workplace carcinogens. Ever vs. never smoking was obtained through interviews with cohort members, and their colleagues and relatives in the Moulin *et al*. study and from occupational health department records in the Wild *et al.* study. However, in both studies, it is unclear whether the analyses of cobalt alone included models for adjusting for co-exposures to other carcinogens or smoking. In the Wild *et al.* (2000) study, exposure to any IARC carcinogen without considering exposure to cobalt-tungsten carbide was related to lung cancer (SMR = 2.05, 95% CI = 1.34 to 3.0).

Potential confounding from exposure to smoking is less of a concern in this study than potential confounding from exposure to other carcinogens. There is no evidence from data presented to indicate that exposure to cobalt alone and smoking was related. In addition, the low mortality from smoking-related disease suggests a limited potential for confounding, as smoking is unlikely to be more prevalent among the workers than in the overall population. In the French cohort, mortality from chronic bronchitis and emphysema was low (SMR = 0.4, 95% CI = 0.05 to 1.44) and there was no consistent mortality pattern for other smoking-related cancers (e.g., larynx, bladder, buccal cavity/pharynx, and esophagus). In addition, as internal analyses are usually assumed to be less affected by confounding from lifestyle factors (e.g., smoking) than SMRs, the OR estimate from the multivariate model reported by Moulin *et al.* (1998) in the internal analysis is likely to be the better estimate for cobalt and lung cancer from this cohort. Due to the lack of information about control of carcinogenic co-exposures, confidence in the finding is reduced.

***Stainless and alloyed steel cohort***

No association between cobalt exposure and lung cancer was found in this study (Moulin *et al.* 2000a). In internal analyses of cobalt exposure based on the JEM in the stainless and alloyed steel plant, Moulin *et al*. reported a crude OR of 0.64 (95% CI = 0.33 to 1.25), and an OR adjusted for PAHs and silica of 0.58 (95% CI = 0.29 to 1.17) based on 17 exposed cases and 67 controls in 10-year lagged analyses. Similar findings were found among those with known smoking habits (e.g., 12 cases and 36 controls). Moulin *et al*. (2000a) also reported significant decreasing trends in duration, and frequency un-weighted and weighted cumulative dose for workers with known smoking habits. (The overall cohort SMR for smoking and lung cancer was 5.37 [95% CI = 1.74 to 12.53] for those working less than 10 years). ORs adjusted for smoking were all less than 1.0 (Moulin *et al*.). It is likely that non-differential exposure misclassification was introduced into the exposure assessment because some job periods of cases or controls went back many decades, yet exposure was assessed based on memories of processes and exposures of current workers or reports in the literature, as historical exposure measurements were lacking. Models were reported controlling for PAHs and silica, none of which made any material difference; however, in the correlation matrix, neither of these was related to cobalt exposure. Exposure to nickel and/or chromium was related to cobalt exposure, although these exposures were not included in the cobalt model. However, these exposures were also not associated with lung cancer risk in these analyses.

In this study, chromium and/or nickel and asbestos, all lung carcinogens classified by RoC and IARC, were found to be unrelated to lung cancer, decreasing the confidence in this study and in the findings for cobalt. Only exposure to PAHs and silica were statistically significantly related to lung cancer along with increasing trends not confounded by smoking.

Misclassification of exposure in this study, its inability to control for the appropriate confounders correlated with cobalt, and the negative findings for lung cancer and other known lung carcinogens (e.g., nickel, chromium, asbestos) suggest little confidence in the evidence put forth in this study.

***Norwegian nickel refinery workers***

The Grimsrud *et al.* (2005) cancer incidence study of nickel and lung cancer in a Norwegian nickel refinery was conducted to determine if cobalt or other potential carcinogens could explain the elevated risks of lung cancer in nickel workers. The authors reported that the cobalt variable could not be retained in the full model in its categorical form due to collinearity (all individuals exposed to nickel were also exposed to cobalt, although the correlation between cobalt and nickel was reported as r = 0.63); however, the positive exposure-response effect noted for the continuous cobalt variable adjusted only for smoking changed sign when smoking and co-exposures (nickel, arsenic, asbestos, and sulfuric acid mists) were controlled. The smoking-adjusted rise in OR per $mg/m^3 \times$ year was 1.3 (95% CI = 0.9 to 1.8), which was reduced to 0.7 (95% CI = 0.3 to 1.4) after adjustment for occupational co-exposures. The categorical ORs adjusted only for smoking were: low exposure (0.31 to 29.5 $\mu g/m^3$) based on 49 cases, OR = 1.5 (95% CI = 0.6 to 3.8); medium exposure (29.7 to 142 $\mu g/m^3$) based on 73 cases, OR = 2.4 (95% CI = 1.0 to 5.6); and high exposure (144 to 3,100 $\mu g/m^3$) based on 82 cases, OR = 2.9 (95% CI = 1.2 to 6.8). No value for trend was reported for the smoking-adjusted variable. However, the

fully adjusted model for this cobalt variable (including smoking as well as all co-exposures) could not be calculated due to collinearity.

The authors reported that cobalt levels typically amount to 4% to 15% of the total nickel levels, except in the cobalt electrolysis process where cobalt levels are triple the amount of nickel levels. This process is included in hydrometallurgical production, for which results are reported by duration of work. Strong gradients were found by duration of work in the hydrometallurgical production department with a 5-fold increase in the OR for 12 or more years (OR = 5.1, 95% CI = 2.9 to 9.1) based on 62 exposed cases, with the linear trend (per 10 years) (OR = 1.7, 95% CI = 1.4 to 2.1). However, no analyses were provided to help separate effects of exposure to cobalt and nickel.

Although the design of this study was of high quality, due to the collinearity with exposure to nickel, this study cannot separate out the effects of cobalt and nickel on lung cancer and thus the findings from the study are unclear.

#### Integration of evidence across studies

While almost all the cohort studies reported approximately a doubling of the risk of lung cancer mortality or incidence from exposure to various cobalt compounds, it is unclear that the excess lung cancer was due to exposure specifically to cobalt, because 1) it was not possible to rule out confounding by carcinogenic co-exposures, or 2) other complications prevented a clear interpretation of a cobalt effect.

The Danish porcelain painters study showed similarly elevated risks of lung cancer in both the exposed and unexposed workers, and could not control directly for smoking. Findings from the French electrochemical workers cohort were based on two papers analyzing the same cohort using different methods to ascertain cancer, and publishing conflicting results – the first indicated a significantly elevated risk of lung cancer based on four exposed cases, and the second showed virtually no differences in risk of lung cancer among the exposed and unexposed workers based on three exposed cases in a subset of workers born in France. In two French studies of hard-metal workers, measures of cobalt exposures were likely mixed with other carcinogens and the methods did not clearly indicate whether these were controlled in the analyses. Although an exposure-response relationship between cobalt exposure and lung cancer was observed in the Norwegian nickel refinery workers study, risk estimates could not be calculated in models controlling for other co-exposures because nickel and cobalt were highly correlated. However, in this study a significant trend was reported with increasing duration of employment in workshops where cobalt concentrations tripled those of nickel, with control for employment in other workshops and smoking. Confounding by smoking was considered in each of the studies to varying degrees, and smoking either did not reduce the risk estimates materially when it was controlled, or was unlikely to materially reduce the risk estimates in studies where there was only auxiliary information.

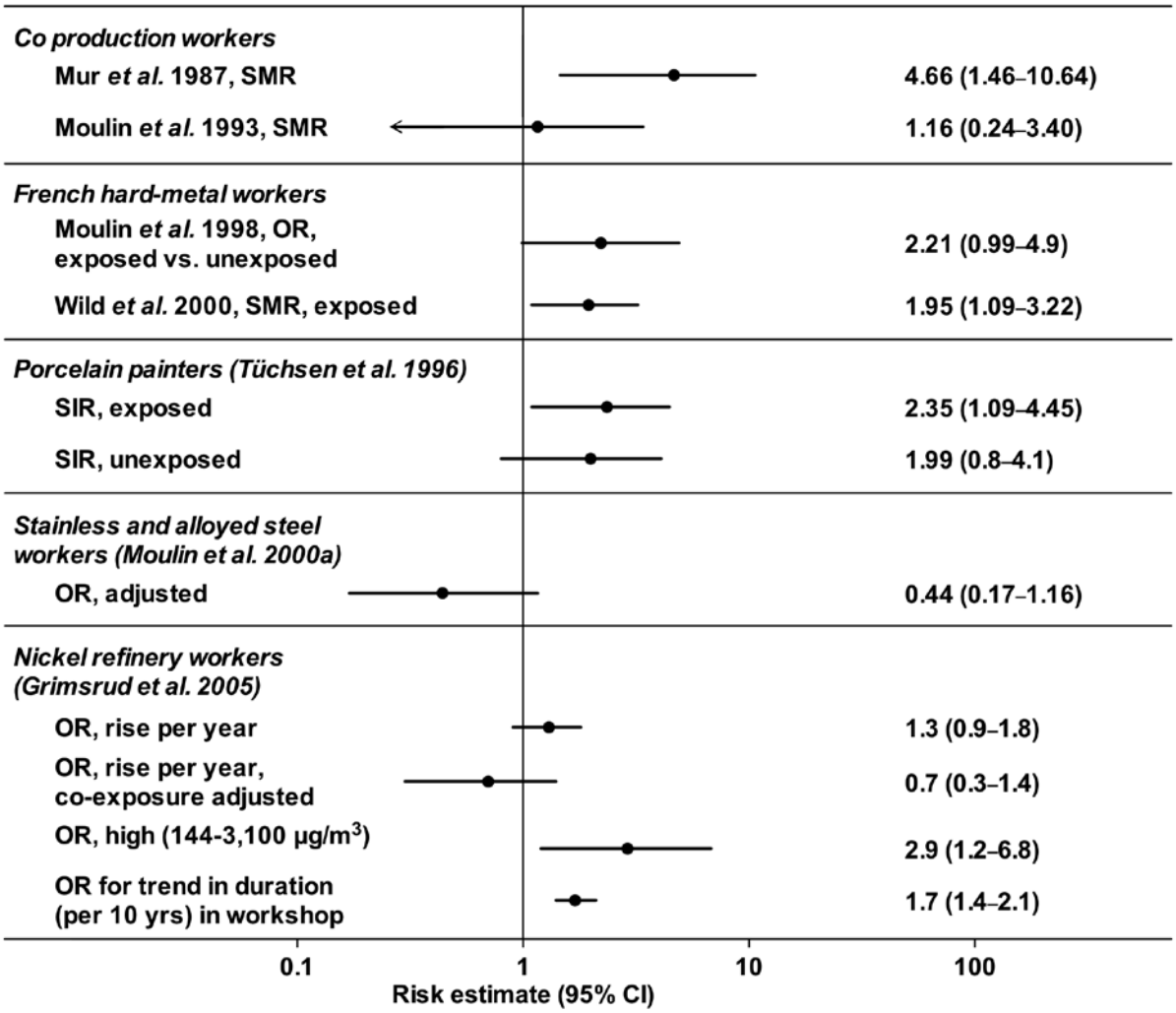


**Figure 4-1. Forest plot showing lung cancer risk ratios (SIR, SMR, or OR as noted) and 95% CI for epidemiological cohort studies of cobalt exposure**

### 4.3 Case-control studies

This section provides an overview of the case-control studies (Section 4.3.1), an overview of the adequacy of the studies to inform the cancer hazard evaluation (Section 4.3.2) and an assessment of the evidence from the studies on the association between cobalt exposure and esophageal cancer risk (Section 4.3.3).

#### 4.3.1 Overview of the methodologies and study characteristics

The available epidemiological studies that satisfy the criteria for inclusion in the review consist of two population-based case-control studies of metals in biological tissues of cancer cases (lung, esophageal, oral cavity, and laryngeal cancers) and controls published in the literature between 1986 and 2012 (Table 4-4). Both of these studies (O'Rorke *et al.* 2012, Rogers *et al.* 1993) were initiated from an interest in the role of metals in the etiology of cancer, and specifically metals derived from nutritional sources. Detailed data on study design, methods, and findings were

systematically extracted from relevant publications, as described in the study protocol, into Table 4-5, Tables C-1h,i in Appendix C, and Table 4-6 in Section 4.3.2.

**Table 4-4. Case-control biomarker studies of exposure to cobalt**

| Reference | Design and population | Outcome | Exposure: Cobalt compounds, assessment, metrics |
|---|---|---|---|
| (Rogers *et al.* 1993) | Population-based case-control biomarker study<br>Western WA state USA<br>1983–1987<br>501 cases (153 laryngeal, 73 esophageal, 359 oral cavity cancers)/434 controls | ICD-O<br>Larynx (140.0–141.9)<br>Esophagus (143.0–146.9)<br>Oral cavity (148.0–150.9; 161.0–161.9) | Source and type of compounds unknown<br>Cobalt levels in toenails measured<br>Tertiles (ppm) |
| (O'Rorke *et al.* 2012) | Population-based case-control biomarker study<br>Ireland<br>FINBAR* study<br>2002–2004 | ICD not reported<br>Esophagus<br>Barrett's esophagus (metastatic precursor to esophageal cancer) | Source and type of compounds unknown<br>Cobalt levels in toenails measured<br>Tertiles (log transformed - cut points μg/g) |

*FINBAR = Factors Influencing the Barrett's Adenocarcinoma Relationship.

### 4.3.2 Study quality and utility evaluation

This section provides an overview of the adequacy of the cohort and nested case-control studies to inform the cancer hazard evaluation (see Appendix C for details on the assessment). This assessment considers factors related to study quality (potential for selection and attrition bias, information bias regarding exposure and outcome, and concern for inadequate analytical methods, selected reporting, and inadequate methods or information to evaluate confounding) and study sensitivity (e.g., such as adequate numbers of individuals exposed to substantial levels of cobalt). The ratings for each of these factors are provided in Table 4-5 and a detailed description of the rationale for the rating is provided in Appendix C.

Both of the case-control studies of cobalt in toenails have either low/minimal or some concern for most biases except for exposure assessment and sensitivity. Their overall low utility to inform the cancer hazard evaluation, however, is due to the potentially irrelevant window of exposure. Toenail clippings likely reflect an integrated exposure that occurred 12 to 18 months prior to clipping, and toenail samples were collected after cancer diagnosis in these studies. Many factors (including disease) can affect nail growth and metal deposition. The available studies (that evaluated cobalt levels and cancer stage [lung or laryngeal] are conflicting, thus it unclear whether the cancer process can affect cobalt levels in toenails (Benderli-Cihan *et al.* 2011; Kuo *et al.* 2006, Klatka *et al.* 2011). However, although exposure was assessed after the disease process began, in most cases it represents at least some pre-diagnosis exposure, but not pre-cancer exposure as the latency period of both esophageal cancer and Barrett's esophagus is

of long duration (Butt and Kandel 2014). Rogers *et al.* conducted stratified analyses on tumor stage and time of diagnosis, which indicated no differences in cobalt levels, suggesting that reverse causality may not be a concern.

**Table 4-5. Bias and quality summary for case-control studies**

| | Bias[a] | | | | | | Quality[a] | Utility[b] |
|---|---|---|---|---|---|---|---|---|
| Citation | Selection | Exposure | Outcome | Confounding methods | Adequacy of analysis | Selective reporting | Sensitivity | Integration |
| Rogers *et al.* (1993) | +++ | + | +++ | +++ | +++ | +++ | + | + |
| O'Rorke *et al.* (1993) | ++ | + | +++ | +++ | +++ | +++ | + | + |

[a]Levels of concern for bias and for study quality rating – Equal column width for types of bias does not imply they have equal weight (see appendix for description of terms): +++: low/minimal concern or high quality; ++: some concern or medium quality; +: major concern or low quality; 0: critical concern.
[b]Utility of the study to inform the hazard evaluation (See appendix for description of terms): ++++ high utility; +++: moderate utility; ++: moderate/low utility; +: low utility; 0: inadequate utility.

### 4.3.3 Cancer assessment: Esophageal cancer

#### Background information

Esophageal cancer is a relatively rare cancer, ranking as the eighteenth most common cancer in the United States, making up 1.1% of all new cancers. The age-adjusted annual rates of esophageal cancer (per 100,000 males or females) in the United States from 2007 to 2011 (SEER 2015b) were approximately 7.7 (male) and 1.8 (female) for incidence; and 7.5 (male) and 1.6 (female) for mortality, with a 5-year survival rate of 17.5%. Like lung cancer, these data suggest that mortality and incidence data are approximately comparable for informing the cancer assessment. Incidence trends and rates in European countries where all of the cohort studies were conducted are broadly similar (Ferlay *et al.* 2013); and in the European Union the annual incidence of esophageal cancer is 8.4 and the annual mortality rate is 7.0 (Cancer Research UK 2014). Evaluations of esophageal cancer risk factors have reported that sufficient evidence exists for x-and gamma-radiation, alcoholic beverages, betel quid, tobacco smoking, and smokeless tobacco; limited evidence exists for dry-cleaning, mate drinking, pickled vegetables, rubber production industry, tetrachloroethylene exposures, red and processed meats, and high temperature drinks. The sub-types of esophageal cancer, esophageal adenocarcinoma and, however, have distinct risk factors and trends. esophageal adenocarcinoma, with risk factors being white race, increasing age, body fatness, and male gender, is the predominant histological type among men, while for women, esophageal squamous-cell cancer is more common and rates are still increasing in several European countries. Unlike esophageal squamous-cell carcinoma, alcohol is not a risk factor for either Barrett's esophagus or for esophageal adenocarcinoma (Freedman *et al.* 2011, Anderson *et al.* 2009, Kubo *et al.* 2009); however, smoking is a risk factor for both subtypes and Barrett's esophagus (Cook *et al.* 2010).

Barrett's esophagus is a condition of intestinal metaplasia in which tissue that is similar to the lining of the intestine replaces the tissue lining the esophagus. The prevalence of Barrett's

esophagus is estimated to be between 1.6% and 6.8% (Gilbert *et al.* 2011), although a more precise estimate is not possible as many patients are asymptomatic, and its natural history has been difficult to assess. Barrett's esophagus has an extended latency period prior to progressing to cancer (Butt and Kandel 2014). A recent meta-analysis of studies reports incidence rates for the development of esophageal cancer in nondysplastic Barrett's esophagus of 0.33% per year and 0.19% for short-segment Barrett's esophagus (Desai *et al.* 2012). About 5% of patients with esophageal adenocarcinoma have a pre-cancer diagnosis of Barrett's esophagus (Corley *et al.* 2002); but its presence conveys a 30- to 40-fold increased risk of esophageal carcinoma (Sharma 2004). As incidence of esophageal adenocarcinoma has increased more than six-fold in the last decade, investigations of the risk factors for Barrett's esophagus have been of interest (Jemal *et al.* 2013). Barrett's esophagus incidence increases with age; the prevalence among non-Hispanic whites is 6.1% compared to 1.7% among Hispanics and 1.6% among blacks; and the male/female ratio is about 2:1 (Abrams *et al.* 2008), similar to esophageal cancer.

#### Evidence from individual studies

Both of the case-control studies (O'Rorke *et al.* 2012, Rogers *et al.* 1993) compared cobalt in toenails of cases of esophageal cancer and population-based controls. O'Rorke *et al.* limited their analysis to esophageal adenocarcinoma, while no histologic information was provided by Rogers *et al*., thus it is likely that the Rogers *et al*. study included both subtypes in unknown proportions. Findings are presented in Table 4-6.

**Table 4-6. Evidence from studies of aerodigestive cancers and exposure to cobalt**

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| (Rogers *et al.* 1993)<br>Case-control<br>Western WA state, USA<br>9/1/83–2/28/87 | Population based study of aerodigestive cancers, USA<br>Cases: N = 507; N = 153 laryngeal, N = 73 esophageal, N = 359 oral cavity cancers; Controls: N = 434<br>Exposure assessment method: personal monitoring | **Esophagus (143.0-146.9)** | | | | **Exposure levels:** Tertiles of cobalt in toenails; highest level = 0.17 ppm<br>**Confounding:** Cases and controls were matched on key likely confounders. No information provided about correlation of cobalt with other measured trace metal levels, and nutrients not correlated with cobalt were kept in the model because they resulted in ORs closer to the null. ORs for esophageal cancer were significantly elevated for iron and calcium<br>**Strengths:** Population-based study; histologically confirmed cancers; cases and controls from same source population.<br>**Limitations:** Not all samples reflect pre-diagnostic window of exposure. No USDA data available on cobalt levels in food as measured by a food frequency questionnaire. Single sample collected even though cobalt in toenails shown to have low reproducibility; window of exposure a concern with long latency cancer. |
| | | < 0.05 | 92 | OR = 1.0 | Age, sex, smoking (pack-years), alcohol (drink-years), beta-carotene (mg/day), energy intake (kcal/day), ascorbic acid (mg/day) | |
| | | 0.05−0.17 | 127 | 2.4 (0.8–7.2) | | |
| | | > 0.17 | 66 | 9 (2.7–30) | | |
| | | **Larynx (140.0-141.9)** | | | | |
| | | < 0.05 | 114 | OR = 1.0 | Age, sex, smoking (pack-years), energy intake (kcal/day), beta-carotene (mg/day), ascorbic acid (mg/day), alcohol (drink-years) | |
| | | 0.05-0.17 | 168 | 2 (1–3.8) | | |
| | | > 0.17 | 62 | 1 (0.4–2.6) | | |
| | | **Oral cavity cancer (148.0-150.9; 161.0-161.9)** | | | | |
| | | < 0.05 | 135 | OR = 1.0 | Age, sex, smoking (pack-years), alcohol (drink-years), energy intake (kcal/day), ascorbic acid (mg/day), beta-carotene (mg/day) | |
| | | 0.05−0.17 | 190 | 1.5 (0.9–2.6) | | |
| | | > 0.17 | 92 | 1.9 (1–3.6) | | |

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| (O'Rorke *et al.* 2012)<br>Case-control<br>All Ireland (Republic and Northern)<br>3/2002–12/2004 | All Ireland population-based study of esophageal cancer and Barrett's esophagus<br>Cases: N = 137 for esophageal cancer, N = 182 for Barrett's esophagus;<br>Controls: N = 221<br>Exposure assessment method: personal monitoring | **Esophageal cancer** | | | | **Exposure levels:** Average (µg/g) ± SD: cases = 0.02 ± 0.06; controls = 0.02 ± 0.04. Range: cases = 0.002–0.60; controls = 0.002–0.47<br>**Confounding:** No correlation of cobalt levels with selenium, chromium, zinc, mercury, and cerium reported, nor were other metals included in models.<br>**Strengths:** Population based; histologically confirmed cancer.<br>**Limitations:** Differences in sources of cases and controls in N. Ireland and Rep. of Ireland may introduce some selection bias; low participation rate in controls, especially in Rep. of Ireland. Not all samples reflect pre-diagnostic window of exposure. Single sample collected even though cobalt in toenails shown to have low reproducibility; window of exposure a concern with long latency cancer. |
| | | < -5.4824 | 34 | OR = 1.0 | Age, sex, GI reflux, education, *H. pylori* infection, location, smoking | |
| | | ≥ -5.4824 | 39 | 1.06 (0.57–1.98) | | |
| | | ≥ -4.4705 | 52 | 1.54 (0.84–2.85) | | |
| | | Trend-test *P*-value: 0.16 | | | | |
| | | **Esophageal cancer** | | | | |
| | | < -5.4824 | 34 | OR = 1.0 | Age, sex | |
| | | ≥ -5.4824 | 39 | 1.13 (0.64–1.99) | | |
| | | ≥ -4.4705 | 52 | 1.54 (0.9–2.68) | | |
| | | Trend-test *P*-value: 0.11 | | | | |
| | | **Barrett's Esophagus** | | | | |
| | | < -5.4824 | 55 | OR = 1.0 | Age, sex, GI reflux, *H. pylori* infection, smoking habits, energy intake, location | |
| | | ≥ -5.4824 | 54 | 1.08 (0.55–2.1) | | |
| | | ≥ -4.4705 | 64 | 1.97 (1.01–3.85) | | |
| | | Trend-test *P*-value: 0.05 | | | | |
| | | **Barrett's Esophagus** | | | | |
| | | < 5.4824 | 55 | OR = 1.0 | Age, sex | |
| | | ≥ 5.4824 | 54 | 0.97 (0.59–1.59) | | |
| | | ≥ 4.4705 | 64 | 1.18 (0.72–1.93) | | |
| | | Trend-test *P*-value: 0.5 | | | | |
| (Mur *et al.* 1987)<br>Cohort<br>France<br>1950–1980 | Electrochemical workers<br>N = 1,143; number of cobalt production workers NR ~ 25% of | **Buccal cavity, pharynx, larynx (140-149, 161)** | | | | Exposure duration: 60% worked greater than 10 years; 75% hired before 1975. |
| | | Employed only in cobalt Production | 2 | SMR<br>3.36 (0.29–10.3) | Age, year of death | |

| Reference, study design, location, and year | Population description & exposure assessment method | Exposure category or level | Exposed cases/ deaths | Risk estimate (95% CI) | Co-variates controlled | Comments, strengths, and weaknesses |
|---|---|---|---|---|---|---|
| | current staff at time of publication<br>**Exposure assessment method:** company records | | | | | **Confounding**: Likely inadequate control for smoking; however, likely co-exposure to nickel and arsenic with no control for co-exposures.<br>**Strengths:** Cobalt production workers exposed primarily to cobalt compounds.<br>**Limitations:** Small number of exposed cases; high loss to follow-up (20%); potential for selection bias due to left-truncation |

GI = gastrointestinal; HWE = healthy worker effect; HWSE = healthy worker survival effect; OR = odds ratio.

***Western Washington state study of aerodigestive cancers***

Rogers *et al*. (1993) reported elevated odds ratio for esophageal cancer for those with the highest levels (≥ 0.17 ppm) of cobalt concentration in toenails compared to those with the lowest level (< 0.05 ppm) of cobalt (OR = 9.0, 95% CI = 2.7 to 30.0). The OR was elevated but not significant for those with medium levels (0.05 to 0.17 ppm) of cobalt concentration compared to those with low levels (OR = 2.4, 95% CI = 0.8 to 7.2). The exposure-response test for trend was significant ($P < 0.001$). It is not possible to comment on the distribution of levels of cobalt in the cases compared to the controls, as cases and controls are combined across exposure levels.

Confounding from known risk factors for esophageal cancer can reasonably be ruled out, however, other metals measured and associated with esophageal cancer in this analysis, were not controlled for in the cobalt models, nor were additional data presented to show any relationship between cobalt levels and other metal levels. In this study, the risk of esophageal cancer was also associated with elevated levels of calcium and iron. Smoking and alcohol use were controlled in the multivariate models along with age and gender, energy intake, beta-carotene and ascorbic acid; however, while cases were less educated than controls, this variable was not included in the model. Neither beta-carotene nor ascorbic acid confounded the relationships between cobalt and esophageal cancer, but the authors included these two nutrients in the logistic model as it reduced the ORs slightly, raising the concern that the model estimates might have been over-controlled, biasing them slightly towards the null. Co-exposures from other metals were not reported or considered in the analysis of cobalt, and no correlations among the metals were reported.

The source of the cobalt exposure is unknown. When cobalt in nail tissue was expressed as a continuous variable, there were no associations between nail concentration of cobalt and dietary intake of foods high in cobalt (e.g., meat) suggesting that diet does not explain the elevated levels of cobalt in cases. Although occupational histories using questionnaires were collected in this study, no exposure assessment or analyses were done specifically for exposure to cobalt.

Although the Rogers *et al*. study provides some evidence of an association, the analysis of a single sample of toenail clippings collected near the time of diagnosis, with no accompanying data on potential sources of cobalt from the environment or occupational exposure, limits the utility of the study. Based on data on reproducibility of measurements of metals in toenails, cobalt has low to intermediate within-person reliability, suggesting that a single sample is less than ideal. Measurements of nail cobalt reflect an integration of exposures that occurred 12 to 18 months prior to clipping, raising the question about whether cobalt levels sampled in toenails close to, and in many cases after cancer diagnosis, reflect the relevant period of exposure for long latency cancer. No differences in cobalt levels were found between those with early or late stage cancer nor between those who provided samples within 7 months or beyond 7 months of diagnosis, which helps reduce concerns regarding reverse causality.

***Finbar study – Ireland***

O'Rorke *et al*. (2012) reported a non-significant elevated risk of esophageal adenocarcinoma among those with the highest cobalt levels (OR = 1.54, 95% CI = 0.84 to 2.85). In addition, they reported a significantly increased risk of Barrett's esophagus among participants with higher toenail concentrations of cobalt (≥ -4.4705, log transformed values equivalent to ≥ 0.011 μg/g) (OR = 1.97, 95% CI = 1.01 to 3.85), with a significant ($P = 0.05$) linear test for trend. Both of the

estimates were adjusted for age, sex, smoking, location (Northern Ireland or Republic of Ireland), energy intake, gastro-esophageal reflux, and *H. pylori* infection. O'Rorke *et al.* reported no information regarding the correlation between dietary intake of cobalt and nail concentration. In this study, a 2-fold risk of Barrett's esophagus was also associated with higher toenail concentrations of zinc.

The major limitation of this study, similar to the Rogers *et al.* study, however, is the exposure assessment method, which is an analysis of a single sample of toenail clippings collected near the time of diagnosis, with no accompanying data on potential sources of cobalt from the environment or occupational exposure. Given the long latency period for both Barrett's esophagus and esophageal cancer, there is concern that a measurement reflecting integrated exposures 12 to 18 months in the past is relevant. Similar to the Rogers *et al.* study, co-exposures from other metals were not reported or considered in the analysis of cobalt, and no correlations among the metals were reported.

#### Integration of the evidence across studies

While these two well-conducted population-based case-control studies in Ireland and in Western Washington state reported relatively consistent findings, had adequate numbers of participants, used sound methodologies, and demonstrated exposure-response relationships, the key issue of temporality remains unaddressed. The dependence of these studies upon a single sample of toenails collected at the time of diagnosis meant that neither had complete or even adequate data on cobalt during the relevant windows of exposure throughout the natural history of the two conditions to definitely establish temporality.

### 4.4 Cancer assessment: Other cancers

#### 4.4.1 Other aerodigestive cancers - oral cavity, pharyngeal, and laryngeal cancers

The available data to evaluate cobalt in relation to other aerodigestive cancers, specifically cancers of the oral cavity, pharynx, and larynx, consist of the electrochemical workers cohort study (Mur *et al.* 1987), and one population-based case-control biomarker study (Rogers *et al.* 1993). The first publication from the electrochemical workers cohort (Mur *et al*.) provided an SMR for buccal cavity, pharyngeal, and laryngeal cancers for those working in cobalt production. Rogers *et al*. provided OR estimates of cobalt in toenails among incident laryngeal cancers and oral cavity cancers and controls, and included exposure-response data as well. These are rare cancers (incidence 11.0 per 100,000 men and women for oral cavity cancer; and 3.3 per 100,000 men and women for laryngeal cancers) (SEER 2015c); and unlike lung and esophageal cancers, 5-year survival rates are much higher for oral cavity/pharyngeal and laryngeal cancers (62.7% and 60.0%, respectively), suggesting that mortality statistics are less useful for informing the cobalt and cancer assessment. Potential risk factors for these cancers include smoking and other tobacco use, alcohol (tobacco and alcohol together are worse than either alone), asbestos, and nickel.

The risk of death from buccal cavity, pharyngeal, and laryngeal cancer among electrochemical workers was SMR = 3.36 (95% CI = 0.29 to 10.29), based on 2 observed deaths (Mur *et al.* 1987).

Rogers *et al*. (1993) reported a borderline significantly elevated odds ratio for oral cavity cancer for the highest level (≥ 0.17 ppm) of cobalt concentration in toenails compared to the lowest level (< 0.05 ppm) of cobalt (OR = 1.9, 95% CI = 1.0 to 3.6). The OR was elevated but not significant for those with medium levels (0.05 to 0.17 ppm) of cobalt concentration compared to those with low levels (OR = 1.5, 95% CI = 0.9 to 2.6). The exposure-response test for trend was not significant (*P*-value not reported). The finding was present in both *in situ*/localized tumors and individuals with regional/distant tumors. In this study, diet was not found to be an explanation for the higher risks, and tobacco and alcohol levels were controlled in the analyses.

A borderline significantly elevated odds ratio for laryngeal cancer was reported for medium toenail levels (0.05 to 0.17 ppm) compared to the lowest level (< 0.05 ppm) of cobalt (OR = 2.0, 95% CI = 1.0 to 3.8). However, the OR for the highest level of cobalt was 1.0 (95% CI = 0.4 to 2.6), with no indication of a trend in exposure response.

As with esophageal cancer, it is not possible to assess the actual exposure levels among cases and controls as they are combined at each concentration level. Because nails were collected after diagnosis, to address potential reverse causation, cases were stratified by stage at diagnosis (*in situ*/localized versus regional/distant) and by time from diagnosis to interview (< 7 months vs. ≥ 7 months). No statistically significant differences in the odds ratios by time from diagnosis to interview or stage of disease were observed, which argues against reverse causation.

With respect to these aerodigestive cancers, information is inadequate to evaluate the association with exposure to cobalt based on findings from these two studies, one of which was underpowered (Mur *et al.* 1987) and one of which had critical concerns regarding exposure misclassification due to the use of a single sample of toenails collected at the time of diagnosis, which might not have been the relevant window of exposure (Rogers *et al.* 1993).

#### 4.4.2 Other cancers

The available data to evaluate cobalt in relation to other cancers is inadequate as it was primarily limited to one cohort study reporting on multiple cancers (Tüchsen *et al.* 1996) and two studies reporting on brain cancer (Tüchsen *et al.* 1996, Moulin *et al.* 1993) (data not shown). Neither of the two studies had adequate numbers of exposed cases (2 cases or fewer) to evaluate brain cancer risk from exposure to cobalt. Among porcelain painters exposed to cobalt dyes, the authors reported that cervical cancer was elevated (SIR = 2.31, lower confidence limit > 1.0) based on 12 exposed cases (Tüchsen *et al.* 1996). For other cancer sites with at least four cases, elevated SIRs (not statistically significant) were also observed for ovary and other skin, and the SIR was close to 1.0 for breast cancer.

### 4.5 Preliminary listing recommendation

The data available from studies in humans are inadequate to evaluate the relationship between human cancer and exposure to cobalt. While almost all the cohort studies reported approximately a doubling of the risk of lung cancer mortality or incidence from exposure to various cobalt compounds, it is unclear that the excess lung cancer was due to exposure specifically to cobalt, because 1) it was not possible to rule out confounding by carcinogenic co-exposures; or 2) other complications prevented a clear interpretation of a cobalt effect.

The relevant data for evaluation of exposure specifically to cobalt are from studies of five major cohorts of workers exposed to cobalt in Denmark (Tüchsen *et al.* 1996), France (Mur *et al.* 1987; Moulin *et al.* 1993; Moulin *et al.* 1998; Wild *et al.* 2000; Moulin *et al.* 2000), Norway (Grimsrud *et al.* 2005), and two population based case-control studies of aerodigestive cancers: one in Ireland (O'Rorke *et al.* 2012) and the other in Washington State, United States (Rogers *et al.* 1993). The Danish study showed similarly elevated risks of lung cancer in both the exposed and unexposed workers, and could not control directly for smoking. Findings from the French electrochemical workers cohort were based on two papers using different methods to ascertain cancer, which produced conflicting results – the first indicated a significantly elevated risk of lung cancer based on 4 exposed cases, and the second showed virtually no differences in risk of lung cancer among the exposed and unexposed workers based on 3 exposed cases in a subset of workers born in France. In two French studies of hard-metal workers, measures of cobalt exposures were likely mixed with other carcinogens and the methods did not clearly indicate whether these were controlled in the analyses. The Norwegian study attempted to control for other co-exposures and smoking, but nickel and cobalt were highly correlated and an estimate for the full model could not be produced. However, a significant trend was reported with increasing duration of employment in workshops where cobalt concentrations three times those of nickel was reported in this study, which controlled for employment in other workshops and smoking.

In addition to lung cancer, esophageal cancer was of interest. Increased risks of esophageal cancer were found in the two population-based case-control studies; however, cobalt exposure was assessed based on one sample of toenails collected at or after cancer diagnosis. Thus, it is unclear whether these cobalt levels reflect exposure to cobalt during the relevant time window necessary for the induction of cancer. The data were inadequate to evaluate cancer at other tissue sites.

# 5 Studies of Cancer in Experimental Animals

This section reviews and assesses the evidence from carcinogenicity studies in experimental animals exposed to cobalt and cobalt compounds that release cobalt ions *in vivo* (hereinafter referred to as cobalt). Cancer and co-carcinogen studies in experimental animals were identified using methods described in the protocol and literature search strategy document (http://ntp.niehs.nih.gov/go/730697). In all, 23 publications (16 carcinogenicity and 9 co-carcinogenicity studies) were identified that met the inclusion criteria. Some of these publications overlap since some co-carcinogenicity studies had a cobalt exposure alone group and a corresponding control as part of their design. The criteria to evaluate exposure specific to cobalt and/or cobalt compounds require studies that either had observational durations > 12 months for rats and mice, or were co-carcinogen exposure studies (initiation/promotion and other co-carcinogen studies that isolate the effect of cobalt compound exposures) and that report on the presence or absence of neoplastic and related non-neoplastic lesions. Several studies were excluded from the review because they did not have concurrent controls or controls from a closely related study. These included Hopps *et al.* (1954), Delahant (1955), Gilman (1962), Nowak (1966), and Gunn *et al.* (1967). Studies of cobalt alloys and radioactive cobalt in experimental animals were not considered to be informative because of potential confounding by other carcinogens. (See IARC 2006 for a review of studies of cobalt alloys.)

This section is organized by the type of study, i.e., carcinogenicity (Section 5.1) and co-carcinogenicity (Section 5.2). For each of these study types, the monograph provides an overview of the available studies, assesses their quality, discusses the findings and identifies potential treatment-related cancer sites (carcinogenicity studies only). The co-carcinogen studies are only briefly discussed because they do not contribute substantially to the evaluation of potential carcinogenicity. Section 5.3 provides a synthesis of the findings for the different types of cobalt compounds across the cancer sites. The preliminary level of evidence conclusion for the carcinogenicity of cobalt compounds that release cobalt ions *in vivo* as a class from studies in experimental animals is provided in Section 7, which provides the rationale for evaluating them as a class.

## 5.1 Carcinogenicity studies

### 5.1.1 Overview of the studies

Different forms of cobalt were tested in 16 carcinogenicity studies: cobalt metal or cobalt nanoparticles (6 studies); two soluble cobalt salts, cobalt sulfate heptahydrate (2 studies) and cobalt chloride (1 study); and two poorly soluble cobalt compounds, cobalt(II) oxide (6 studies) and cobalt sulfide (1 study); (see Table 5-1). Most carcinogenicity studies were conducted in rats, with three studies in mice, and one study in hamsters. Routes of administration included either administration through the respiratory tract (inhalation or intratracheal instillation) or by local injection (subcutaneous, intramuscular, intraperitoneal, intrapleural, or intrarenal). Three publications that did not have concurrent controls for all or part of their series of studies were included in the evaluation because the authors either reported non-concurrent controls from other parts of their series of studies (Shabann 1977, Heath 1956) or authors reported non-concurrent controls from a previous study in the same laboratory (Heath 1962).

**Table 5-1. Overview of cancer studies in experimental animals reviewed**

| Strain (sex) | Substance | Route | Exposure period/ study duration | Reference |
|---|---|---|---|---|
| ***Cobalt metal*** | | | | |
| Rat F344/NTac (M&F) | Cobalt metal | Inhalation | 2 yr/2 yr | (NTP 2014b) |
| Mouse B6C3F$_1$ (M&F) | Cobalt metal | Inhalation | 2 yr/2 yr | (NTP 2014b) |
| Rat Sprague-Dawley (M) | Cobalt metal [nano] and<br>Cobalt metal [bulk] | IM inj.<br>SC inj. | Single dose/ 1 yr | (Hansen *et al.* 2006) |
| Rat Sprague-Dawley (F) | Cobalt metal | Intrarenal inj. | Single dose/ 1 yr | (Jasmin and Riopelle 1976) |
| Rat Hooded (F) | Cobalt metal | Intrapleural inj. | Single dose/ 2.3 yr | (Heath and Daniel 1962) |
| Rat Hooded (M&F) | Cobalt metal | IM inj. | Single dose/lifespan | (Heath 1956) |
| ***Soluble cobalt compounds*** | | | | |
| Rat F344/N (M&F) | Cobalt sulfate heptahydrate | Inhalation | 2 yr/2 yr | (NTP 1998) |
| Mouse B6C3F$_1$ (M&F) | Cobalt sulfate heptahydrate | Inhalation | 2 yr/2 yr | (NTP 1998) |
| Rat Wistar (M) | Cobalt chloride | SC inj. | 8–12 mo/8–12 mo | (Shabaan *et al.* 1977) |
| ***Poorly soluble cobalt compounds*** | | | | |
| Rat Sprague-Dawley (M&F) | Cobalt(II) oxide | Intratracheal instill. | 1.5 yr/lifespan | (Steinhoff and Mohr 1991) |
| Rat Sprague-Dawley (M&F) | Cobalt(II) oxide | IP inj. | 6 mo/lifespan | (Steinhoff and Mohr 1991) |
| Rat Sprague-Dawley (M) | Cobalt(II) oxide | SC inj. | 730 day/lifespan | (Steinhoff and Mohr 1991) |
| Rat Wistar (M&F) | Cobalt(II)oxide | IM inj. | Single dose/1.3 yr | (Gilman and Ruckerbauer 1962) |
| Mouse Swiss (F) | Cobalt(II) oxide | IM inj. | Single dose/2 yr | (Gilman and Ruckerbauer 1962) |
| Hamster Syrian Golden (M) | Cobalt(II) oxide | Inhalation | Lifespan/lifespan | (Wehner *et al.* 1977) |
| Rat Sprague-Dawley (F) | Cobalt sulfide | Intrarenal inj. | Single dose/1 yr | (Jasmin and Riopelle 1976) |

M = male, F = female, instill. = instillation, inj. = injection, IP = intraperitoneal, IM = intramuscular, SC = subcutaneous, wk = week, yr = year.

### 5.1.2 Study quality assessment

Each of these primary studies was systematically evaluated for its ability to inform the cancer hazard evaluation using a series of signaling questions related to the following study performance elements: population, exposure conditions, outcome assessment, potential confounding, and statistics and reporting (see Protocol for Preparing the RoC Monograph on Cobalt [NTP 2014c]). An overview of the quality evaluations for the carcinogenicity studies is shown in Table 5-3 and discussed below. Details of each study assessment and quality criteria on a study-by-study basis are reported in Appendix D.

No critical concerns for biases were identified in any of the 16 carcinogenicity studies and they were all considered to have some utility for the cancer hazard evaluation. The four NTP inhalation studies (cobalt metal and cobalt sulfate in rats and mice) were considered to be the most informative (high utility) because they used a sufficient number of experimental animals of both sexes for a near lifetime exposure duration and tested three dose levels along with an untreated control. Two inhalation/intratracheal instillation studies of exposure to cobalt(II) oxide (Steinhoff and Mohr 1991, Wehner *et al.* 1977) and three injection studies of cobalt metal or cobalt sulfide in two publications (Hansen *et al.* 2006, Steinhoff and Mohr 1991) were considered to have moderate utility. In general, most of the limitations of the studies were related to low sensitivity of the study to detect an effect, e.g., due to the use of a single dose, short study duration, or small numbers of animals. In the remaining seven injection studies (Heath 1956, Heath and Daniel 1962, Gilman and Ruckerbauer 1962, Jasmin and Riopelle 1976, Shabaan *et al.* 1977), there were major concerns for several potential biases; thus, these studies were considered to have lower utility. Most of these studies had low sensitivity or incomplete necropsies. Poor reporting of methods and results was also a common problem and in some studies there were concerns about potential confounding. Historical controls from a related study by the same authors were used in lieu of concurrent controls in one study (Heath and Daniel 1962). Overall, the major limitations in the studies with low and moderate utility were primarily (but not exclusively) due to low sensitivity and for these cases there is little concern that these limitations would decrease confidence in a positive finding.

**Table 5-2. Overview of experimental animal carcinogenicity study quality evaluations**

| Study | Quality | | | | | | | | | Sensitivity | | | Overall utility |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Controls | Historical data | Randomi-zation | Purity | Dosing | Treatment-related survival | Pathology | Con-founding | Reporting & analysis | Animal model | Stat power | Duration | |
| (NTP 2014b) R | Cobalt metal | +++ | Yes | +++ | +++ | +++ | ++ | +++ | +++ | +++ | +++ | +++ | +++ | High |
| (NTP 2014b) M | Cobalt metal | +++ | Yes | +++ | +++ | +++ | ++ | +++ | +++ | +++ | +++ | +++ | +++ | High |
| (Hansen *et al.* 2006)[a] | Cobalt metal and nano | +++ | No | NR | NR | ++ | +++ | +++ | ++ | ++ | ++ | + | + | Moderate |
| (Jasmin and Riopelle 1976)[a] | Cobalt metal and sulfide | +++ | No | NR | ++ | + | NR | ++ | ++ | ++ | ++ | ++ | + | Low |
| (Heath and Daniel 1962) | Cobalt metal | + | Yes[b] | NR | ++ | + | NR | ++ | ++ | + | ++ | + | +++ | Low |
| (Heath 1956) | Cobalt metal | ++ | Yes[b] | NR | ++ | + | NR | ++ | ++ | + | ++ | + | +++ | Low |
| (NTP 1998) R | Cobalt sulfate | +++ | Yes | +++ | +++ | +++ | +++ | +++ | +++ | +++ | +++ | +++ | +++ | High |
| (NTP 1998) M | Cobalt sulfate | +++ | Yes | +++ | +++ | +++ | +++ | +++ | +++ | +++ | +++ | +++ | +++ | High |
| (Shabaan *et al.* 1977) | Cobalt chloride | ++ | Yes[b] | NR | NR | + | ++ | + | + | + | ++ | ++ | + | Low |
| (Steinhoff and Mohr 1991)- | Cobalt(II) oxide | +++ | No | NR | ++ | ++ | ++ | ++ | ++ | ++ | +++ | +++ | +++ | Moderate |

| Study | | Quality | | | | | | | | | Sensitivity | | | Overall utility |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Controls | Historical data | Randomi-zation | Purity | Dosing | Treatment-related survival | Pathology | Con-founding | Reporting & analysis | Animal model | Stat power | Duration | |
| **(intratracheal)** | | | | | | | | | | | | | | |
| **(Steinhoff and Mohr 1991) - (IP)** | **Cobalt(II) oxide** | +++ | **No** | **NR** | ++ | + | **NR** | ++ | ++ | ++ | +++ | + | +++ | **Moderate** |
| **(Steinhoff and Mohr 1991) - (SC)** | **Cobalt(II) oxide** | +++ | **No** | **NR** | ++ | ++ | **NR** | ++ | ++ | ++ | ++ | + | +++ | **Moderate** |
| **(Gilman and Ruckerbauer 1962) R** | **Cobalt(II) oxide** | +++ | **No** | **NR** | + | + | ++ | ++ | + | + | +++ | + | ++ | **Low** |
| **(Gilman and Ruckerbauer 1962) M** | **Cobalt(II) oxide** | +++ | **No** | **NR** | + | + | ++ | ++ | + | ++ | ++ | ++ | +++ | **Low** |
| **(Wehner *et al.* 1977)** | **Cobalt(II) oxide** | +++ | **No** | **NR** | ++ | ++ | +++ | +++ | ++ | + | ++ | + | +++ | **Moderate** |

+++ = high quality/little to no concerns, ++ = moderate quality/moderate concerns, + = low quality/high concerns, 0 = inadequate, NR = not reported; M = mice; R = rats.
[a]Includes test results for two forms of cobalt, so considered two studies.
[b]Limited number of controls (less than 15) from an earlier study.

### 5.1.3 Assessment of neoplastic findings from carcinogenicity studies

Discussions of the findings from the 16 carcinogenicity studies grouped by site of tumor development are reported below and in Tables 5-3 to 5-5. The main neoplasm locations were the lung in inhalation and intratracheal studies (six studies) and injection sites in studies using various routes of injection (subcutaneous, intramuscular, intraperitoneal, intrapleural, and intrarenal). In addition, in some inhalation studies, some tumors were observed in sites distal from the site of administration. Findings for cobalt compounds across organ sites are discussed in Section 5.3.

#### Lung (Table 5-3)

Different types of cobalt compounds – cobalt metal (NTP 2014b), a soluble cobalt salt, cobalt sulfate heptahydrate (NTP 1998), and a poorly soluble cobalt compound, cobalt(II) oxide (Steinhoff and Mohr 1991) – caused lung neoplasms after exposure by inhalation or intratracheal instillation. Study results for six respiratory exposure studies are reported in Table 5-3 including two studies in mice, three studies in rats, and one study in hamsters. Four of these studies were high-quality, well-designed, and well-conducted studies (NTP 2014b, 1998) and all had either high (NTP 2014b, 1998) or moderate (Steinhoff and Mohr 1991, Wehner *et al.* 1977) utility for evaluating potential cancer hazards.

Four studies found strong evidence that cobalt (both cobalt metal and cobalt sulfate) causes lung tumors in both mice and rats (NTP 2014b, 1998). Significant dose-related increases were seen for alveolar/bronchiolar carcinoma and for alveolar/bronchiolar adenoma or carcinoma combined in all dose groups (low, 1.25 mg/m$^3$; medium, 2.5 mg/m$^3$; high, 5 mg/m$^3$) in male and female mice and rats exposed to cobalt metal by inhalation (NTP 2014b). The incidences of alveolar/bronchiolar adenoma were also significantly increased in rats and mice, although not always in all dose groups. The incidences of carcinoma were very high; when adjusted for intercurrent mortality, incidences in the high-dose groups were 81% for male rats, 69% for female rats, 94% for male mice, and 88% for female mice. In addition, dose-related significant increases in multiplicity (animals with more than one lung tumor) of carcinoma were also found for all dose groups in male and female mice and male rats and in the high-dose (5 mg/m$^3$) groups for female rats (NTP 2014b). Female rats also had, in all dose groups, non-significant increases in cystic keratinizing epithelioma, which is a benign squamous-cell neoplasm that can progress to squamous-cell carcinoma. Cystic keratinizing epithelioma (CKE) is considered to be exposure related in females, because it is very rare and a single squamous-cell carcinoma was also observed in the high-dose group. In males, a single CKE was found in each of the low- and high-exposure groups, and may have been exposure related. Lesions of alveolar or bronchiolar epithelial hyperplasia, which can progress to neoplasms, was also significantly increased in both sexes of rats and mice in all dose levels tested, except for bronchiolar epithelium hyperplasia in mice, which were significantly increased in mid- and high-dose groups in females and high-dose group in males.

In the NTP (1998) inhalation studies of cobalt sulfate heptahydrate, significant dose-related increases were observed for alveolar/bronchiolar carcinoma, and alveolar/bronchiolar adenoma in male and female mice (high dose, 3.0 mg/m$^3$) and female rats (high and mid dose, 1.0 mg/m$^3$) and for alveolar/bronchiolar carcinoma or adenoma combined for male rats (high dose) (NTP 1998). A single squamous-cell carcinoma was also found in the mid- and high-dose groups of

female rats. Non-neoplastic lesions of alveolar or bronchiolar epithelial hyperplasia (considered pre-neoplastic) and metaplasia were also significantly increased in both sexes of rats, but not in mice.

The fifth study reported significant increases in lung neoplasms (alveolar/bronchiolar adenoma, benign squamous epithelial neoplasm, or alveolar/bronchiolar carcinoma combined) in male rats administered cobalt(II) oxide by intratracheal instillation (Steinhoff and Mohr 1991). Non-significant increases in lung neoplasms (alveolar/bronchiolar carcinoma and alveolar/bronchiolar adenoma) were seen in females. There were significant increases in alveolar/bronchiolar proliferation (types of lesions not described) in both sexes combined. Histological examinations were performed on all high-dose group animals; in the low-dose group and untreated control group, only those organs with gross lesions suspected of having tumors and all respiratory tracts were examined, which could underestimate the incidence by not detecting microscopic neoplasms.

In the last study, lung tumors were not observed in hamsters exposed to cobalt(II) oxide by inhalation, although exposure did cause pneumoconiosis, which was evidenced by a variety of lesions including, e.g., interstitial pneumonitis, diffuse granulomatous pneumonia, fibrosis of alveolar septa, and bronchial and bronchiolar epithelial (basal cell) hyperplasia (Wehner *et al.* 1977). There was relatively poor survival among the cobalt-treated animals and the corresponding dust sham-treated controls, which may have limited the sensitivity to detect an effect. In addition, hamsters have been described as a less sensitive model for detecting lung tumors than rats or mice (McInnes *et al.* 2013, Steinhoff and Mohr 1991). (Findings not reported in Table 5-3 because no tumors were observed.)

**Table 5-3. Lung neoplasms and non-neoplastic lesions in experimental animals exposed to cobalt compounds**

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence ($n/N^{+}$) (%) | Comments |
|---|---|---|---|---|---|---|
| **NTP 2014b**<br>Rat (F344/NTac)<br>Male (5–6 wk old)<br>105 wk | Cobalt metal<br>98% pure<br>mass median aerodynamic diameter 1–3 μm) | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Multiple alveolar/bronchiolar carcinoma** | | | **Survival** in exposed groups was similar to controls.<br>**Strengths:** A well-designed study in all factors.<br>**Limitations:** Decreases in body weight in mid and high dose rats.<br>**Other comments:** Historical controls were limited (100 rats).<br>**Significantly increased non-neoplastic lesions**: Alveolar epithelium hyperplasia (pre-neoplastic) - all dose levels<br>Bronchiolar hyperplasia (pre-neoplastic) - all dose levels |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 20 | 6/50 (12%)* | |
| | | | 2.5 mg/m³ | 16 | 14/50 (28%)** | |
| | | | 5 mg/m³ | 16 | 30/50 (60%)** | |
| | | | **Alveolar/bronchiolar carcinoma[a]** | | | |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 20 | 16/50 (38%)*** | |
| | | | 2.5 mg/m³ | 16 | 34/50 (77%)*** | |
| | | | 5 mg/m³ | 16 | 36/50 (81%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Multiple alveolar/bronchiolar adenoma** | | | |
| | | | 0 mg/m³ | 17 | 1/50 (2%) | |
| | | | 1.25 mg/m³ | 20 | 3/50 (6%) | |
| | | | 2.5 mg/m³ | 16 | 2/50 (4%) | |
| | | | 5 mg/m³ | 16 | 6/50 (12%) | |
| | | | **Alveolar/bronchiolar adenoma[a]** | | | |
| | | | 0 mg/m³ | 17 | 2/50 (5%) | |
| | | | 1.25 mg/m³ | 20 | 10/50 (24%)* | |
| | | | 2.5 mg/m³ | 16 | 10/50 (23%)* | |
| | | | 5 mg/m³ | 16 | 14/50 (33%)*** | |
| | | | Trend-test *P*-value: 0.011 | | | |
| | | | **Alveolar/bronchiolar carcinoma or adenoma combined[a]** | | | |
| | | | 0 mg/m³ | 17 | 2/50 (5%) | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | 1.25 mg/m³ | 20 | 25/50 (58%)*** | |
| | | | 2.5 mg/m³ | 16 | 39/50 (85%)*** | |
| | | | 5 mg/m³ | 16 | 44/50 (94%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Cystic keratinizing epithelioma** | | | |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 20 | 1/50 (2%) | |
| | | | 2.5 mg/m³ | 16 | 0/50 (0%) | |
| | | | 5 mg/m³ | 16 | 1/50 (2%) | |
| **NTP 2014b**<br>Rat (F344/NTac)<br>Female (5–6 wk old)<br>105 wk | Cobalt metal<br>98% pure<br>mass median aerodynamic diameter 1–3 μm | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Multiple alveolar/bronchiolar carcinoma** | | | **Survival** was significantly decreased in the mid-dose group.<br>**Strengths:** A well-designed study in almost all factors<br>**Limitations:** A significant decrease in survival of female rats and decreases in body weight in mid- and high-dose rats.<br>**Other comments:** Historical controls were limited (100 rats).<br>**Significantly increased non-neoplastic lesions:** Alveolar hyperplasia (pre-neoplastic) - all dose levels. |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 4/50 (8%) | |
| | | | 2.5 mg/m³ | 24 | 3/50 (6%) | |
| | | | 5 mg/m³ | 25 | 18/50 (36%)** | |
| | | | **Alveolar/bronchiolar carcinoma[a]** | | | |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 9/50 (21%)*** | |
| | | | 2.5 mg/m³ | 24 | 17/50 (42%)*** | |
| | | | 5 mg/m³ | 25 | 30/50 (69%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Multiple alveolar/bronchiolar adenoma** | | | |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 1/50 (2%) | |
| | | | 2.5 mg/m³ | 24 | 3/50 (6%) | |
| | | | 5 mg/m³ | 25 | 4/50 (8%) | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | **Alveolar/bronchiolar adenoma**[a] | | | Bronchiolar hyperplasia (pre-neoplastic) - all dose levels |
| | | | 0 mg/m³ | 35 | 2/50 (5%) | |
| | | | 1.25 mg/m³ | 26 | 7/50 (16%) | |
| | | | 2.5 mg/m³ | 24 | 9/50 (22%)* | |
| | | | 5 mg/m³ | 25 | 13/50 (31%)** | |
| | | | Trend-test *P*-value: 0.002 | | | |
| | | | **Alveolar/bronchiolar carcinoma or adenoma combined**[a] | | | |
| | | | 0 mg/m³ | 35 | 2/50 (4%) | |
| | | | 1.25 mg/m³ | 26 | 15/50 (35%)*** | |
| | | | 2.5 mg/m³ | 24 | 20/50 (49%)*** | |
| | | | 5 mg/m³ | 25 | 38/50 (86%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Squamous cell carcinoma** | | | |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 0/50 (0%) | |
| | | | 2.5 mg/m³ | 24 | 0/50 (0%) | |
| | | | 5 mg/m³ | 25 | 1/50 (2%) | |
| | | | **Cystic keratinizing epithelioma**[a] | | | |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 4/50 (10%)[i] | |
| | | | 2.5 mg/m³ | 24 | 1/50 (3%)[i] | |
| | | | 5 mg/m³ | 25 | 2/50 (5%)[i] | |
| | | | Trend-test *P*-value: 0.002 | | | |
| **NTP 2014b** Mouse ($B6C3F_1$/N) | Cobalt metal | Inhalation (dry particulate) | **Multiple alveolar/bronchiolar carcinoma** | | | **Survival** significantly decreased at 2.5 and 5 |
| | | | 0 mg/m³ | 39 | 3/50 (6%) | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| Male (5–6 wk old)<br>105 wk | 98% pure<br>mass median aerodynamic diameter 1–3 μm) | 6 hr/day, 5 day/wk × 105 wk | 1.25 mg/m³ | 31 | 18/49 (36%)** | mg/m³.<br>**Strengths:** A well-designed study in almost all factors.<br>**Limitations:** A significant decrease in survival of male mice and decrease in body weight in high dose mice<br>**Significantly increased non-neoplastic lesions:** Alveolar/bronchiolar epithelium hyperplasia (pre-neoplastic) - all dose levels<br>Alveolar epithelium hyperplasia (pre-neoplastic) - all dose levels<br>Bronchiolar epithelium hyperplasia (pre-neoplastic) - high dose |
| | | | 2.5 mg/m³ | 29 | 24/50 (48%)** | |
| | | | 5 mg/m³ | 25 | 36/50 (72%)** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Alveolar/bronchiolar carcinoma[a]** | | | |
| | | | 0 mg/m³ | 39 | 11/50 (23%) | |
| | | | 1.25 mg/m³ | 31 | 38/49 (79%)*** | |
| | | | 2.5 mg/m³ | 29 | 42/50 (88%)*** | |
| | | | 5 mg/m³ | 25 | 46/50 (94%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Multiple alveolar/bronchiolar adenoma** | | | |
| | | | 0 mg/m³ | 39 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 31 | 1/49 (2%) | |
| | | | 2.5 mg/m³ | 29 | 1/50 (2%) | |
| | | | 5 mg/m³ | 25 | 0/50 (0%) | |
| | | | **Alveolar/bronchiolar adenoma[a]** | | | |
| | | | 0 mg/m³ | 39 | 7/50 (15%) | |
| | | | 1.25 mg/m³ | 31 | 11/49 (25%) | |
| | | | 2.5 mg/m³ | 29 | 15/50 (36%)* | |
| | | | 5 mg/m³ | 25 | 3/50 (7%) | |
| | | | **Alveolar/bronchiolar carcinoma or adenoma combined[a]** | | | |
| | | | 0 mg/m³ | 39 | 16/50 (33%) | |
| | | | 1.25 mg/m³ | 31 | 41/49 (85%)*** | |
| | | | 2.5 mg/m³ | 29 | 43/50 (90%)*** | |
| | | | 5 mg/m³ | 25 | 47/50 (96%)*** | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | Trend-test *P*-value: 0.001 | | | |
| **NTP 2014b**<br>Mouse ($B6C3F_1$/N)<br>Female (5–6 wk old)<br>105 wk | Cobalt metal<br>98% pure,<br>mass median aerodynamic diameter 1–3 μm) | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Multiple alveolar/bronchiolar carcinoma** | | | **Survival** in exposed groups was similar to controls.<br>**Strengths:** A well-designed study in all factors.<br>**Limitations:** Decrease in body weight in high<br>**Significantly increased non-neoplastic lesions**: Alveolar/bronchiolar epithelium hyperplasia (pre-neoplastic) - all dose levels; Alveolar epithelium hyperplasia (pre-neoplastic) - all dose levels; Bronchiolar epithelium hyperplasia (pre-neoplastic) – mid- and high-dose levels |
| | | | 0 mg/m³ | 36 | 1/49 (10%) | |
| | | | 1.25 mg/m³ | 36 | 7/50 (50%)* | |
| | | | 2.5 mg/m³ | 27 | 20/50 (76%)** | |
| | | | 5 mg/m³ | 26 | 24/50 (86%)** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Alveolar/bronchiolar carcinoma[a]** | | | |
| | | | 0 mg/m³ | 36 | 5/49 (11%) | |
| | | | 1.25 mg/m³ | 36 | 25/50 (54%)*** | |
| | | | 2.5 mg/m³ | 27 | 38/50 (79%)*** | |
| | | | 5 mg/m³ | 26 | 43/50 (88%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Multiple alveolar/bronchiolar adenoma** | | | |
| | | | 0 mg/m³ | 36 | 0/49 (0%) | |
| | | | 1.25 mg/m³ | 36 | 1/50 (2%) | |
| | | | 2.5 mg/m³ | 27 | 0/50 (0%) | |
| | | | 5 mg/m³ | 26 | 1/50 (2%) | |
| | | | **Alveolar/bronchiolar adenoma[a]** | | | |
| | | | 0 mg/m³ | 36 | 3/49 (7%) | |
| | | | 1.25 mg/m³ | 36 | 9/50 (20%) | |
| | | | 2.5 mg/m³ | 27 | 8/50 (19%) | |
| | | | 5 mg/m³ | 26 | 10/50 (25%)* | |
| | | | Trend-test *P*-value: 0.037 | | | |
| | | | **Alveolar/bronchiolar carcinoma or adenoma combined[a]** | | | |
| | | | 0 mg/m³ | 36 | 8/49 (18%) | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | 1.25 mg/m³ | 36 | 30/50 (64%)*** | |
| | | | 2.5 mg/m³ | 27 | 41/50 (85%)*** | |
| | | | 5 mg/m³ | 26 | 45/50 (92%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| **NTP 1998**<br>Rat (F344)<br>Male (6 wk old)<br>2 yr | Cobalt sulfate<br>99% pure,<br>mass median aerodynamic diameter 1–3 µm) | Inhalation (dry particulate)<br>6 hr/day, 5 days/wk × 105 wk | **Alveolar/bronchiolar carcinoma[b]** | | | **Survival** in exposed groups was similar to controls.<br>**Strengths:** A well-designed study in all factors<br>**Limitations:** None.<br>**Significantly increased non-neoplastic lesions:** Alveolar epithelium metaplasia - all dose levels;<br>Alveolar epithelium hyperplasia (pre-neoplastic) - all dose levels |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 0.3 mg/m³ | 15 | 0/50 (0%) | |
| | | | 1.0 mg/m³ | 21 | 3/48 (11%) | |
| | | | 3.0 mg/m³ | 15 | 1/50 (7%) | |
| | | | **Alveolar/bronchiolar adenoma[b]** | | | |
| | | | 0 mg/m³ | 17 | 1/50 (2%) | |
| | | | 0.3 mg/m³ | 15 | 4/50 (18%) | |
| | | | 1.0 mg/m³ | 21 | 1/48 (2%) | |
| | | | 3.0 mg/m³ | 15 | 6/50 (28%) | |
| | | | **Alveolar/bronchiolar adenoma or carcinoma combined[b]** | | | |
| | | | 0 mg/m³ | 17 | 1/50 (2%) | |
| | | | 0.3 mg/m³ | 15 | 4/50 (18%) | |
| | | | 1.0 mg/m³ | 21 | 4/48 (13%) | |
| | | | 3.0 mg/m³ | 15 | 7/50 (34%)* | |
| | | | Trend-test *P*-value: 0.032 | | | |
| **NTP 1998**<br>Rat (F344)<br>Female (6 wk old)<br>2 yr | Cobalt sulfate (99% pure, mass median aerodynamic diameter 1–3 µm) | Inhalation (dry particulate)<br>6 hr/day, 5 days/wk × 105 wk | **Alveolar/bronchiolar carcinoma[b]** | | | Survival in exposed groups was similar to controls.<br>**Strengths:** A well-designed study in all factors and survival was |
| | | | 0 mg/m³ | 28 | 0/50 (0%) | |
| | | | 0.3 mg/m³ | 25 | 2/49 (8%) | |
| | | | 1.0 mg/m³ | 26 | 6/50 (20%)* | |
| | | | 3.0 mg/m³ | 30 | 6/50 (18%)* | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | Trend-test *P*-value: 0.023 | | | similar to controls. **Limitations:** None. **Significantly increased non-neoplastic lesions**: Alveolar epithelium metaplasia - all dose levels; Alveolar epithelium hyperplasia (pre-neoplastic) - high dose; Alveolar epithelium hyperplasia, atypical (pre-neoplastic) - high dose |
| | | | **Alveolar/bronchiolar adenoma[b]** | | | |
| | | | 0 mg/m³ | 28 | 0/50 (0%) | |
| | | | 0.3 mg/m³ | 25 | 1/49 (3%) | |
| | | | 1.0 mg/m³ | 26 | 10/50 (36%)*** | |
| | | | 3.0 mg/m³ | 30 | 9/50 (30%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Alveolar/bronchiolar adenoma or carcinoma combined[b]** | | | |
| | | | 0 mg/m³ | 28 | 0/50 (0%) | |
| | | | 0.3 mg/m³ | 25 | 3/49 (11%)[c] | |
| | | | 1.0 mg/m³ | 26 | 15/50 (51%)***[c] | |
| | | | 3.0 mg/m³ | 30 | 15/50 (46%)***[c] | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Squamous cell carcinoma** | | | |
| | | | 0 mg/m³ | 28 | 0/50 (0%) | |
| | | | 0.3 mg/m³ | 25 | 0/49 (0%) | |
| | | | 1.0 mg/m³ | 26 | 1/50 (2%) | |
| | | | 3.0 mg/m³ | 30 | 1/50 (2%) | |
| | | | **Alveolar/bronchiolar adenoma, carcinoma, or squamous cell carcinoma combined[b]** | | | |
| | | | 0 mg/m³ | 28 | 0/50 (0%) | |
| | | | 0.3 mg/m³ | 25 | 3/49 (11%) | |
| | | | 1.0 mg/m³ | 26 | 16/50 (54%)*** | |
| | | | 3.0 mg/m³ | 30 | 16/50 (49%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| **NTP 1998** | Cobalt sulfate | Inhalation (dry | **Alveolar/bronchiolar carcinoma[b]** | | | S**urvival** in exposed |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| Mice ($B6C3F_1$)<br>Male (6 wk old)<br>2 yr | 99% pure<br>mass median aerodynamic diameter 1–3 µm | particulate)<br>6 hr/day, 5 days/wk × 105 wk | 0 mg/m³ | 22 | 4/50 (13%) | groups was similar to controls.<br>**Strengths:** A well-designed study in all factors and survival was similar to controls.<br>**Limitations:** None.<br>**No significant increase in non-neoplastic lesions.** |
| | | | 0.3 mg/m³ | 31 | 5/50 (16%) | |
| | | | 1.0 mg/m³ | 24 | 7/50 (25%) | |
| | | | 3.0 mg/m³ | 20 | 11/50 (44%)*[d] | |
| | | | Trend-test *P*-value: 0.006 | | | |
| | | | **Alveolar/bronchiolar adenoma[b]** | | | |
| | | | 0 mg/m³ | 22 | 9/50 (30%) | |
| | | | 0.3 mg/m³ | 31 | 12/50 (31%) | |
| | | | 1.0 mg/m³ | 24 | 13/50 (41%) | |
| | | | 3.0 mg/m³ | 20 | 18/50 (55%)*[e] | |
| | | | Trend-test *P*-value: 0.018 | | | |
| | | | **Alveolar/bronchiolar carcinoma or adenoma combined[b]** | | | |
| | | | 0 mg/m³ | 22 | 11/50 (36%) | |
| | | | 0.3 mg/m³ | 31 | 14/50 (37%) | |
| | | | 1.0 mg/m³ | 24 | 19/50 (57%) | |
| | | | 3.0 mg/m³ | 20 | 28/50 (79%)***[f] | |
| | | | Trend-test *P*-value: 0.001 | | | |
| **NTP 1998**<br>Mice ($B6C3F_1$)<br>Female (6 wk old)<br>2 yr | Cobalt sulfate<br>99% pure<br>mass median aerodynamic diameter 1–3 µm | Inhalation (dry particulate)<br>6 hr/day, 5 days/wk × 105 wk | **Alveolar/bronchiolar carcinoma[b]** | | | **Survival** in exposed groups was similar to controls.<br>**Strengths:** A well-designed study in all factors and survival was similar to controls.<br>**Limitations:** None.<br>**No significant increase in non-neoplastic** |
| | | | 0 mg/m³ | 34 | 1/50 (3%) | |
| | | | 0.3 mg/m³ | 37 | 1/50 (3%) | |
| | | | 1.0 mg/m³ | 32 | 4/50 (9%) | |
| | | | 3.0 mg/m³ | 28 | 9/50 (25%)**[g] | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Alveolar/bronchiolar adenoma[b]** | | | |
| | | | 0 mg/m³ | 34 | 3/50 (9%) | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | 0.3 mg/m³ | 37 | 6/50 (15%) | **lesions.** |
| | | | 1.0 mg/m³ | 32 | 9/50 (25%) | |
| | | | 3.0 mg/m³ | 28 | 10/50 (33%)*[h] | |
| | | | Trend-test *P*-value: 0.024 | | | |
| | | | **Alveolar/bronchiolar carcinoma or adenoma combined[b]** | | | |
| | | | 0 mg/m³ | 34 | 4/50 (12%) | |
| | | | 0.3 mg/m³ | 37 | 7/50 (18%) | |
| | | | 1.0 mg/m³ | 32 | 13/50 (33%)*[i] | |
| | | | 3.0 mg/m³ | 28 | 18/50 (50%)***[i] | |
| | | | Trend-test *P*-value: 0.001 | | | |
| **Steinhoff and Mohr 1991**<br>Rat (Sprague-Dawley) Male (10 wk old)<br>life-span | Cobalt(II) oxide<br>"Chemically pure."<br>80% of particles were 5–40 μm) | Intratracheal instillation (dry particulate)<br>1 dose/2 wk × 18 doses, then 1 dose/4 weeks × 11 doses (up to 30th dose), then 1 dose/2 weeks × 9 doses (total 39 doses) | **Bronchioalveolar carcinoma** | | | **Survival** in exposed groups was similar as controls.<br>**Strengths:** Two dose levels tested in a high number of both sexes of rats for two years, with observations for the lifespan without any significant difference in survival compared to untreated controls.<br>**Limitations:** Only the high-dose group received full necropsies. Details of the chemical and animal husbandry were not reported.<br>**Significantly increased** |
| | | | 0 mg/kg bw | NR | 0/50 (0%) | |
| | | | 2 mg/kg bw | NR | 0/50 (0%) | |
| | | | 10 mg/kg bw | NR | 3/50 (6%)[j] | |
| | | | **Bronchioalveolar adenoma** | | | |
| | | | 0 mg/kg bw | NR | 0/50 (0%) | |
| | | | 2 mg/kg bw | NR | 0/50 (0%) | |
| | | | 10 mg/kg bw | NR | 2/50 (4%) | |
| | | | **Bronchioalveolar adenomas or bronchioalveolar carcinomas combined** | | | |
| | | | 0 mg/kg bw | NR | 0/50 (0%) | |
| | | | 2 mg/kg bw | NR | 0/50 (0%) | |
| | | | 10 mg/kg bw | NR | 5/50 (10%)* | |
| | | | **Benign squamous epithelial tumor** | | | |
| | | | 0 mg/kg bw | NR | 0/50 (0%) | |
| | | | 2 mg/kg bw | NR | 1/50 (2%) | |

| Reference & year, animal, study duration | Substance, purity, size | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | 10 mg/kg bw | NR | 0/50 (0%) | **non-neoplastic lesions:** Bronchioalveolar proliferation - both dose levels. |
| **Steinhoff and Mohr 1991**<br>Rat (Sprague-Dawley) Female (10 wk old)<br>life-span | Cobalt(II) oxide<br>"Chemically pure"<br>80% of particles were 5–40 μm) | Intratracheal instillation (dry particulate)<br>1 dose/2 wk × 18 doses, then 1 dose/4 weeks × 11 doses (up to 30th dose), then 1 dose/2 weeks × 9 doses (total 39 doses) | **Bronchioalveolar carcinoma** | | | **Survival** in exposed groups was similar to controls.<br>**Strengths:** Two dose levels tested in a high number of both sexes of rats for two years, with observations for the lifespan without any significant difference in survival compared to untreated controls.<br>**Limitations:** Only the high-dose group received full necropsies. Details of the chemical and animal husbandry were not reported.<br>**Significantly increased non-neoplastic lesions:** Bronchioalveolar proliferation - both dose levels. |
| | | | 0 mg/kg bw | NR | 0/50 (0%) | |
| | | | 2 mg/kg bw | NR | 0/50 (0%) | |
| | | | 10 mg/kg bw | NR | 1/50 (2%) | |
| | | | **Bronchioalveolar adenoma** | | | |
| | | | 0 mg/kg bw | NR | 0/50 (0%) | |
| | | | 2 mg/kg bw | NR | 1/50 (2%) | |
| | | | 10 mg/kg bw | NR | 0/50 (0%) | |
| | | | **Bronchioalveolar adenoma or bronchioalveolar carcinoma combined** | | | |
| | | | 0 mg/kg bw | NR | 0/50 (0%) | |
| | | | 2 mg/kg bw | NR | 1/50 (2%) | |
| | | | 10 mg/kg bw | NR | 1/50 (2%) | |

* = *P*-value ≤ 0.05; ** = *P*-value ≤ 0.01; *** = *P*-value ≤ 0.001. NR = Not reported, wk = week, yr = year.

[+] = Number of animals necropsied for NTP 2014b and NTP 1998 (each group started with 50 animals per sex in the NTP studies) and is the number of animals at the beginning of the study for all other studies.

[a]Adjusted percent incidence based on Poly-3 estimated neoplasm incidence after adjustment for intercurrent mortality.

[b]Adjusted percent incidence based on Kaplan-Meier estimated incidence at the end of the study after adjustment for intercurrent mortality.

[c]Increased over historical control levels with a mean of 7/650 and range of 0% to 4%.
[d]Increased over historical control levels with a mean of 75/947 and range of 0% to 16%.
[e]Increased over historical control levels with a mean of 141/947 and range of 6% to 36%.
[f]Increased over historical control levels with a mean of 205/947 and range of 10% to 42%.
[g]Increased over historical control levels with a mean of 38/939 and range of 0% to 12%.
[h]Increased over historical control levels with a mean of 61/939 and range of 0% to 14%.
[i]Increased over historical control levels with a mean of 97/939 and range of 0% to 16%.
[j] Includes adenocarcinoma (2) and bronchioalveolar adenocarcinoma (1).

**Injection sites (subcutaneous, intramuscular, intraperitoneal, intrapleural, and intrarenal)**

Exposure to several different cobalt forms (cobalt metal, cobalt chloride, and cobalt(II) oxide) by injection increased injection-site tumors in several studies in rats (Hansen *et al.* 2006, Steinhoff and Mohr 1991, Shabaan *et al.* 1977, Gilman and Ruckerbauer 1962, Heath and Daniel 1962, Heath 1956). However, no injection tumors were observed in other studies in rats (Hansen *et al.* 2006, Jasmin and Riopelle 1976) or in the only study in mice (Gilman and Ruckerbauer 1962). Differences in dose levels, sex, and inadequate statistical power could explain these different findings. These studies were considered to have moderate (Steinhoff and Mohr 1991, Hansen *et al.* 2006) or low utility (Heath *et al.* 1956, Heath and Daniel 1962, Gilman and Ruckerbauer 1962, Jasmin and Riopelle 1976, Shabaan *et al*. 1977). However, many concerns for potential biases were related to sensitivity such as limited dosing regimens and statistical power and thus would not necessarily decrease confidence in positive findings. Many studies also had limited reporting, which in part may be typical of older studies (published in the 1950s to 1970s). The relevance of injection studies for evaluating carcinogenicity in humans is discussed in the synthesis (Section 5.3).

Injection of cobalt metal (nanoparticles or microparticles) caused significant increases in the incidences of various types of sarcoma in several studies. Hansen *et al*. (2006) directly compared potential carcinogenic effects of cobalt metal nanoparticles and larger size cobalt metal particles in rats. However, both sizes of particles were placed into the same animals; cobalt nanoparticles were administered intramuscularly and bulk cobalt metal was administered subcutaneously. The study also used a similar design to test other materials (nickel, titanium dioxide, and silicon dioxide). Cobalt-treated animals were sacrificed at 6 and 8 months (due to mortality from tumors) and compared to controls, which were administered polyvinyl chloride (PVC) and sacrificed at 6 and 12 months. Local sarcomas developed around the site of the nanoparticles in one of four rats at the 6-month sacrifice and in five of six rats at the 8-month sacrifice. No tumors were observed around the injection site of the bulk cobalt metal at either sacrifice time, although a single lesion of local fibroblastic proliferation occurred in one of six rats sacrificed at 8 months. The short duration period of 8 months limited the ability to see if the fibroblastic proliferation caused by microparticles would progress into neoplasms. The study also had limited statistical power because of small numbers of animals in the exposed and control groups. With respect to the other materials, tumors were observed in animals after implantation (nanoparticles) or subcutaneous injection (bulk) with nickel but not with injections of titanium dioxide or silicon dioxide. The ratio of surface area to volume between the nickel/cobalt and other compounds was not significantly different, which suggests that the neoplasms were not mediated by physical events and thus supports that the carcinogenic effect is due to cobalt.

A series of studies in hooded rats (Heath and Daniel 1962, Heath 1956) that injected cobalt metal by different exposure routes rats reported sarcomas – rhabdomyofibrosarcoma (including in the heart, intercostal muscle), rhabdomyosarcoma, fibrosarcoma, or other sarcoma – at the site of injection, but not in the controls. The earlier study (Heath 1956) injected cobalt into male and female rats intramuscularly in the thigh and the later study injected cobalt into the intrathoracic region (Heath and Daniel 1962). The controls from the 1956 study were used for the 1962 study. Rhabdomyofibrosarcoma, especially cardiac rhabdomyofibrosarcoma, are very rare tumors. Evidence that the sarcomas were caused by a local carcinogenic effect—beyond the fact that they only developed at injection sites—was seen by their tissue of origin. The 1962 study was limited

by poor survival at the beginning of the study (eight rats died within three days) caused by the injections. Sarcomas originating from muscle tissue were only found in studies that injected cobalt metal by intramuscular injection (rhabdomyofibrosarcoma or rhabdomyosarcoma) or intrapleural injection (cardiac or intercostal muscle rhabdomyosarcoma). Relatively high incidences in sarcomas were observed in both studies although the studies had limited sensitivity because only a few animals were tested at only one dose.

In contrast, no neoplasms were reported in a study in which cobalt metal was injected directly into the kidney of female rats, (Jasmin and Riopelle 1976). Compared to the other injection-site studies that used a single dose, Jasmin and Riopelle used a lower dose (10 mg/rat) than those used in the studies that induced neoplasms (> 20 mg/rat) (Gilman and Ruckerbauer 1962, Heath and Daniel 1962, Heath 1956), suggesting that the dose might have been too low; in addition the study duration was only 12 months. The purpose of this study was to evaluate kidney carcinogenicity.

Cobalt chloride was tested in only one study by subcutaneous injection in male rats (Shabaan *et al.* 1977) in two similar experiments, one that ended after 8 months and one that lasted for 12 months. Only the 12-month study included an untreated control, but it seems reasonable to use that control for the 8-month study, especially since no neoplasms developed in the controls at 12 months. In the 12-month experiment, fibrosarcomas were found in 8/11 survivors at both the subcutaneous injection sites (4) and at sites distant from the injection site (4). In the 8-month experiment, 6 of the 16 animals who were alive at the end of the observation period had tumors (Shabaan *et al.* 1977). (Animals who died before 8 or 12 months were not examined for tumors.) Due to poor reporting, it was not possible to differentiate between tumors that occurred at injection sites versus non-injection sites. The cobalt-exposed animals developed persistent hyperlipaemia, and mortality was high for the treated animals.

Cobalt(II) oxide was injected (i.p., s.c., i.m.) into rats in three studies (Steinhoff and Mohr 1991, Gilman and Ruckerbauer 1962) and into mice (i.m.) in one study (Gilman and Ruckerbauer 1962). All rat studies reported significant increases in local neoplasms, either sarcoma, histiocytoma, or both combined. Although few rats were used in the studies, more than 50% of the rats developed injection-site tumors. No treatment-related increase in neoplasms was found in the one study in mice. The number of animals was adequate in this study; however, only one dose was used (lower than the rat study) and there was little information on dose selection. There were some concerns about potential for confounding from the animal husbandry conditions and limited information on chemical purity in the studies in rats and mice by Gilman and Ruckerbauer (1962). However, no tumors were observed in mice, the controls, or rats and mice injected with thorium dioxide, thus arguing against any potential confounding.

Only one study tested cobalt sulfide, which was injected intrarenally into female rats (Jasmin and Riopelle 1976). No neoplasms were reported in this study; however, the doses used in this study may have been low since they were similar to the doses used in the study with cobalt metal that was also negative.

**Table 5-4. Injection site neoplasms and non-neoplastic lesions in experimental animals exposed to cobalt compounds**

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| **Hansen 2006**<br>Rat (Sprague-Dawley)<br>Male (NR)<br>12 mo | Cobalt metal [bulk and nano]-<br>Bulk metal particles: 6.5 mm diameter by 1 mm in height; surface area to mass ratio of 4.73;<br>nano-particles: 50–200 nm in size (average 120 nm); surface area to mass ratio of 50,000;<br>PVC (bulk and nano)- bulk PVC, without additives: 10 mm in diameter by 1 mm in height; surface area to mass ratio of 4.2;<br>PVC nano-particles: 60–170 nm in size (average 130 nm); surface area to mass ratio of 50,000.) | Nano (dry particles): IM implant (left side of vertebra) Single dose<br>Bulk (solid metal): SC implant (right side of vertebra) Single dose | **Fibroblastic proliferation 6 months** | | | 4 animals (PVC control and treated) sacrificed at 6 months and the remaining 6 animals sacrificed at either 8 (treated) or 12 months (PVC controls). Treated animals sacrificed at 8 months due to mortality.<br>**Strengths:** Tested multiple materials in addition to cobalt and thus able to provide information on whether effects were due to physical state.<br>**Limitations:** Inert polyvinyl chloride particles were used as a negative control. Only a small number of males were tested at a single dose level. Short duration and unable to fully evaluate effects from cobalt bulk particles. |
| | | | 0 cm² | 4 | 0 | |
| | | | Nano 2 cm² | 4 | 2 | |
| | | | Bulk 2 cm² | 4 | 0 | |
| | | | **Sarcoma 6 months** | | | |
| | | | 0 cm² | 4 | 0 | |
| | | | Nano 2 cm² | 4 | 1 | |
| | | | Bulk 2 cm² | 4 | 0 | |
| | | | **Fibroblastic proliferation 8 months** | | | |
| | | | 0 cm² (12 mo) | 6 | 0/6 (0%) | |
| | | | Nano 2 cm² | 6 | 1/6 (16.7%) | |
| | | | Bulk 2 cm² | 6 | 1/6 (16.7%) | |
| | | | **Sarcoma 8 months** | | | |
| | | | 0 cm² (12 mo) | 6 | 0/6 (0%) | |
| | | | Nano 2 cm² | 6 | 5/6 (83.3%)[**] | |
| | | | Bulk 2 cm² | 6 | 0/6 (0%) | |
| **Heath 1956**<br>Rat (Hooded)<br>Male (2–3 mo old)<br>life span | Cobalt metal<br>"Spectroscopically pure"<br>Particle size: 3.5 × 3.5 μm to 17 × 12 | IM inj. (in fowl serum)<br>Single dose | **Rhabdomyofibrosarcoma or sarcoma combined** | | | **Survival**: No data was given on the survival of untreated controls. 2/10 treated males without tumors died before final |
| | | | 0 mg/rat | NR | 0/10 (0%) | |
| | | | 28 mg/rat | 8 | 4/10 (40%) | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence ($n/N^+$) (%) | Comments |
|---|---|---|---|---|---|---|
| | μm) | | | | | sacrificed.<br>**Strengths:** Observation duration was sufficient and both sexes were tested.<br>**Limitations:** Incomplete reporting of many elements. Limited sensitivity due to only one dose level and few rats tested. Full necropsies were not reported. |
| **Heath 1956**<br>Rat (Hooded)<br>Female (2–3 mo old)<br>life span | Cobalt metal<br>"Spectroscopically pure"<br>Particle size: 3.5 × 3.5 μm to 17 × 12 μm) | Series I and Series II<br>i.m. inj. (in fowl serum)<br>Single dose | **Sarcoma (Rhabdomyofibrosarcoma or fibrosarcoma)** | | | **Survival**: No data were reported on the survival of untreated controls. For treated animals, 4/10 rats (Series I) and 0/10 (Series II) without tumors died before final sacrificed.<br>**Strengths:** Observation duration was sufficient and both sexes were tested.<br>**Limitations:** Incomplete reporting of many elements. Limited sensitivity due to only one dose level and few rats tested. Full necropsies were not reported. |
| | | | 0 mg/rat | NR | 0/10 (0%) | |
| | | | 28 mg/rat Series I | 6 | 5/10 (50%) | |
| | | | 28 mg/rat Series II | 10 | 7/10 (70%) | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | | | | **Other comments:** Series I used a concurrent control, but Series II used the same controls, which was non-concurrent. 6/7 sarcoma in Series I and 2/5 in Series II were rhabdomyo-fibrosarcoma |
| **Heath and Daniel 1962**<br>Rat (Hooded)<br>Female (2–3 mo old)<br>28 months | Cobalt metal<br>Purity not reported,<br>Particle size: 3.5 × 3.5 μm to 17 × 12 μm) | Intrathoracic inj. (in serum)<br>Single injection | **Mixed sarcoma intrathoracic region** | | | **Survival** was only reported for exposed rats, which was 12/20 on day 3 and 11/20 after 11 months.<br>**Strengths:** Observation duration was sufficient<br>**Limitations:** Historical controls from Heath 1956 used because there was no concurrent control. Few animals were used, and full necropsies were not done, only skin tumors were histologically examined. Incomplete reporting of many elements.<br>**Other comments:** 3 of 4 tumors originated in part from cardiac muscle, which are very rare. |
| | | | 0 mg/dose[a] | NR | 0/10 (0%) | |
| | | | 28 mg/dose | 11 | 4/12 (33%) | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| **Jasmin and Riopelle 1976**<br>Rat (Sprague-Dawley)<br>Female (120–140 g)<br>12 months | Cobalt metal<br>NR | Intrarenal placement (in glycerin)<br>Single dose | **Kidney neoplasm NOS** | | | **Survival** was not reported.<br>**Strengths:** Moderate number of animals.<br>**Limitations:** Only a single dose level, which was lower than other studies, was tested in only females. Incomplete reporting for many elements. Full necropsies were not performed, though the abdominal and thoracic cavities were examined. |
| | | | 0 mg/rat | NR | 0/16 (0%) | |
| | | | 10 mg/rat | NR | 0/18 (0%) | |
| **Shabaan 1977**<br>Rat (Wistar)<br>Male (4 wk old)<br>8 and 12 mo | Cobalt chloride<br>NR | SC inj. (in saline)<br>1 dose/day × 5 days, then 9 days off, then 1 dose/day × 5 days (total 19 days) | **Injection site and non-injection fibrosarcoma** | | | Treatment-related decrease in **survival;** 16/20 survived at 8 months and 11/20 survived at 12 months.<br>**Limitations:** Exposure resulted in persisent hyperlipaemia and high mortality. Animals dying before the end of observation period were not exmained for tumors. The tumors at injection sites and non-injection sites weren't clearly reported<br>**Other comments:** No concurrent untreated |
| | | | 0 mg/kg bw 12 mo | 19 | 0/19 (0%) | |
| | | | 40 mg/kg bw 8 mo | 16 | 6/16 (30%)[**] | |
| | | | 40 mg/kg bw 12 mo | 11 | 8/11 (40%)[***] | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N$^{+}$) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | | | | controls used at 8 months, 12 months controls used as comparison group. Statistical testing (Fisher's Exact Test) reported by IARC. |
| **Steinhoff and Mohr 1991**<br>Rat (Sprague-Dawley)<br>Male and Female (10 wk old)<br>life span | Cobalt(II) oxide<br>"Chemically pure,<br>80% of particles were 5–40 μm) | i.p. inj. (in saline)<br>1 dose/2 mo × 6 mo | **Sarcoma** | | | **Survival** was not reported.<br>**Strengths:** Both sexes of rats were tested with a long duration of observation.<br>**Limitations:** Incomplete reporting. Limited sensitivity because of few animals per group, only one dose level was tested, and exposure was for less than one year. Limited histological examination<br>**Other comments:** Results were reported as combined for males and females. |
| | | | 0 mg/kg | NR | 1/20 (5%) | |
| | | | 200 mg/kg | NR | 3/20 (15%)[*] | |
| | | | **Mesothelioma** | | | |
| | | | 0 mg/kg | NR | 0/20 (0%) | |
| | | | 200 mg/kg | NR | 1/20 (5%) | |
| | | | **Histiocytoma** | | | |
| | | | 0 mg/kg | NR | 1/20 (5%) | |
| | | | 200 mg/kg | NR | 10/20 (50%)[**] | |
| **Steinhoff and Mohr 1991**<br>Rat (Sprague-Dawley)<br>Male (10 wk old)<br>life span | Cobalt oxide<br>("Chemically pure", 80% of particles were 5–40 μm) | s.c. inj. (in saline)<br>1 inj/day, 5 day/week × 730 days | **Histiocytoma or sarcoma combined** | | | **Survival** was not reported.<br>**Strengths:** Duration of exposure and observation were sufficient. One dose level was tested, at two |
| | | | 0 mg/kg/wk | NR | 0/10 (0%) | |
| | | | 0 mg/kg/wk | NR | 0/10 (0%) | |
| | | | 2 mg/kg × 5/wk | NR | 5/10 (50%)[*] | |
| | | | 10 mg/kg/wk | NR | 4/10 (40%)[*] | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N$^{+}$) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | | | | intensity levels and two untreated control groups used.<br>**Limitations:** Limited sensitivity due to few animals per group and only males tested. Limited histological examination. Incomplete reporting of many elements. |
| **Gilman and Ruckerbauer 1962**<br>Rat (Wistar)<br>Male and female (2–3 mo old)<br>489 days | Cobalt oxide<br>purity not reported,<br>particle size was < 5 µm | i.m. inj. (in aqueous suspension of penicillin G procaine)<br>Single dose | **Sarcoma** | | | **Survival** was similar to control at 90 days.<br>**Strengths:** The duration of observation was sufficient and both sexes were tested.<br>**Limitations**: Limited sensitivity because only a single dose was given at one dose level and few animals per group were tested. Incomplete reporting for many elements. Animal bedding was periodically dusted with rotenone powder.<br>**Other comments:** Results were reported as combined for males and females. |
| | | | 0 mg/rat | 10 | 0/10 (0%) | |
| | | | 30 mg/rat | 10 | 5/10 (50%)[*] | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N$^{+}$) (%) | Comments |
|---|---|---|---|---|---|---|
| **Gilman and Ruckerbauer 1962**<br>Mouse (Swiss)<br>Female (2–3 mo old)<br>751 days | Cobalt oxide<br>purity not reported,<br>particle size was < 5 µm | i.m. inj. (in aqueous suspension of penicillin G procaine)<br>Single dose | **Sarcoma** | | | **Survival** was similar to control at 90 days.<br>**Strengths:** The duration of observation and the numbers of animals per group were sufficient.<br>**Limitations:** Limited sensitivity due to only a single dose was given at one dose level, without a rationale, to females only. Half of the mice were survivors from a preliminary study who received unwashed cobalt, which was known to contain other toxic chemicals. Bedding was periodically dusted with rotenone powder. Incomplete reporting for many elements. |
| | | | 0 mg/mouse | 48 | 0/51 (0%) | |
| | | | 20 mg/mouse | 46 | 0/50 (0%) | |
| **Jasmin and Riopelle 1976**<br>Rat (Sprague-Dawley)<br>Female (120–140 g)<br>12 months | Cobalt sulfide<br>NR | Intrarenal placement (in glycerin)<br>Single dose | **Kidney neoplasm NOS** | | | **Survival** was not reported.<br>**Strengths:** Moderate number of rats per groups.<br>**Limitations:** Limited sensitivity due to only a single dose level, which was lower than other studies and only females tested. Incomplete |
| | | | 0 mg/rat | NR | 0/16 (0%) | |
| | | | 10 mg/rat | NR | 0/20 (0%) | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | | | | reporting. Full necropsies were not performed, though the abdominal and thoracic cavities were examined. |

* = *P*-value ≤ 0.05; ** = *P*-value ≤ 0.01; *** = *P*-value ≤ 0.001.

NR = Not reported, inj. = injection, i.p. = intraperitoneal, i.m. = intramuscular, s.c. = subcutaneous, wk = week, mo = month.

[+] = Number of animals at the beginning of the study, except for Hansen 2006 and Heath and Daniel 1962, which used the number of animals that were examined at the time of sacrifice, 10 animals were originally assigned to each group (Hansen 2006) or the number of animals that survived beyond day 4, 10 control and 20 exposed animals were originally assigned (Heath and Daniel 1962).

[ ] = Statistical significance calculated by NTP using Fisher's Exact Test.

[a]Historical control group from earlier study by the same author.

**Other neoplasms including those at distal sites**

Several lines of evidence support systemic exposure of rats and mice to cobalt. Cobalt concentrations and burdens increased with increasing exposure concentrations in all studies in all tissues examined; however, tissue burdens normalized by exposure concentration showed increased levels only in the liver (NTP 2014b; see Section 5.1.3). In addition, neoplasms were observed at several organ sites (pancreas, hematopoietic system, and kidney distal to the route of administration.

***Adrenal gland***

Neoplasms of the adrenal gland were reported in two inhalation studies that tested cobalt metal and cobalt sulfate (see Table 5-5) (NTP 2014b, 1998, Wehner *et al.* 1977). In the four NTP studies, cobalt metal and cobalt sulfate heptahydrate were each tested in both mice and rats, but adrenal gland neoplasms developed only in rats. One study reported a single adrenal gland neoplasm in hamsters exposed to cobalt(II) oxide (Wehner *et al.* 1977). There is a high background of adrenal tumors in the male rats in the two NTP studies. Adrenal gland neoplasms can develop because of damage to lungs that causes obstructive sequelae by causing systemic hypoxemia, leading to chronic stimulation of catecholamine release by the adrenal medulla and subsequent neoplastic development (NTP 2014b). Since inhalation of cobalt caused lesions in the lung that could cause obstruction (chronic inflammation), it is possible that the adrenal glands are not directly caused by systemic exposure to cobalt, but could be a secondary response to lung damage. However, there is not enough evidence to differentiate between a direct or indirect cause of adrenal gland neoplasms from cobalt exposure.

The strongest evidence for a treatment-related effect comes from the rat studies with cobalt metal. Inhalation exposure to cobalt metal significantly increased bilateral malignant pheochromocytoma in the high-dose group (5 mg/m$^3$) and all malignant pheochromocytoma, malignant or benign pheochromocytoma combined, and benign pheochromocytoma in both the mid- (2.5 mg/m$^3$) and high-dose groups in male rats. In females, there was a significantly increased incidence of bilateral malignant pheochromocytoma as well as malignant pheochromocytoma overall at the high dose and malignant or benign pheochromocytoma combined, and bilateral benign pheochromocytoma as well as benign pheochromocytoma in both the mid- and high-dose groups (NTP 2014b). Hyperplasia of the adrenal gland was also significantly increased in females at mid and high doses, and was significantly decreased in males in the mid- and high-dose groups.

Cobalt sulfate heptahydrate caused significant increases in malignant, benign, or complex adrenal neoplasms combined in both sexes, which were higher than historical controls (NTP 1998). However, increases were only significant in the high-dose (3 mg/m$^3$) group in females and the mid-dose (1 mg/m$^3$) group in males. Females had a significant trend of increasing tumor incidence with increasing dose for benign pheochromocytoma and all tumor types combined. Hyperplasia was significantly increased in females and the high-dose, but was significantly decreased in the low-dose (0.3 mg/m$^3$) males.

Wehner reported finding a single adrenal gland adenoma in the cortex of hamsters after inhalation of cobalt(II) oxide. (Wehner *et al.* 1977). Wehner only tested one dose level, 10 mg/m$^3$, which was higher than those used in mice or rats in the two NTP studies. The significant

increases in rats, but not mice or hamsters, could indicate a species difference in sensitivity to developing adrenal gland tumors from cobalt exposure, especially considering hamsters received a higher dose level than the rats.

***Distal sites: Pancreatic islet cell, hematopoietic system, and kidney***

Inhalation exposure to cobalt metal also caused other tumors at sites distant from the route of administration: pancreas in male rats and mononuclear-cell leukemia in female rats in the NTP inhalation bioassay of cobalt metal (Behl *et al.* 2015, NTP 2014b). A non-significant increase in the incidence of kidney tumors was observed in male rats. It is not clear whether the kidney tumors were treatment related. Tumors were not observed in the pancreas, kidney, or hematopoietic system of rats exposed to cobalt sulfate or mice exposed to either form of cobalt. Findings are presented in Table 5-5 and briefly summarized below.

Male rats exposed to cobalt metal were found to have a significant increase in the incidences of pancreatic islet-cell carcinoma or adenoma combined in both the mid- and high-dose groups and a significant positive dose-related trend was observed. A significant increase in the incidence of pancreatic adenoma was also observed in the mid-dose group in males. The non-significant increases in the incidence of pancreatic islet-cell carcinoma observed in female rats exceeded the historical controls for all routes of administration and thus might have been related to exposure. However, historical controls were limited as they were based on a dataset of only 100 Fischer 344/NTac rats from two NTP carcinogenicity studies. Significant increases in the incidence of mononuclear-cell leukemia were seen in females in all dose groups, which exceeded the limited historical controls for all exposure routes. In addition, time to first tumor was shorter in cobalt-exposed animals (117 to 590 days) compared to the concurrent control (663 days) albeit there was no pattern of decreasing duration with increasing dose and because of the limited historical control database, it is not known how much time to first tumor in untreated animals varies across studies. The incidence of mononuclear-cell leukemia was similar in male rats compared to the untreated controls.

The incidence of kidney neoplasms (adenoma or carcinoma combined) was higher (although not significantly so) in the low- and high-dose male rats compared to the concurrent controls and a significant trend was observed. The incidence exceeded the historical controls for all routes of administration, but the historical controls are limited as mentioned above. Four of the five neoplasms were adenomas. In analyses of standard and extended evaluations, a significant trend was observed; two of the seven neoplasms in the high-dose group were carcinomas. Kidney neoplasms are relatively rare, so non-significant increases may be related to cobalt exposure (NTP 2014b). No treatment-related non-neoplastic lesions were observed. Two studies injected cobalt sulfide or cobalt metal directly into the kidneys of female rats in one publication (Jasmin and Riopelle 1976). No kidney tumors or any other tumors were reported as being significantly increased. Only a single dose was given at one dose level and the dose was lower than that used in other injection studies.

**Table 5-5. Other and distal site neoplasms and relevant non-neoplastic lesions in experimental animals exposed to cobalt compounds**

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| **Adrenal gland** | | | | | | |
| **NTP 2014b**<br>Rat (F344/NTac)<br>Male (5–6 wk old)<br>105 wk | Cobalt metal<br>98% pure<br>mass median aerodynamic diameter 1–3 μm | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Bilateral malignant pheochromocytoma** | | | **Survival** was similar to controls.<br>**Strengths:** A well-designed study in all factors.<br>**Limitations:** Decreases in body weight in mid and high dose rats.<br>**Other comments:** Historical controls were limited (100 rats).<br>**No significantly increased non-neoplastic lesions.** |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 20 | 0/50 (0%) | |
| | | | 2.5 mg/m³ | 16 | 0/50 (0%) | |
| | | | 5 mg/m³ | 16 | 7/50 (14%)** | |
| | | | **Malignant pheochromocytoma[a]** | | | |
| | | | 0 mg/m³ | 17 | 2/50 (5%) | |
| | | | 1.25 mg/m³ | 20 | 2/50 (5%) | |
| | | | 2.5 mg/m³ | 16 | 9/50 (21%)* | |
| | | | 5 mg/m³ | 16 | 16/50 (39%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Benign pheochromocytoma[a]** | | | |
| | | | 0 mg/m³ | 17 | 15/50 (36%) | |
| | | | 1.25 mg/m³ | 20 | 23/50 (54%) | |
| | | | 2.5 mg/m³ | 16 | 37/50 (81%)*** | |
| | | | 5 mg/m³ | 16 | 34/50 (76%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Malignant or benign combined pheochromocytoma[a]** | | | |
| | | | 0 mg/m³ | 17 | 17/50 (40%) | |
| | | | 1.25 mg/m³ | 20 | 23/50 (54%) | |
| | | | 2.5 mg/m³ | 16 | 38/50 (83%)*** | |
| | | | 5 mg/m³ | 16 | 41/50 (91%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N$^{+}$) (%) | Comments |
|---|---|---|---|---|---|---|
| **NTP 2014b**<br>Rat (F344/NTac)<br>Female (5–6 wk old)<br>105 wk | Cobalt metal<br>98% pure, mass median aerodynamic diameter 1–3 μm | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Bilateral malignant pheochromocytoma** | | | **Survival** was significantly decreased in the mid-dose group.<br>**Strengths:** A well-designed study in almost all factors.<br>**Limitations:** A significant decrease in survival of female rats. Decreases in body weight in mid- and high-dose rats.<br>**Other comments:** Historical controls were limited, as Fischer 344/NTac rats (100 rats).<br>**Significantly increased non-neoplastic lesions:** Hyperplasia - low and medium |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 1/50 (2%) | |
| | | | 2.5 mg/m³ | 24 | 1/49 (2%) | |
| | | | 5 mg/m³ | 25 | 4/50 (8%)* | |
| | | | **Malignant pheochromocytoma[a]** | | | |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 2/50 (5%) | |
| | | | 2.5 mg/m³ | 24 | 3/49 (8%) | |
| | | | 5 mg/m³ | 25 | 11/50 (27%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Bilateral benign pheochromocytoma** | | | |
| | | | 0 mg/m³ | 35 | 2/50 (4%) | |
| | | | 1.25 mg/m³ | 26 | 4/50 (8%) | |
| | | | 2.5 mg/m³ | 24 | 8/49 (16%)* | |
| | | | 5 mg/m³ | 25 | 19/50 (38%)** | |
| | | | **Benign pheochromocytoma[a]** | | | |
| | | | 0 mg/m³ | 35 | 6/50 (14%) | |
| | | | 1.25 mg/m³ | 26 | 12/50 (27%) | |
| | | | 2.5 mg/m³ | 24 | 22/49 (52%)*** | |
| | | | 5 mg/m³ | 25 | 36/50 (81%)*** | |
| | | | Trend-test *P*-value: 0.001 | | | |
| | | | **Malignant or benign combined pheochromocytoma[a]** | | | |
| | | | 0 mg/m³ | 35 | 6/50 (14%) | |
| | | | 1.25 mg/m³ | 26 | 13/50 (29%) | |
| | | | 2.5 mg/m³ | 24 | 23/49 (55%)*** | |
| | | | 5 mg/m³ | 25 | 40/50 (89%)*** | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | Trend-test *P*-value: 0.001 | | | |
| **NTP 1998**<br>Rat (F344)<br>Male (6 wk old)<br>2 yr | Cobalt sulfate<br>99% pure) | Inhalation (dry particulate)<br>6 hr/day, 5 days/wk × 105 wk | **Benign pheochromocytoma[b]** | | | **Survival** was similar to controls.<br>**Strengths:** A well-designed study in all factors and survival was similar to controls..<br>**Limitations:** None.<br>**No significantly increased non-neoplastic lesions.** |
| | | | 0 mg/m³ | 17 | 14/50 (51%) | |
| | | | 0.3 mg/m³ | 15 | 19/50 (70%) | |
| | | | 1.0 mg/m³ | 21 | 23/48 (72%) | |
| | | | 3.0 mg/m³ | 15 | 20/50 (71%) | |
| | | | **Malignant, benign, or complex pheochromocytoma combined[b]** | | | |
| | | | 0 mg/m³ | 17 | 15/50 (52%) | |
| | | | 0.3 mg/m³ | 15 | 19/50 (70%) | |
| | | | 1.0 mg/m³ | 21 | 25/48 (74%)*[c] | |
| | | | 3.0 mg/m³ | 15 | 20/50 (71%) | |
| **NTP 1998**<br>Rat (F344)<br>Female (6 wk old)<br>2 yr | Cobalt sulfate<br>99% pure | Inhalation (dry particulate)<br>6 hr/day, 5 days/wk × 105 wk | **Benign pheochromocytoma[b]** | | | **Survival** was similar to controls.<br>**Strengths**: A well-designed study in all factors and survival was similar to controls.<br>**Limitations:** None<br>**Significantly increased non-neoplastic lesions**: Adrenal gland: hyperplasia - high dose. |
| | | | 0 mg/m³ | 28 | 2/48 (5%) | |
| | | | 0.3 mg/m³ | 25 | 1/49 (3%) | |
| | | | 1.0 mg/m³ | 26 | 3/50 (9%) | |
| | | | 3.0 mg/m³ | 30 | 8/48 (26%)* | |
| | | | Trend-test *P*-value: 0.004 | | | |
| | | | **Malignant, benign, or complex combined[b]** | | | |
| | | | 0 mg/m³ | 28 | 2/48 (4%) | |
| | | | 0.3 mg/m³ | 25 | 1/49 (2%) | |
| | | | 1.0 mg/m³ | 26 | 4/50 (8%) | |
| | | | 3.0 mg/m³ | 30 | 10/48 (21%)*[d] | |
| | | | Trend-test *P*-value: 0.001 | | | |
| **Wehner 1977** | Cobalt(II) oxide | Inhalation (dry | **Adenoma (cortex)** | | | **Survival** in exposed |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N$^{+}$) (%) | Comments |
|---|---|---|---|---|---|---|
| Hamster (Syrian Golden, random bred ENG:ELA)<br>Male (2 mo old)<br>Lifespan | Purity not reported<br>median diameter of particles 0.14 µm,<br>median mass diameter 0.45 µm<br>geometric standard deviation 1.9 µm | particulate)<br>7 hr/day, 5 days/wk × lifespan | 0 µg/L | NR | 0/51 (0%) | group is similar to control<br>**Strengths:** Duration of exposure and observation were sufficient.<br>**Limitations:** Incomplete reporting. Low sensitivity because of relatively poor survival of both exposed and controls, only a single dose level was tested with no justification for choosing that level.<br>**Other comments:** The study looked at cobalt's effect on cigarette smoke, but a cobalt oxide only group was tested. Cobalt-exposed hamsters developed pneumoconiosis. |
| | | | 10.1 µg/L | NR | 1/50 (2%) | |
| **Pancreas** | | | | | | |
| **NTP 2014b**<br>Rat (F344/NTac)<br>Male (5–6 wk old)<br>105 wk | Cobalt metal<br>(98% pure, mass median aerodynamic diameter 1–3 µm) | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Carcinoma**[a] | | | **Survival** was similar to controls.<br>**Strengths:** A well-designed study in all factors.<br>**Limitations:** Decreases in body |
| | | | 0 mg/m³ | 17 | 2/50 (5%) | |
| | | | 1.25 mg/m³ | 20 | 1/50 (3%) | |
| | | | 2.5 mg/m³ | 16 | 5/48 (13%)[e] | |
| | | | 5 mg/m³ | 16 | 6/49 (15%)[e] | |
| | | | Trend-test *P*-value: 0.021 | | | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N$^{+}$) (%) | Comments |
|---|---|---|---|---|---|---|
| | | | **Adenoma**[a] | | | weight in mid- and high-dose rats.<br>**Other comments:** Historical controls were limited (100 rats).<br>**No significantly increased non-neoplastic lesions.** |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 20 | 1/50 (3%) | |
| | | | 2.5 mg/m³ | 16 | 6/48 (15%)* | |
| | | | 5 mg/m³ | 16 | 3/49 (8%) | |
| | | | **Carcinoma or adenoma combined**[a] | | | |
| | | | 0 mg/m³ | 17 | 2/50 (5%) | |
| | | | 1.25 mg/m³ | 20 | 2/50 (5%) | |
| | | | 2.5 mg/m³ | 16 | 10/48 (25%)*[e] | |
| | | | 5 mg/m³ | 16 | 9/49 (23%)*[e] | |
| | | | Trend-test *P*-value: 0.002 | | | |
| **NTP 2014b**<br>Rat (F344/NTac)<br>Female (5–6 wk old)<br>105 wk | Cobalt metal<br>(98% pure, mass median aerodynamic diameter 1–3 μm) | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Carcinoma**[a] | | | **Survival** was significantly decreased in the mid-dose group.<br>**Strengths:** A well-designed study in almost all factors.<br>**Limitations:** A significant decrease in survival of female rats. Decreases in body weight in mid- and high-dose rats.<br>**Other comments:** Historical controls were limited (100 rats).<br>**No significantly increased non-neoplastic lesions** |
| | | | 0 mg/m³ | 35 | 1/50 (2%) | |
| | | | 1.25 mg/m³ | 26 | 0/50 (0%) | |
| | | | 2.5 mg/m³ | 24 | 0/50 (0%) | |
| | | | 5 mg/m³ | 25 | 3/50 (7%)[f] | |
| | | | **Adenoma** | | | |
| | | | 0 mg/m³ | 35 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 26 | 0/50 (0%) | |
| | | | 2.5 mg/m³ | 24 | 0/50 (0%) | |
| | | | 5 mg/m³ | 25 | 1/50 (2%) | |
| | | | **Carcinoma or adenoma combined**[a] | | | |
| | | | 0 mg/m³ | 35 | 1/50 (2%) | |
| | | | 1.25 mg/m³ | 26 | 0/50 (0%) | |
| | | | 2.5 mg/m³ | 24 | 0/50 (0%) | |
| | | | 5 mg/m³ | 25 | 3/50 (7%)[f] | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| **Hematopoietic system** | | | | | | |
| **NTP 2014b**<br>Rat (F344/NTac)<br>Male (5–6 wk old)<br>105 wk | Cobalt metal<br>(98% pure, mass median aerodynamic diameter 1–3 μm) | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Mononuclear cell leukemia[a]** | | | **Survival** was similar to controls.<br>**Strengths:** A well-designed study in all factors.<br>**Limitations:** None.<br>**Other comments:** Historical controls were limited (100 rats).<br>**No significantly increased non-neoplastic lesions.** |
| | | | 0 mg/m³ | 17 | 21/50 (49%) | |
| | | | 1.25 mg/m³ | 20 | 25/50 (58%) | |
| | | | 2.5 mg/m³ | 16 | 22/50 (50%) | |
| | | | 5 mg/m³ | 16 | 22/50 (48%) | |
| **NTP 2014b**<br>Rat (F344/NTac)<br>Female (5–6 wk old)<br>105 wk | Cobalt metal<br>(98% pure, mass median aerodynamic diameter 1–3 μm) | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Mononuclear cell leukemia[a]** | | | **Survival** was significantly decreased in the mid-dose group.<br>**Strengths:** A well-designed study in almost all factors.<br>**Limitations:** A significant decrease in survival of female rats. Decreases in body weight in mid- and high-dose rats.<br>**Other comments:** Historical controls were limited (100 rats).<br>**No significantly increased non-neoplastic lesions** |
| | | | 0 mg/m³ | 35 | 16/50 (36%) | |
| | | | 1.25 mg/m³ | 26 | 29/50 (62%)**[g] | |
| | | | 2.5 mg/m³ | 24 | 28/50 (61%)*[g] | |
| | | | 5 mg/m³ | 25 | 27/50 (59%)*[g] | |

| Reference & year, animal, study duration | Substance & purity | Dosing regimen | Dose levels | # Animals at sacrifice | Tumor incidence (n/N[+]) (%) | Comments |
|---|---|---|---|---|---|---|
| **Kidney** | | | | | | |
| **NTP 2014b**<br>Rat (F344/NTac)<br>Male (5–6 wk old)<br>105 wk | Cobalt metal<br>(98% pure, mass median aerodynamic diameter 1–3 μm) | Inhalation (dry particulate)<br>6 hr/day, 5 day/wk × 105 wk | **Tubule adenoma[a]** | | | **Survival** was similar to controls.<br>**Strengths:** A well-designed study in all factors.<br>**Limitations:** Decreases in body weight in mid- and high-dose rats.<br>**Other comments:** Historical controls were limited (100 rats.)<br>**No significantly increased non-neoplastic lesions** |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 20 | 1/50 (3%)[h] | |
| | | | 2.5 mg/m³ | 16 | 0/50 (0%) | |
| | | | 5 mg/m³ | 16 | 3/50 (8%)[h] | |
| | | | **Tubule carcinoma or adenoma[a]** | | | |
| | | | 0 mg/m³ | 17 | 0/50 (0%) | |
| | | | 1.25 mg/m³ | 20 | 1/50 (3%)[h] | |
| | | | 2.5 mg/m³ | 16 | 0/50 (0%) | |
| | | | 5 mg/m³ | 16 | 4/50 (10%)[h] | |
| | | | Trend-test *P*-value: 0.018 | | | |
| | | | **Tubule carcinoma or adenoma[ai]** | | | |
| | | | 0 mg/m³ | 17 | 3/50 (8%) | |
| | | | 1.25 mg/m³ | 20 | 1/50 (3%) | |
| | | | 2.5 mg/m³ | 16 | 1/50 (2%) | |
| | | | 5 mg/m³ | 16 | 7/50 (17%) | |
| | | | Trend-test *P*-value: 0.023 | | | |

*$P$-value < 0.05; **$P$-value < 0.01; ***$P$-value < 0.01.

[+] = Number of animals necropsied for NTP 2014b and NTP 1998 (each group started with 50 animals per sex in the NTP studies) and is the number of animals at the beginning of the study for all other studies.

NR = Not reported, M = male, F = female, hr = hour, wk = week, mo = month, yr = year.

[a]Adjusted percent incidence based on Poly-3 estimated neoplasm incidence after adjustment for intercurrent mortality.

[b]Adjusted percent incidence based on Kaplen-Meier estimated incidence at the end of the study after adjustment for intercurrent mortality.

[c]Increased over historical control levels with a mean of 176/623 and range of 8% to 50%.

[d]Increased over historical control levels with a mean of 39/608 and range of 2% to 14%.

[e]Increased over historical control levels with a mean of 2/100 and range of 0% to 4%.

[f]Increased over historical control levels with a mean of 1/100 and range of 0% to 2%.

[g]Increased over historical control levels with a mean of 35/100 and range of 32% to 38%.

[h]Increased over historical control levels with a mean of 1/100 and range of 0% to 2%.
[i]Analyzed by standard and extended evaluation. In a standard evaluation a single section of each kidney is examined histologically, while in an extended evaluation, three to four additional sections, taken at 1 mm intervals are examined histologically.

## 5.2 Co-carcinogenicity studies

### 5.2.1 Overview of the studies

Nine co-carcinogen studies were identified that tested soluble compounds, including four studies using cobalt chloride (Zeller 1975, Finogenova 1973, O'Hara *et al.* 1971, Kasirsky *et al.* 1965) and three studies using sodium cobaltinitrite (O'Hara *et al.* 1971, Thompson *et al.* 1965, Orzechowski *et al.* 1964); and a poorly soluble compound, cobalt(II) oxide, in two studies (Steinhoff and Mohr 1991, Wehner *et al.* 1977) (see Table 5-6). Most co-carcinogen studies were conducted in mice, though two studies were conducted in rats (Steinhoff and Mohr 1991, Zeller 1975) and one study conducted in hamsters (Wehner *et al.* 1977). Almost all of the co-carcinogen studies used dermal exposure to methylcholanthrene as the known carcinogen, with Zeller using subcutaneous injections of diethylnitrosamine, Steinhoff and Mohr using intratracheal instillation of benzo[*a*]pyrene, and Wehner using inhalation exposure to cigarette smoke. Methylcholanthrene induced skin tumors, while diethylnitrosamine induced liver and nasal tumors, benzo[*a*]pyrene induced lung tumors, and cigarette smoke increased incidences of total malignant or total benign neoplasms. Cobalt compounds were administered by intraperitoneal injection in all but four studies, which used subcutaneous injection (Zeller 1975), drinking water (Thompson *et al.* 1965), inhalation (Wehner *et al.* 1977), and intratracheal instillation (Steinhoff and Mohr 1991) as routes of exposure.

**Table 5-6. Overview of co-carcinogenicity studies in experimental animals reviewed**

| Strain (sex) | Substance | Route | Co—carcinogen & route | Exposure period/ study duration | Reference |
|---|---|---|---|---|---|
| Rat Wistar (M&F) | Cobalt chloride | SC inj. | diethylnitrosamine SC inj. | 43 wk/ lifespan | (Zeller 1975) |
| Mouse CBAxC57B$_1$ (F) | Cobalt chloride | IP inj. | methylcholanthrene dermal | 8 wk/ 8wk | (Finogenova 1973) |
| Mouse CF-1 (M&F) | Cobalt chloride | IP inj. | methylcholanthrene dermal | 5 wk/ 17 wk | (O'Hara *et al.* 1971) |
| Mouse CF-1 (M&F) | Cobalt chloride | IP inj. | methylcholanthrene dermal | 10 wk/ 10wk | (Kasirsky *et al.* 1965) |
| Mouse CF-1 (M&F) | Sodium cobaltinitrite | IP inj. | methylcholanthrene dermal | 5 wk/ 17 wk | (O'Hara *et al.* 1971) |
| Mouse CF-1 (M&F) | Sodium cobaltinitrite | Drinking water | methylcholanthrene dermal | 11wk/1 1wk | (Thompson *et al.* 1965) |
| Mouse CF-1 (M&F) | Sodium cobaltinitrite | IP inj. | methylcholanthrene dermal | 72 days/ 75 days | (Orzechowski *et al.* 1964) |
| Rat Sprague-Dawley (F) | Cobalt(II) oxide | Intratracheal instill. | benzo[*a*]pyrene intratracheal instill. | 47 wk/ lifespan | (Steinhoff and Mohr 1991) |
| Hamster Syrian Golden (M) | Cobalt(II) oxide | Inhalation | cigarette smoke inhalation | Lifespan/ lifespan | (Wehner *et al.* 1977) |

M = male, F = female, instill. = instillation, inj. = injection, IP = intraperitoneal, IM = intramuscular, SC = subcutaneous, wk = week, yr = year.

### 5.2.2 Overview of the assessment of study quality and utility

Each of these primary studies was systematically evaluated for its ability to inform the cancer hazard similar to that described for the carcinogenicity studies in Section 5.1.2. O'Hara *et al.* (1971) conducted two co-carcinogenicity studies (one using cobalt chloride and the other using sodium cobaltinitrite) that were considered inadequate for evaluation of the carcinogenicity of cobalt, because the authors did not test the influence of cobalt on tumor formation, as cobalt was not administered until after neoplasms were already detectable. No critical concerns were identified in the remaining studies although they were considered to be of low quality. Finogenova (1973) did not report neoplasm incidences, but did report neoplasm onset and latency. The other studies had poor reporting of duration, survival, and results, as they were not reported for each gender, but had combined data for both sexes. The study quality assessment is discussed in Appendix D. All co-carcinogenicity studies were categorically restricted to being ranked no higher than "low" for the utility to inform the carcinogenicity evaluation. This restriction was applied to account for the indirect measure of carcinogenicity that co-carcinogenicity studies provide.

### 5.2.3 Assessment of findings from co-carcinogenicity studies

Co-carcinogenicity studies are also divided by site of neoplasm development into skin, lung, liver, nasal neoplasms, and neoplasms of unspecified location. Only one co-carcinogen study demonstrated an increased incidence of lung neoplasms from cobalt (cobalt(II) oxide), while three studies showed no effect from cobalt (cobalt chloride and cobalt(II) oxide) and three studies reported a decrease in neoplastic incidence with the additional exposure to cobalt compounds (cobalt chloride and sodium cobaltinitrite).

#### Skin

Four co-carcinogenicity studies of cobalt and methylcholanthrene were reviewed (Finogenova 1973, O'Hara *et al.* 1971, Kasirsky *et al.* 1965, Thompson *et al.* 1965, Orzechowski *et al.* 1964). In all of the studies, methylcholanthrene was applied dermally to mice and either sodium cobaltinitrite or cobalt chloride was administered in drinking water or by i.p injection. All studies reported skin squamous-cell carcinoma (Finogenova was translated from Russian and was reported as skin cancer NOS). Skin tumor incidences were reduced by co-administration of cobalt in three of the four studies (Kasirsky *et al.* 1965, Thompson *et al.* 1965, Orzechowski *et al.* 1964). In the fourth study, no differences were seen in the onset or latency of neoplasm development for either skin "cancer NOS" or papilloma from the addition of cobalt chloride (Finogenova 1973). The authors didn't report any tumor incidences.

#### Lung

Two co-carcinogenicity studies used either inhalation or intratracheal instillation as the route of exposure for both the cobalt compound and the known carcinogen (Steinhoff and Mohr 1991, Wehner *et al.* 1977). Steinhoff and Mohr administered benzo[*a*]pyrene and cobalt(II) oxide to female rats by intratracheal instillation. The addition of cobalt(II) oxide increased the incidence of squamous-cell carcinoma of the lung (Steinhoff and Mohr 1991). An adenocarcinoma was also reported in the group exposed to both compounds, but not in the group exposed to just benzo[*a*]pyrene. However, the incidence of adenocarcinoma was not significantly increased by cobalt(II) oxide. Wehner exposed male hamsters to cigarette smoke and cobalt(II) oxide by

inhalation (Wehner *et al.* 1977). No significant change in tumor incidence from the addition of cobalt(II) oxide was reported, but the locations of the neoplasms were not clearly reported.

#### Liver and nose

Only one co-carcinogen study reported neoplasms of the liver and nose (Zeller 1975). In this study, the known carcinogen, diethylnitrosamine, was subcutaneously injected together with cobalt chloride into male and female rats. Diethylnitrosamine induced neoplasms of the nose (esthesioneuroepithelioma, poorly differentiated carcinoma NOS, and squamous-cell carcinoma) and liver (hepatoma NOS, hepatocellular carcinoma, and cholangioma), but the addition of cobalt chloride had no effect on the incidences.

#### Locations of unspecified neoplastisc or non-neoplastic lesions

Only one co-carcinogen study reported neoplasms that were not specified as to their location or even their histological type (Wehner *et al.* 1977). Significant decreases in the incidences of neoplasms in cigarette smoke-exposed groups were seen with the addition of cobalt oxide. Groups that were exposed to cobalt and cigarette smoke also had significantly lower body weights than those exposed to just cigarette smoke, which might account for the lower neoplasm incidence. This co-carcinogen study included a cobalt(II) oxide alone group, which did not show a significant increase in neoplasm incidence above that of untreated controls.

### 5.3 Synthesis of the findings across studies

Strengths of the available dataset include testing of cobalt compounds with different properties such as particle versus salt and poorly soluble vs. readily soluble compounds. For some compounds, several studies were available including robust studies with high utility for evaluating carcinogenicity; importantly these include inhalation studies on both a water-soluble (cobalt sulfate) and poorly soluble species (cobalt metal). For other cobalt compounds, there were few studies, some of which were of more limited utility. The overall results for the carcinogenicity studies are summarized by cobalt compound in Table 5-7.

In general, the injection studies were less robust than the inhalation studies. Occupational exposure to cobalt compounds usually occurs by inhalation and not by injection. However, the injection route may be relevant to human exposure, in that cobalt is used in many types of surgical implant materials. The interpretation of the carcinogenicity of the injection studies is limited because many different types of particles or metals, including substances that are considered to be relatively inert, have induced tumors in rats (IARC 2006). Nevertheless, Hansen *et al*. found that implantation of some substances (e.g., titanium dioxide and silicon dioxide) did not induce neoplasms and these materials had the same physical characteristics (i.e., surface to volume ratio) as those material that did (cobalt and nickel) tumors, which suggests that the tumors were due to carcinogenic properties of cobalt and not just to a reaction to any physical implant. Further, neoplasms developed at the injection sites when exposed to a soluble cobalt compound, cobalt chloride, indicating a cobalt-specific, rather than a particle-specific effect (Shabaan *et al.* 1977). Overall, the injection studies are considered to provide supporting evidence for the carcinogenicity of cobalt.

Most of the neoplasms induced by cobalt compounds occur at the site of administration. Lung tumors are only seen in inhalation or intratracheal instillation studies and tissue sarcoma

developed in the local tissue at the sites of injection. Both the lung tumors from inhalation and tissue sarcomas from injections were caused by different cobalt forms including cobalt metal, a poorly soluble compound (cobalt(II) oxide) and two water-soluble compounds (cobalt sulfate for lung tumors and cobalt chloride for injection tumors). In addition, cobalt metal induced several types of tumors distal from the site of administration that were not caused by the other cobalt species (with the possible exception of adrenal tumors from cobalt sulfate), although most of the cobalt compounds were not adequately tested in models to evaluate these sites.

The most widely studied form of cobalt was cobalt metal. Lung tumors were observed in rats and mice in both sexes after inhalation exposure (NTP 1998, 2014b), and injection-site sarcomas (primarily rhabdomyofibrosarcoma, fibrosarcoma or sarcoma) were observed in male and female rats in several studies injecting cobalt metal by different methods (i.m. or intrathoracic) (Heath *et al.* 1956, Heath and Daniel 1962). In addition, inhalation exposure to cobalt metal also increased the incidences of adrenal gland tumors and tumors at distal sites – mononuclear-cell leukemia and pancreas, and possibly kidney tumors (NTP 2014b). Cobalt metal nanoparticles, when administered by i.m. injection, caused sarcoma in male rats; however, no inhalation studies were identified (Hansen *et al.* 2006).

Similarly, a poorly soluble cobalt compound (cobalt(II) oxide) caused both lung neoplasms (after intratracheal instillation) in male rats and sarcoma and histiocytoma in several studies of male and/or female rats after injection by various methods (s.c., i.m., i.p.) (Steinhoff and Mohr 1991, Gilman and Ruckerbauer 1962). Inhalation exposure to cobalt(II) oxide did not increase the incidences of lung tumors in Syrian golden hamsters, but the hamster is a less sensitive model for evaluating lung carcinogenicity (McInnes *et al.* 2013, Steinhoff and Mohr 1991) than the rat or mouse. No tumors were observed in the only study of another poorly soluble cobalt compound, cobalt sulfide, after intrarenal injection, but there were concerns about the dose level in that study (Jasmin and Riopelle 1976).

Finally, consistent findings are also found for soluble cobalt salts. Inhalation exposure to cobalt sulfate heptahydrate caused lung tumors in rats and mice and adrenal tumors in female rats. Adrenal gland tumors were also induced by exposure to cobalt sulfate (NTP 1998). Although no injection studies were identified that tested cobalt sulfate heptahydrate, a subcutaneous study of cobalt chloride provided suggestive evidence that cobalt causes fibrosarcoma at the site of administration and possibly at sites distant from the sites of administration; however, the confidence in the evidence is reduced somewhat because of possible inadequate reporting or procedures (Shabaan *et al.* 1977).

Co-carcinogenicity studies overall provided little if any support for the co-carcinogenicity of cobalt compounds. One study reported that cobalt enhanced carcinogenicity, but the remaining co-carcinogenicity studies reported either no effect or a decrease in carcinogenicity with co-exposure to cobalt.

**Table 5-7. Overall results of carcinogenicity studies in experimental animals sorted by cobalt compound**

| Substance | Strain (sex) | Route | Exposure period/ study duration | Results | Reference |
|---|---|---|---|---|---|
| ***Cobalt metal*** | | | | | |
| Cobalt metal | Rat F344/NTac (M&F) | Inhalation | 2 yr/2 yr | Lung<br>Alveolar/bronchiolar adenoma and carcinoma M&F<br>Squamous-cell tumors (primarily cystic keratinizing epithelioma) F;<br>[Equivocal] M<br>Mononuclear-cell leukemia F<br>Adrenal gland<br>Benign and malignant pheochromocytoma M&F<br>Pancreas<br>Islet-cell adenoma or carcinoma M;<br>[Equivocal: carcinoma] F<br>Kidney<br>Adenoma or carcinoma combined<br>[Equivocal] M | (NTP 2014b) |
| Cobalt metal | Mouse $B6C3F_1/N$ (M&F) | Inhalation | 2 yr/2 yr | Lung<br>Alveolar/bronchiolar adenoma and carcinoma M&F | (NTP 2014b) |
| Cobalt metal [Nano] | Rat Sprague-Dawley (M) | i.m. inj. | Single dose/1 yr | Injection site<br>Sarcoma M | (Hansen *et al.* 2006) |
| Cobalt metal [Bulk] | Rat Sprague-Dawley (M) | s.c. inj. | Single dose/1 yr | Negative<br>Fibroblastic proliferation (non-neoplasia) | (Hansen *et al.* 2006) |
| Cobalt metal | Rat Sprague-Dawley (F) | Intrarenal inj. | Single dose/ 1 yr | Negative | (Jasmin and Riopelle 1976) |
| Cobalt metal | Rat Hooded (F) | Intrathoracic | Single dose/2.3 yr | Injection-site sarcoma [including rhabdomyosarcoma of cardiac and intercostal muscle, mixed | (Heath and Daniel 1962) |
| Cobalt metal | Rat Hooded (M&F) | i.m. inj. | Single dose/lifespan | Injection-site sarcoma [rhabdomyofibrosarcoma M&F; sarcoma M; fibrosarcoma F | (Heath 1956) |
| ***Soluble cobalt compounds*** | | | | | |
| Cobalt | Rat F344/N | Inhalation | 2 yr/2 yr | Lung | (NTP 1998) |

| Substance | Strain (sex) | Route | Exposure period/ study duration | Results | Reference |
|---|---|---|---|---|---|
| sulfate heptahydrate | (M&F) | | | Alveolar/bronchiolar adenoma and carcinoma M&F<br>Adrenal<br>Benign or malignant pheochromocytoma F | |
| Cobalt sulfate heptahydrate | Mouse $B6C3F_1$ (M&F) | Inhalation | 2 yr/2 yr | Lung<br>Alveolar/bronchiolar adenoma and carcinoma M&F | (NTP 1998) |
| Cobalt chloride | Rat Wistar (M) | s.c. inj. | 8–12 mo/8–12 mo | Injection site<br>Fibrosarcoma M<br>Non-injection site<br>Fibrosarcoma M | (Shabaan *et al.* 1977) |
| ***Poorly soluble cobalt compounds*** | | | | | |
| Cobalt oxide | Rat Sprague-Dawley (M&F) | Intratracheal instill. | 1.5 yr/lifespan | Lung<br>Alveolar/bronchiolar carcinoma, benign squamous epithelial neoplasm, or alveolar/bronchiolar adenoma combined M | (Steinhoff and Mohr 1991) |
| Cobalt oxide | Rat Sprague-Dawley (M&F) | i.p. inj. | 6 mo/lifespan | Injection site<br>Histiocytoma and sarcoma M&F | (Steinhoff and Mohr 1991) |
| Cobalt oxide | Rat Sprague-Dawley (M) | s.c. inj. | 730 day/lifespan | Injection site<br>Histiocytoma and sarcoma M | (Steinhoff and Mohr 1991) |
| Cobalt oxide | Rat Wistar (M&F) | i.m. inj. | Single dose/1.3 yr | Injection site<br>Sarcoma M&F | (Gilman and Ruckerbauer 1962) |
| Cobalt oxide | Mouse Swiss (F) | i.m. inj. | Single dose/2 yr | Negative | (Gilman and Ruckerbauer 1962) |
| Cobalt oxide | Hamster Syrian Golden (M) | Inhalation | Lifespan/lifespan | Negative | (Wehner *et al.* 1977) |
| Cobalt sulfide | Rat Sprague-Dawley (F) | Intrarenal inj. | Single dose/1 yr | Negative | (Jasmin and Riopelle 1976) |

F = female; inj. = injection; instill. = instillation; i.m. = intramuscular; i.p. = intraperitoneal; M = male; mo = month; s.c. = subcutaneous; wk = week; yr = year.

# 6 Mechanistic and Other Relevant Effects

Cobalt particles and ions induce similar biological effects *in vivo* (e.g., respiratory and inflammatory responses in both experimental animals and humans and carcinogenic effects in experimental animals) and *in vitro* (e.g., cytotoxicity, genotoxicity, and at high concentrations, necrosis with an inflammatory response). This section discusses the relative role of cobalt particles and ions in cobalt toxicity (Section 6.1), several proposed modes of action for cobalt carcinogenicity (Section 6.2), other biological responses (Section 6.3), and a synthesis (Section 6.4). Although the mechanism(s) of action for the reported cobalt-induced carcinogenic effects are not completely understood, the experimental support for several possible modes of action, including genotoxicity, is reviewed below. Studies on genotoxicity and cell transformation of cobalt and cobalt compounds are reviewed in Appendix E.

### 6.1 Cobalt particles and cobalt ions

Studies with toxic metals in general, and cobalt specifically, show that solubility and particle size can play an important role in metal-induced toxicity, genotoxicity, and carcinogenicity (Smith *et al.* 2014). The main cobalt compounds studied for toxicological effects (including both micro- and nanoparticles) are metallic cobalt (Co(0)), cobalt(II) oxide (CoO), cobalt(II,III) oxide ($Co_3O_4$), and various cobalt(II) salts (e.g., cobalt sulfate, cobalt chloride) (Lison 2015, Ortega *et al.* 2014, Sabbioni *et al.* 2014a, Smith *et al.* 2014, Beyersmann and Hartwig 2008). Many cobalt(II) salts are readily soluble in water and biological fluids (see Section 1).

Several *in vitro* studies that specifically compared the cellular uptake and/or molecular and cellular effects (e.g., cytotoxicity, genetic toxicity, reactive oxygen species [ROS] production) of cobalt ions and particles (i.e., cobalt metal nanoparticles or cobalt(II) oxide micro or nanoparticles are shown in Table 6-1. *In vitro* studies generally show that cobalt nanoparticles are more toxic than cobalt microparticles due to increased surface reactivity resulting from a higher surface area/volume ratio (Simonsen *et al.* 2012, Mo *et al.* 2008, Peters *et al.* 2007, Zhang *et al.* 2000). In addition, relatively soluble cobalt particles (e.g., cobalt metal) are generally more cytotoxic and genotoxic than cobalt ions (Sabbioni *et al.* 2014, Ponti *et al.* 2009, Peters *et al.* 2007) and cobalt ions are generally more cytotoxic than cobalt particles with low solubility (e.g., cobalt oxides) (Table 6-1) (Ortega *et al.* 2014, Smith *et al.* 2014, Papis *et al.* 2009). NTP (2009) previously reviewed cobalt-tungsten carbide powders and hard-metals and reported that cobalt-tungsten carbide particles were more cytotoxic and/or genotoxic than cobalt powder when tested *in vivo* (rat lung) or *in vitro* in mammalian cells. The greater toxicity of cobalt-tungsten carbide was attributed to a synergistic effect between the particles of cobalt and tungsten carbide that resulted in enhanced production of ROS. Synergistic toxicity *in vitro* was also reported for cobalt with zinc (Bresson *et al.* 2013) and cobalt with nickel (Patel *et al.* 2012) but not with chromium (Allen *et al.* 1997).

**Table 6-1. *In vitro* mechanistic data comparing effects of cobalt nanoparticles, microparticles, and ions**

| Reference | Cobalt form (size, nm) and cell types | Cytotoxicity | Genotoxicity[a] | ROS | Cellular uptake |
|---|---|---|---|---|---|
| (Sabbioni *et al.* 2014a,b) | Co NP (3.4)<br>Co MP (2,200)<br>$CoCl_2$<br><br>Balb/3T3 mouse fibroblasts | IC50 µg/mL<br>Time Co MP Co NP $Co^{2+}$<br>4 h 12 19.5 47<br>12 h 10 10 22<br>24 h 11 10 10<br>48 h 10 9.9 10 | Relative amount of Co incorporated into the DNA was<br>Co MP > Co NP > cobalt ions.<br>Cell transformation: Co MP > Co NP; negative for $Co^{2+}$ | Dose-dependent increase in ROS production by Co NP > Co MP; $Co^{2+}$ did not induce significant increase. All forms induced lipid peroxidation: Co NP > Co MP > $Co^{2+}$ | Co uptake was dose dependent but significantly higher for NP and MP than for cobalt ions. Maximum uptake at 4 hours post-exposure. |
| (Ortega *et al.* 2014) | $Co_3O_4$ MP (100-400)<br>$CoCl_2$<br><br>BEAS-2B human lung | $Co_3O_4$ $CoCl_2$<br>IC25 µg/mL 50 2.9<br>IC50 170 4.4<br>IC75 600 6.5 | No data | No data | $Co_3O_4$ particles entered cells via endocytosis and released cobalt ions within lysosomes over long periods of time and were responsible for toxicity. |
| (Smith *et al.* 2014) | CoO MP (270–3,560)<br>$CoCl_2$<br><br>WTHBF-6 human lung fibroblasts | Both forms induced concentration-dependent increase in cytotoxicity; however, similar levels of cytotoxicity at intracellular cobalt levels < 1,000 µM while cobalt ions were more cytotoxic than particulate Co at higher levels. | Chromosome aberrations (similar effect for particulate and soluble forms). | No data | Both particulate and soluble Co induced a concentration-dependent increase in intracellular cobalt ion levels. Particle-cell contact was required for uptake of CoO. |
| (Alarifi *et al.* 2013) | $Co_3O_4$ NP (21)<br>$CoCl_2$<br><br>HepG2 human hepatocarcinoma cells | Both forms induced concentration-dependent increase in cytotoxicity but particulate Co was more cytotoxic than soluble Co. | DNA damage (comet assay, NP were more potent than soluble form) | Particles induced ROS and oxidative stress. Effects were lower for cobalt ions. | No data |

| Reference | Cobalt form (size, nm) and cell types | Cytotoxicity | Genotoxicity[a] | ROS | Cellular uptake |
|---|---|---|---|---|---|
| (Horie *et al.* 2012) | CoO NP (> 10)<br>$CoCl_2$<br><br>HaCaT human keratinocytes<br><br>A549 human lung carcinoma cells | Both forms induced similar concentration-dependent increase in cytotoxicity in both cell types. | No data | No increase in intracellular ROS in cells treated with cobalt ions or particles. | No data |
| (Papis *et al.* 2009) | $Co_3O_4$ NP (45)<br>$CoCl_2$<br><br>HepG2 and ECV-304 human cell lines | Both forms induced concentration-dependent increase in cytotoxicity but cobalt ions were more toxic. HepG2 cells not as sensitive as ECV-304 cells. | No data | Particles but not ions induced dose-dependent increase in ROS production in both cell lines. HepG2 cells less sensitive. | No data |
| (Limbach *et al.* 2007) | $Co_3O_4$ NP (20-75)<br>$Co_3O_4$/silica NP<br>Cobalt salt<br><br>A549 human lung adenocarcinoma epithelial cells | No data | No data | Release of ROS was up to 8 times higher for particles than cobalt ions. | No data |
| (Nyga *et al.* 2015) | CoNP (2-60)<br>$CoCl_2$<br><br>U937 human monocytic cell line, peripheral blood mononuclear cells, and alveolar macrophages | NPs induced a concentration-dependent reduction in all three monocytic cell lines (prevented by co-incubation with ascorbic acid). $CoCl_2$ at comparable concentrations (50–350 μM) was not cytotoxic. | No data | NPs induced ROS in a concentration-dependent manner in all cell lines (prevented by both ascorbic acid and glutathione). $CoCl_2$ did not significantly increase ROS. | No data |

| Reference | Cobalt form (size, nm) and cell types | Cytotoxicity | Genotoxicity[a] | ROS | Cellular uptake |
|---|---|---|---|---|---|
| (Annangi *et al.* 2014) | CoNP (30.7 ± 20.2)<br><br>Ogg1+/+ and Ogg1-/- mouse embryo fibroblasts (MEF) | NPs induced dose-dependent cytotoxicity in wild-type and knockout MEF cells (more toxic to knockout cells). | Sub-toxic doses for 12 weeks induced cell transformation (knockout cells were more sensitive). | Acute and subchronic exposure induced ROS. Greater toxicity in knockout cells attributed to increased sensitivity to oxidative damage. | Dose-dependent increase in cellular uptake of CoNPs in wild-type and knockout cells. |
| (Horev-Azaria *et al.* 2011) | Co NP (10–50)<br>$CoCl_2$<br><br>A549, NCIH441, Caco-2, HepG2 (human lung, colorectal, liver); MDCK (dog kidney); murine dendritic cells | NPs and ions induced dose-dependent cytotoxicity. NPs were generally more toxic. Ion sensitivity: A549 > MDCK > NCIH441 > Caco-2 > HepG2 > DC; NP sensitivity: A549 = MDCK = NCIH441 = Caco-2 > DC > HepG2. Toxicity of NP aggregates attributed to extracellular cobalt ion dissolution (34%–44% at 48 and 72 hrs). | No data | No data | No data |
| (Ponti *et al.* 2009) | Co NP (20–500)<br>$CoCl_2$<br><br>Balb/3T3 mouse fibroblasts | Dose-dependent cytotoxicity for both forms (higher for particles at 2 and 24 h but overlapping at 72 h). | Co NP induced DNA damage, MN, and cell transformation; $CoCl_2$ induced DNA damage only. | No data | No data |
| (Kwon *et al.* 2009) | Co NP (30)<br>$CoSO_4$<br><br>RAW 264.7 murine macrophages | NPs and ions induced dose-dependent cytotoxicity. | No data | No data | NP toxicity likely resulted from cellular uptake rather than extracellular dissolution. |

| Reference | Cobalt form (size, nm) and cell types | Cytotoxicity | Genotoxicity[a] | ROS | Cellular uptake |
|---|---|---|---|---|---|
| (Colognato *et al*. 2008) | Co NP (100–500)<br>$CoCl_2$<br><br>Human peripheral blood leukocytes | Co NP and cobalt ions induced dose-related cytotoxic effects (decrease in the cytokinesis-block proliferation index (CBPI). CBPI was slightly higher for ions at $10^{-5}$ M but similar toxicity at > 2 x $10^{-5}$ M | Cobalt ions induced clear trend in increase of MN frequency while Co NP were less effective; MN response varied with donor. DNA damage with NP only (comet assay, short incubation time). No MN observed at non-cytotoxic concentrations. | No data | NP readily taken up by cells. Cells exposed to cobalt ions showed only slight or no change in intracellular cobalt compared to baseline levels. |
| (Peters *et al.* 2007) | Co NP (28)<br>$CoCl_2$<br><br>Human dermal microvascular endothelial cells | Concentration-dependent effect (greater effect for NP than ions) | No data | Co NP induced strong concentration-dependent increase in ROS, cobalt ions induced less ROS and was concentration independent. | NP readily taken up by cells and stored in vacuoles. Pro-inflammatory activation after exposure to Co NP was attributed to intercellular release of cobalt ions. |

MP = microparticles (diameter > 100 nm), NP = nanoparticles (diameter < 100 nm).
[a]Genotoxicity also includes data for related effects (e.g., cell transformation assay) that do not necessarily measure a specific genotoxic endpoint.

Ortega *et al.* (2014) reported that although cobalt ions were more cytotoxic than poorly soluble $Co_3O_4$ particles, human lung cells exposed to the $IC_{25}$ (inhibitory concentration at which the ATP content was reduced by 25% compared to non-exposed cells) of cobalt chloride (2.9 μg/mL) or $Co_3O_4$ (50 μg/mL) had similar intracellular concentrations of solubilized cobalt (6.5 fg/cell for $Co_3O_4$ compared to 5.4 fg/cell for cobalt chloride) (Figure 6-1). Smith *et al.* (2014) also reported that at intracellular cobalt concentrations less than 1,000 μM, the cytotoxic effects of cobalt chloride and CoO to human lung fibroblasts were similar while cobalt chloride was more cytotoxic than CoO at intracellular concentrations greater than 1,000 μM. Horie *et al.* (2012) studied a variety of metal oxide nanoparticles and concluded that cellular influences (cell viability and oxidative stress) of metal oxide nanoparticles were most dependent on metal ion release (i.e., effects were greater for soluble particles compared to insoluble particles). In addition, Auffan *et al.* (2009) reported that chemically stable nanoparticles did not have significant cellular toxicity while nanoparticles that could be oxidized, reduced, or dissolved were cytotoxic and genotoxic. Thus, the available data indicate that intracellular cobalt ions are the primary toxic form and it is likely that the mode of action for systemic toxicity is related to cobalt ions (Ortega *et al.* 2014, Smith *et al.* 2014, Paustenbach *et al.* 2013, Simonsen *et al.* 2012).

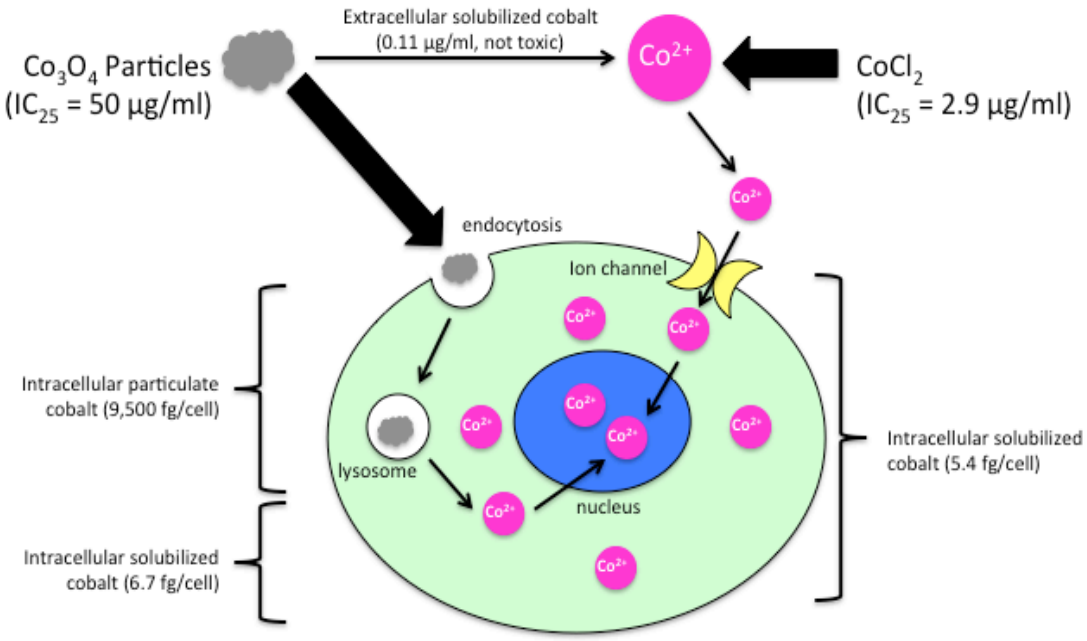


**Figure 6-1. Cellular uptake of cobalt particles and ions**

Source: Ortega *et al.* 2014

Because of similar physical/chemical properties, cobalt ions compete with essential divalent metal ions (e.g., calcium, copper, zinc, iron, manganese, and magnesium) for absorption, specific receptor activation, and ion channel transport (Paustenbach *et al.* 2013). For example, cobalt absorption is increased in humans and animals with iron deficiency suggesting that these metals share a common uptake mechanism (Thomson *et al.* 1971). Further, cobalt ions have the same

size and charge as zinc ions; therefore, both ions bind to the same types of ligands (e.g., oxygen, nitrogen, and sulfur groups of biomolecules) (Beyersmann and Hartwig 2008). The bioavailability of cobalt ions *in vivo* is limited because of extensive binding (90% to 95%) to serum proteins (e.g., albumin, $\alpha_2$-macroglobulin) (Paustenbach *et al.* 2013, Simonsen *et al.* 2012). Thus, the concentration of free, ionized cobalt in serum is about 5% to 12% of the total cobalt concentration (Simonsen *et al.* 2012). However, Heath *et al.* (1969) demonstrated that myoblasts exposed to cobalt-bound protein complexes (primarily globulin and albumin), but not to cobalt chloride, developed cytological alterations (e.g., enlarged hyperchromatic nucleoli, chromocenters, and nuclei) in actively growing cultures that were similar to those seen in pre-malignant myoblasts *in vivo*. In contrast, myoblasts exposed to cobalt chloride were either killed or showed no cytological abnormalities when exposed to sublethal concentrations.

Differences in toxicity reported for cobalt particles and ions may be partially explained by differences in cellular uptake mechanisms (see Figure 6-1). Cobalt ions first saturate binding sites in the extracellular milieu and on cell surfaces and, after saturation, are actively transported inside the cell via metal ion transport systems such as calcium channels or divalent metal ion transporters (Sabbioni *et al.* 2014, Smith *et al.* 2014, Simonsen *et al.* 2012, Garrick *et al.* 2003). However, current knowledge of the molecular mechanisms of cobalt ion-specific transporters is very limited (Guskov and Eshaghi 2012). In contrast, particulate cobalt is transported into cells by phagocytosis/endocytosis. However, nanoparticles are not as readily phagocytized by alveolar macrophages as larger particles and also may enter the systemic circulation by penetrating through the alveolar membrane (Mo *et al.* 2008).

Studies with low-solubility cobalt oxide (CoO or $Co_3O_4$) particles show that these particles readily enter cells through endocytosis via a clathrin-mediated pathway (called a Trojan-horse type mechanism) and are partially solubilized in the low pH environment within the lysosomes (Ortega *et al.* 2014, Smith *et al.* 2014, Papis *et al.* 2009, Limbach *et al.* 2007). Although the intracellular solubilized cobalt content was small compared to the intracellular particulate content, the data suggest that the solubilized fraction was responsible for the overall toxicity to human lung cells (Ortega *et al.* 2014, Smith *et al.* 2014).

Endocytosis of $Co_3O_4$ particles was a more efficient uptake pathway compared to the specific transport or ionic pumps involved with uptake of cobalt ions (Ortega *et al.* 2014). These studies also demonstrated that concentrations of extracellular solubilized cobalt were too low to induce cytotoxicity and that particle-to-cell contact was necessary to generate high intracellular cobalt levels. Further, cobalt particles taken up by lung cells can lead to long-term intracellular release of toxic metal ions. Similarly, cobalt metal nanoparticles are internalized by phagocytosis and endocytosis and spread rapidly to the cytoplasm, cellular organelles, and nucleus where they release cobalt ions (Sabbioni *et al.* 2014, Ponti *et al.* 2009). However, one study reported that the toxic effects of aggregated cobalt metal nanoparticles *in vitro* were attributed to extracellular release of cobalt ions from particle dissolution (Horev-Azaria *et al.* 2011) while another study reported that extracellular release of cobalt ions had no effect on cell viability (Nyga *et al.* 2015).

Sabbioni *et al.* (2014) also reported that the intracellular distribution of cobalt in Balb/3T3 cells was different following exposure to cobalt nanoparticles compared to cobalt ions. Cells exposed to cobalt nanoparticles had a higher nuclear fraction and a lower cytoplasmic fraction than cells exposed to cobalt ions. The amount of cobalt bound to DNA was significantly greater in cells

exposed to cobalt microparticles than nanoparticles but was the lowest in cells exposed to cobalt ions (tested concentrations were 10 and 100 μM for 4 hours). Intracellular distribution studies in primary rhabdomyosarcoma induced by intramuscular injection of metallic cobalt also reported that most of the total cellular content of cobalt was associated with the nuclear fraction and was bound by components of the nucleoplasm, chromatin, and nucleoli (Webb *et al.* 1972, Heath and Webb 1967).

The *in vivo* toxicity and carcinogenicity of soluble cobalt sulfate heptahydrate and cobalt metal particles from the NTP (2014b, 1998) bioassays were recently compared (Behl *et al.* 2015). The findings supported the possibility of a common underlying mechanism of cobalt toxicity irrespective of the form of cobalt exposure based on the following: (1) common sites of carcinogenicity (lung and adrenal gland) and a similar spectrum of nonneoplastic, inflammatory, fibrotic and proliferative lesions in the upper respiratory tract following subchronic and chronic exposure; (2) similar mutation spectrum in the K-*ras* oncogene in lung tumors; (3) toxicity in common extra-pulmonary sites; and (4) similar clinical findings. Possible explanations for the reported differences between cobalt particles and ions may involve a synergistic effect between the particles and the transition metal on reactive oxygen species (ROS) release and/or differences in intracellular cobalt accumulation and distribution (Sabbioni *et al.* 2014, Smith *et al.* 2014, Peters *et al.* 2007).

### 6.2 Proposed modes of action of cobalt carcinogenicity

Similar cytotoxic, genotoxic, and carcinogenic effects have been described for soluble and particulate forms of cobalt. Three major mechanisms have been identified that are applicable for the majority of carcinogenic metal compounds (Angelé-Martínez *et al.* 2014, Koedrith and Seo 2011, Beyersmann and Hartwig 2008). These include (1) oxidative stress, (2) DNA repair modulation, and (3) disturbances of signal transduction pathways that affect cell growth and differentiation. Modes of action most likely involved in cobalt-induced carcinogenesis are consistent with these general mechanisms and include: (1) genotoxicity and inhibition of DNA repair, (2) induction of reactive oxygen species (ROS) and oxidative damage, and (3) induction of hypoxia-like responses by activating hypoxia-inducible factors (HIFs) (see Figure 6-2) (Smith *et al.* 2014, Green *et al.* 2013, Magaye *et al.* 2012, Simonsen *et al.* 2012, Simonsen *et al.* 2011, De Boeck *et al.* 2003a, Lison *et al.* 2001).

In addition to HIFs, signaling pathways, receptors, and transcription factors that are potentially relevant to carcinogenesis and are affected by cobalt include MAPKs, AP-1, P13K/Akt, and NFκB (Davidson *et al.* 2015, Lee *et al.* 2012, Mates *et al.* 2010, Valko *et al.* 2006, Leonard *et al.* 2004). Dysregulation of these signaling pathways alters expression of genes that mediate cell growth, proliferation, differentiation, inflammation, invasion, angiogenesis, metastasis, apoptosis, and transformation and have been implicated in a variety of cancers (Davidson *et al.* 2015). In addition, there is some evidence that cobalt may also has epigenetic effects such as histone modifications that can lead to altered gene expression (e.g., tumor suppressor gene silencing and oncogene activation) and genomic instability; however, epigenetic effects of cobalt have not been as extensively studied as some other carcinogenic metals and are not further reviewed (Davidson *et al.* 2015, Broberg *et al.* 2015, Li *et al.* 2009). The experimental evidence for the proposed modes of action is briefly reviewed below.

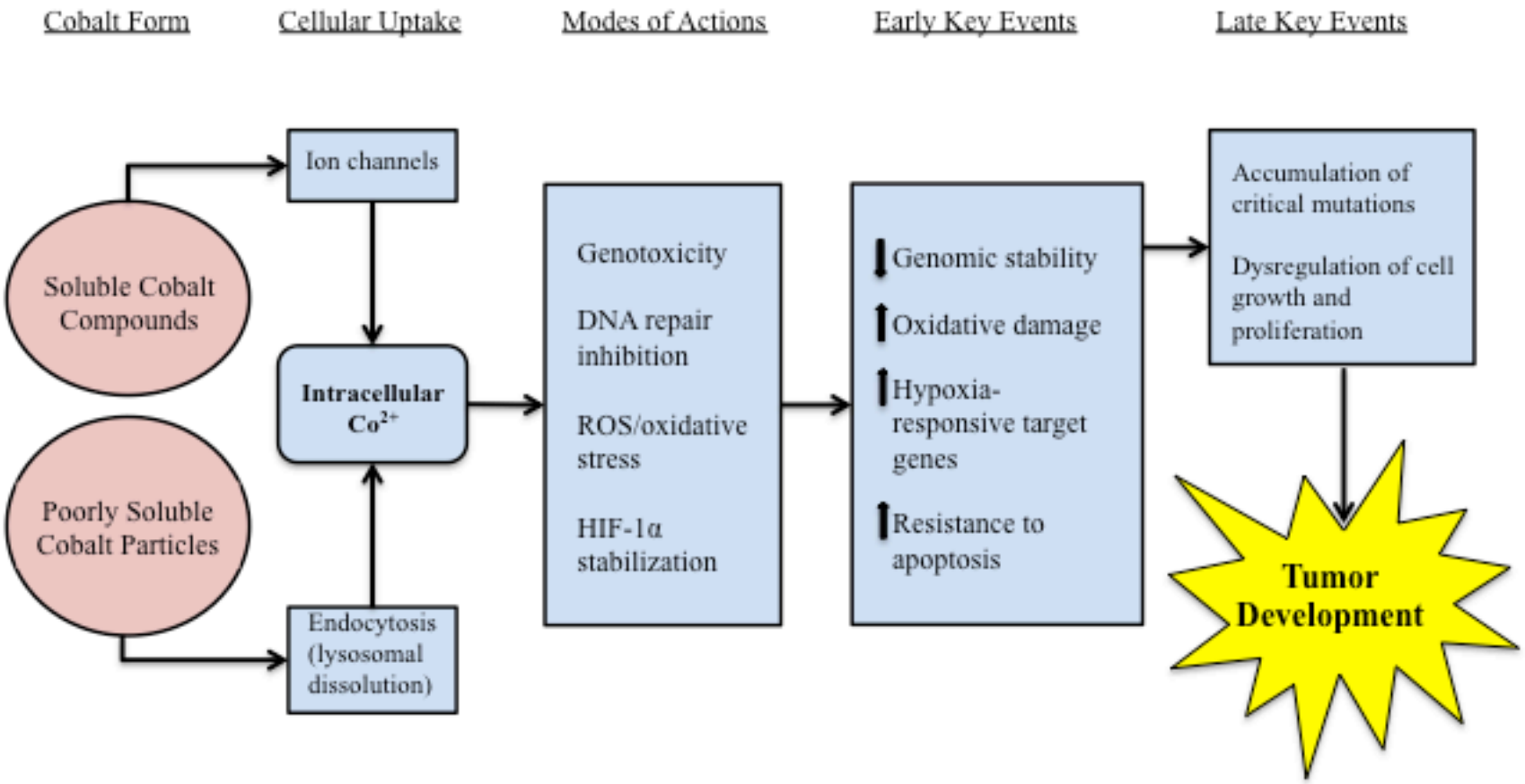


**Figure 6-2. Proposed modes of action of cobalt carcinogenicity.**

(adapted from Beyersmann and Hartwig 2008, De Boeck *et al.* 2003a)

### 6.2.1 Genotoxicity, inhibition of DNA repair, and related key events

This section addresses genotoxicity and related biological adverse effects or key events (e.g., cell transformation, cell-cycle arrest) that are possibly relevant to the mode of action of cobalt-induced carcinogenicity. Genotoxicity (e.g., DNA reactivity, mutagenicity, chromosomal damage, enzyme-mediated effects on DNA damage or repair) are well recognized as key events associated with carcinogenesis (Guyton *et al.* 2009).

#### Overview of genotoxicity findings

The genotoxic and related effects for cobalt metal and soluble and insoluble cobalt compounds are reviewed in Appendix E and briefly summarized here (see Table 6-2). Increases in DNA strand breaks, sister chromatid exchange, micronuclei, aneuploidy, chromosomal aberrations, and DNA-protein crosslinks were reported in mammalian cells *in vitro* following exposure to cobalt and cobalt compounds. These data provide evidence that cobalt mainly causes clastogenic effects and DNA damage. Cobalt compounds were mostly non-mutagenic in bacterial assays and mutagenicity data in mammalian cells were conflicting. The positive genotoxic effects were reported for a variety of cobalt compounds, including water-soluble salts (chloride, sulfate, nitrate), poorly water-soluble cobalt compounds (oxide, sulfide, metal, nanoparticles) and a water-soluble organic cobalt compound (acetate). Although the number of available *in vivo* studies was limited, they indicated that cobalt chloride induced genotoxic effects including aneuploidy in the bone marrow and testes of male hamsters and chromosomal damage and micronucleus formation in mouse bone marrow; cobalt acetate caused oxidative DNA damage in rat kidney, liver, and lung (Kasprzak *et al.* 1994). Dose-dependent responses were reported in some of these studies, supporting the evidence for some types of genotoxicity *in vivo*.

Some recent *in vitro* studies are consistent with the earlier data and show that cobalt ions and particles induce genotoxic effects in human and animal cells, but the studies also compared effects and relative potency of cobalt ions and particles (Table 6-1) (Smith *et al.* 2014, Alarifi *et al.* 2013, Patel *et al.* 2012, Ponti *et al.* 2009, Colognato *et al.* 2008). Smith *et al.* (2014) compared the effect of CoO particles with cobalt chloride and reported similar genotoxic effects (primarily chromatid lesions); however, particle-to-cell contact was required to induce genotoxicity from CoO. Soluble cobalt also induced cell-cycle arrest at a much lower intracellular cobalt concentration than CoO. Alarifi *et al.* (2013) compared $Co_3O_4$ nanoparticles and cobalt chloride and reported that both forms caused DNA damage in human HepG2 cells but the nanoparticles were more potent. Two studies investigated the genetic effects of metallic cobalt nanoparticles in Balb/3T3 mouse fibroblast (Patel *et al.* 2012) and human leukocytes (Colognato *et al.* 2008). Cobalt nanoparticles induced DNA strand breaks, micronuclei, and cell transformation in mouse fibroblasts and DNA damage in human leukocytes. Cobalt ions had no effect in human leukocytes but induced DNA damage in mouse fibroblasts. Ponti *et al.* (2009) reported that cobalt chloride induced double-strand breaks in human lung epithelial cells and that the effects were increased with co-exposure to nickel chloride.

Potential molecular mechanisms for cobalt-induced genotoxicity (primarily clastogenic effects) include (1) a direct effect of cobalt(II) ions to induce oxidative damage to DNA through a Fenton-like mechanism (see Section 6.2.2), and (2) an indirect effect of cobalt(II) ions to inhibit

repair of DNA damage caused by endogenous events or induced by other agents (Lison 2015, IARC 2006). These mechanisms are discussed below.

#### Inhibition of DNA repair

Evidence for cobalt-induced inhibition of DNA repair comes from several studies that show exposure to cobalt enhances the genotoxic effects of some mutagens and that cobalt modifies the catalytic activity of DNA repair proteins (Beyersmann and Hartwig 2008, IARC 2006, Beyersmann and Hartwig 1992). It is thought that interaction with DNA repair proteins, transcription factors, and tumor suppressors may be more relevant for metal-mediated carcinogenesis than direct binding to DNA (Koedrith and Seo 2011, Beyersmann and Hartwig 2008). Possible mechanisms include substitution of cobalt ions for zinc ions resulting in proteins with modified catalytic activity (e.g., p53 tumor suppressor protein and zinc finger domains of DNA repair proteins) or substitution of cobalt for magnesium in DNA polymerases or topoisomerases (Beyersmann and Hartwig 2008, Witkiewicz-Kucharczyk and Bal 2006, Baldwin *et al.* 2004, Kopera *et al.* 2004, Asmuss *et al.* 2000, Hartwig 1998, Kasten *et al.* 1997, Hartwig *et al.* 1991). The DNA binding capacity of p53 protein can be modulated by cobalt(II) ions (Adámik *et al.* 2015, Lee *et al.* 2001, Méplan *et al.* 2000, Palecek *et al.* 1999). In addition to cell-cycle arrest and apoptosis, p53 and its downstream genes also regulate DNA excision repair pathways, including repair of oxidative damage (Smith and Seo 2002). Kasten *et al.* (1997) reported that non-cytotoxic doses of cobalt enhanced DNA damage caused by ultraviolet radiation in human fibroblasts by inhibiting both the incision and polymerization steps of nucleotide excision repair. Kopera *et al.* (2004) and Asmuss *et al.* (2000) showed that cobalt reduced the DNA-binding ability of xeroderma pigmentosum group A (XPA) protein (a zinc finger protein involved in nucleotide excision repair). Further, poly(ADP-ribose)polymerase (PARP), a DNA strand break repair protein also was inhibited by cobalt (Hartwig *et al.* 2002). Unrepaired genotoxicity can contribute to accumulation of critical mutations and dysregulation of cell growth and proliferation that can lead to cancer.

#### Key events

In addition to DNA and chromosome damage and inhibition of DNA repair, cobalt also causes other effects that can contribute to malignant transformation, genomic instability, and survival of damaged cells. There is some evidence that cobalt decreases the cell's resistance to apoptosis (i.e., avoidance of cell death). Green *et al.* (2013) reported that normal human cell lines (IMR90 fibroblasts and primary bronchial epithelial cells) and a lung cancer cell line (H460) treated with cobalt had several times higher accumulation, less efficient activation of p53, and a delayed and weaker caspase activation compared to cells treated with nickel. This facilitates cell survival and proliferation of damaged cells (e.g., such as cells with cobalt–induced chromosomal damage).

Cell transformation assays measure induction of phenotypic alterations characteristic of tumorigenic cells, which could be caused by genotoxic or non-genotoxic mechanisms. Overall, the available studies provide strong evidence that different forms of cobalt can induce cellular transformation; however, cobalt particles were generally more effective than cobalt ions. Some studies suggested that cell transformation was related in part to ROS production or decreases in DNA repair of oxidative DNA damage, which can lead to genotoxicity and these studies are briefly reviewed here.

Cobalt metal particles, water-soluble cobalt compounds (cobalt chloride, cobalt sulfate, cobalt acetate), and water-insoluble cobalt compounds (cobalt sulfides) induced cell transformation in different types of rodent cells (C3H10T1/2 mouse fibroblasts, Syrian hamster embryo cells (SHE), or BALB/3T3 cells) (IARC 2006, Sabbioni *et al.* 2014b, Sighinolfi *et al.* 2014, Annangi *et al.* 2014, Ponti *et al.* 2009). A few studies of either cobalt chloride (Sabbioni *et al.* 2014b, Ponti et al. 2009) or cobalt metal (Doran *et al.* 1998) were negative, which could be due to differences in experimental conditions such as the types of cells, because positive findings were found for the same cobalt forms using other experimental conditions. Sabbioni *et al.* 2014b reported that Type III foci in Balb/3TC cells induced by cobalt nanoparticles and microparticles were inhibited by ascorbic acid and suggested that the response was dependent on ROS production and lipid peroxidation. Another study found that mouse fibroblast cells without a DNA base-pair excision gene (8-oxoguanine glycosylate, $Ogg1^{-/-}$) were more sensitive to cobalt nanoparticle-induced cellular transformation (after 12 weeks of exposure to sub-toxic doses) compared to wild type cells ($Ogg1^{+/+}$) (Annangi *et al.* 2014). Ogg is involved in the repair of 8-oxoguanine and thus, this study supports the role of oxidative DNA damage in cobalt carcinogencitiy. Oxidative stress is discussed in more detail in the following section.

**Table 6-2. Summary assessment of genotoxicity and related effects for cobalt compounds**

| Endpoint (Test system) | Cobalt chloride | | Cobalt sulfate | | Cobalt nitrate | | Cobalt(II) oxide | | Cobalt acetate | | Cobalt metal | | Cobalt sulfide | | Cobalt nanoparticles | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *In vitro* [a] | *In vivo* | *In vitro* [a] | *In vivo* | *In vitro* [b] | *In vivo* | *In vitro* [b] | *In vivo* | *In vitro* [b] | *In vivo* | *In vitro* [a] | *In vivo* | *In vitro* [b] | *In vivo* | *In vitro* [b] | *In vivo* |
| ***Mutation*** | | | | | | | | | | | | | | | | |
| Mutation (prokaryotes) | (–)[1] | | (–)[1] | | | | | | | | (–)[1] | | | | | |
| Mutation (eukaryotes) | ± | | | | + | | | | + | | | | ± | | – | |
| ***Chromosomal damage/cytogenetic effects*** | | | | | | | | | | | | | | | | |
| Chromosomal aberrations | + | + | + | | – | | ± | | – | | | | | | | |
| Micronucleus induction | ± | + | | | | | | | | | + | – | | | | |
| Recombination | + | | | | + | | | | | | | | | | + | |
| Gene conversion | (+) | | | | | | | | | | | | | | | |
| Aneuploidy | + | + | + | | | | | | | | | | | | | |
| Sister chromatid exchange | + | | | | | | | | | | | | | | | |
| ***DNA damage and repair*** | | | | | | | | | | | | | | | | |
| DNA damage/ strand breaks or bases | + | | + | | + | | | | | + | + | | + | | + | |
| DNA repair inhibition | + | | | | | | | | + | | + | | | | | |
| ***Binding/cross-links*** | | | | | | | | | | | | | | | | |
| DNA-protein crosslinks | + | | + | | | | | | | | + | | | | + | |
| DNA-protein binding inhibition | + | | | | + | | | | | | | | | | | |

Sources: IARC (2006) review and additional primary references as described in tables and text.
Positive +, mostly positive evidence (+), mixed results ±, mostly negative evidence (–), and negative –.
[a]Results shown are for –S9; test +S9 was negative.
[b]Results shown are for –S9; not tested with the addition of metabolic activation (S9).

### 6.2.2 Oxidative stress and damage

Reactive oxygen species (ROS) and reactive nitrogen species (RNS) induce oxidative and nitrative stress and are recognized as key contributors to carcinogenesis (Mates *et al.* 2010). Redox-active transition metals (e.g., iron, zinc, copper, chromium, cobalt, nickel, manganese) have been shown to produce oxidative stress through redox reactions *in vivo* and in mammalian cells *in vitro* (Jomova and Valko 2011, Koedrith and Seo 2011, Beyersmann and Hartwig 2008, Valko *et al.* 2006, Valko *et al.* 2005, Kasprzak 2002). Oxidative stress has been demonstrated to be one of the principle injury mechanisms through which metal and metal oxide nanoparticles induce adverse health effects (Zhang *et al.* 2012b). In addition, cobalt nanoparticles that are translocated from the lungs to the blood may directly or indirectly activate peripheral blood neutrophils to release ROS, RNS, and pro-inflammatory cytokines (e.g., IL-1, IL-6, IL-12, MIP-2, and TNF-$\alpha$) (Mo *et al.* 2008). Excessive or inappropriate neutrophil activation is recognized as a potential cause of tissue damage. Increased formation of reactive ROS/RNS can overwhelm body antioxidant defenses leading to oxidative stress and damage to lipids, proteins, and DNA (Romero *et al.* 2014, Jomova and Valko 2011, Petit *et al.* 2005, Valko *et al.* 2005).

#### Mechanisms of ROS

Direct interactions between cobalt metal or ions and oxygen or lipids can generate ROS. High concentrations (10 mg/mL) of aqueous suspensions of Co(0) metal particles can react with dissolved oxygen to generate hydrogen peroxide and hydroxyl radicals in the presence of superoxide dismutase (SOD) as illustrated below (reactions 1-3) (Lee *et al.* 2012, Jomova and Valko 2011, Leonard *et al.* 1998). The hydroxyl radical was not generated when catalase, a hydrogen peroxide scavenger, was added. Cobalt(II) ions alone did not generate significant amounts of hydroxyl radicals from hydrogen peroxide except when bound to certain endogenous chelators such as glutathione and anserine (reaction 4) (Leonard *et al.* 1998, Mao *et al.* 1996, Shi *et al.* 1993). Glutathione and anserine normally function as antioxidants; however, these data suggest that a cobalt(II)-mediated switch to pro-oxidants may occur and cause cellular damage (Valko *et al.* 2005). Cobalt(II) ions also are capable of reacting with lipid hydroperoxides to generate free radicals in the presence of proper chelating agents (Shi *et al.* 1993). Hydroxyl radicals and lipid hydroperoxide-derived free radicals are considered important intermediates in oxidative stress-induced genetic damage and as mediators of tumor initiation and promotion (Barrera 2012, Shi *et al.* 1993, Vaca *et al.* 1988). Thus, under certain conditions, both cobalt metal and cobalt ions are capable of generating ROS through Fenton-like reactions (reactions 3 and 4) with the potential to increase oxidative stress and cellular injury through DNA damage, protein modification, induction of oncogene expression, and nuclear transcription factor activation.

$$Co + O_2 \longrightarrow Co(I) + O_2^{\bullet -} \longrightarrow Co(I) - OO^{\bullet} \quad (1)$$

$$Co(I) - OO^{\bullet} \xrightarrow{SOD} Co(I) + H_2O_2 \quad (2)$$

$$Co(I) + H_2O_2 \longrightarrow Co(II) + {}^{\bullet}OH + OH^{-} \quad (3)$$

$$[Co(II\text{-chelate}] + H_2O_2 \longrightarrow [Co(III)\text{-chelate}] + {}^{\bullet}OH + OH^{-} \quad (4)$$

**Evidence for cobalt-induced oxidative stress**

Petit *et al.* (2005) reported that cobalt ions induced time- and dose-dependent protein oxidation in human U937 macrophages that was inhibited by glutathione. In addition to generating DNA damage, ROS also activate stress-response genes and redox-sensitive transcription factors (e.g., NF-κB, AP1, p53, Nrf2) (Beyersmann and Hartwig 2008, Valko *et al.* 2006, Valko *et al.* 2005). Although high levels of ROS may lead to apoptosis or necrosis, low or transient increases in ROS may lead to increased cell proliferation through altered growth factor and oncogene expression (Klaunig *et al.* 2010). Dysregulation of stress response and redox-sensitive transcription factors have been linked to carcinogenesis because of their role in regulating DNA repair, inflammation, cell proliferation, differentiation, angiogenesis, and apoptosis. Thus, depending on the dose and the extent and timing of interference, ROS may initiate tumor development by mutagenesis and/or promote tumor growth by dysregulation of cell growth and proliferation (Davidson *et al.* 2015, Klaunig *et al.* 2010, Valko *et al.* 2006, 2005, Beyersmann and Hartwig 2008).

Both cobalt ions and cobalt metal can catalyze the formation of ROS *in vivo* and *in vitro* (Chattopadhyay *et al.* 2015, Annangi *et al.* 2014, Scharf *et al.* 2014, Alarifi *et al.* 2013, Patel *et al.* 2012, Papis *et al.* 2009, Qiao *et al.* 2009, Kotake-Nara and Saida 2007, Limbach *et al.* 2007, Peters *et al.* 2007, Dick *et al.* 2003, Pourahmad *et al.* 2003, Zou *et al.* 2001, Kawanishi *et al.* 1994, Hanna *et al.* 1992, Lewis *et al.* 1992, 1991, Kadiiska *et al.* 1989, Kawanishi *et al.* 1989, Moorhouse *et al.* 1985). Cobalt sulfate heptahydrate and cobalt(II) acetate (PubChem 2015) were strongly active in the antioxidant response element signaling pathway (Nrf2/ARE assay) in human hepatocellular carcinoma (HepG2) cells (Shukla *et al.* 2012). Cobalt chloride-induced apoptosis in rat pheochromocytoma (PC12) cells was attributed to ROS formation (Pulido and Parrish 2003, Zou *et al.* 2001). Treatment with antioxidants suppressed ROS formation and blocked apoptosis. Annangi *et al.* (2014) reported that oxidative stress exacerbated the acquisition of a cancer-like phenotype as indicated by greater sensitivity of *Ogg* knockout mouse embryonic fibroblasts compared to wild-type cells. Scharf *et al*. (2014) conducted a proteomic analysis of periprosthetic tissues collected from joint replacement patients during surgery and reported that cobalt ions induced oxidative damage to proteins involved in the cellular redox system, metabolism, molecular transport, cellular motility, cell signaling, and organelle function. Dick *et al*. (2003) reported evidence for a role of ROS in the toxic and inflammatory effects in rat lung following intratracheal instillation of $Co_3O_4$, and Lewis *et al.* (1992, 1991) reported evidence of oxidative stress in hamster lung following exposure to cobalt ions *in vivo* and *in vitro*. Evidence of oxidative stress included decreased levels of reduced glutathione, increased levels of oxidized glutathione, and increased activity of the pentose phosphate pathway.

Simultaneous incubation with hydrogen peroxide potentiated cobalt-induced increases in levels of oxidized glutathione and pentose phosphate pathway activity. Although the data suggested that oxidation of glutathione occurred as an early event in cobalt-induced lung toxicity, the data did not indicate that glutathione oxidation related directly to the observed toxicity. Thus, oxidative effects that occur at sites other than the glutathione system might mediate cobalt toxicity.

#### Oxidative stress and DNA damage

As mentioned above, one of the likely mechanisms for cobalt particles and ions to induce genetic damage is through ROS and oxidative stress. Several types of DNA damage are associated with ROS including single- and double-strand breaks, base modifications, deoxyribose modification, and DNA cross-linking (Klaunig *et al.* 2010). If not repaired prior to DNA replication, DNA damage can lead to cell death, mutations, replication errors, and genomic instability. Kasprzak *et al.* (1994) reported oxidative damage to DNA in the liver, kidney, and lung of rats injected with cobalt ions.

Two studies, using different cobalt forms, evaluated K-*ras* mutations (Figure 6-3) in cobalt-induced lung neoplasms of B6C3$F_1$ mice (cobalt metal and cobalt sulfate heptahydrate) or F344/NTac rats (cobalt metal only). Rodents were exposed by inhalation (Hong *et al.* 2015, NTP 2014a, 1998). Both studies found a higher frequency of G to T transversions in codon 12 of the K-*ras* gene in cobalt-induced neoplasms compared to spontaneous lung neoplasms from historical control or other laboratory control rodents. In contrast, the predominant type of K-*ras* mutation observed in spontaneous lung tumors from historical control mice was G to A transitions. No K-*ras* mutations were observed in spontaneous lung tumors in the concurrent or historical control rats. K-*ras* G to T transversion mutations are associated with the production of 8-hydroxydeoxyguanosine, an oxidative DNA lesion that is formed when ROS reacts with deoxyguanosine (Itsara *et al.* 2014, Klaunig *et al.* 2010). This is also consistent with the mutation pattern observed in bacteria (i.e., results were correlated with ability of the tester strain to detect mutational events at G:C base pairs) (Hong *et al.* 2015). G to T transversions are also the most common type of mutation observed in human lung tumors in the *p53* gene (Harty *et al.* 1996). These studies suggest that oxidative DNA damage may play a role in cobalt-mediated lung tumorigenicity.

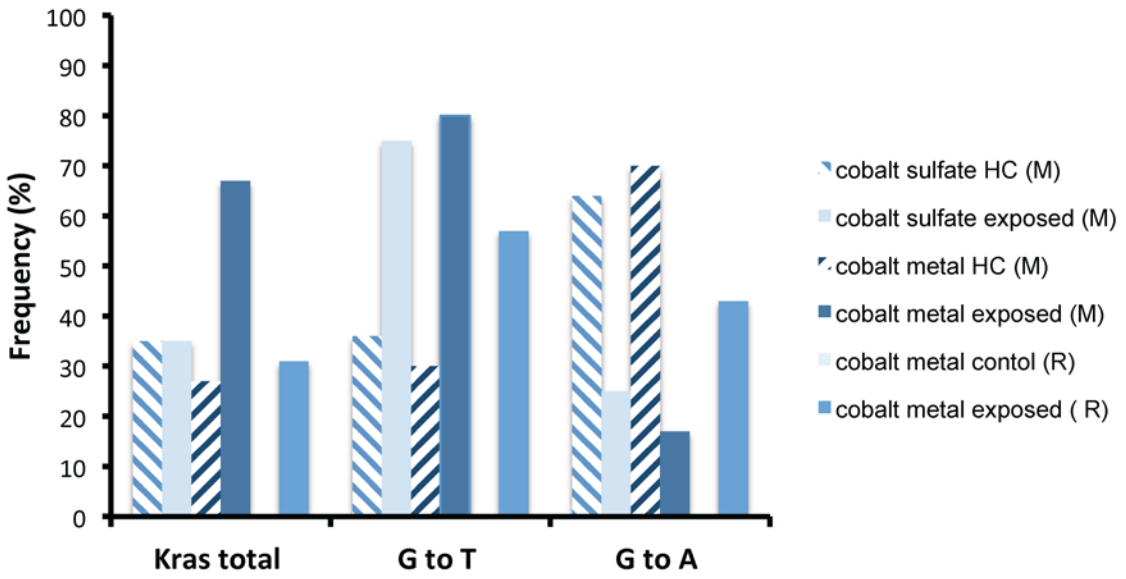


**Figure 6-3. K-*ras* mutations in lung tumors from cobalt-exposed and non-exposed rodents**

Sources: (Hong *et al.* 2015, NTP 2014a, 1998).
HC = historical control, M = mouse, R = rat.
Frequency of K-*ras* mutations from lung tumors in mice or rats exposed to cobalt metal or cobalt sulfate and spontaneous tumors. Total K-*ras* is the incidences of any K-*ras* mutation detected in all samples and includes mutations in codon 12, 13, and 61. G to T and G to A is the frequency of these specific mutations occurring in codon 12 only. i.e., the total number of K-*ras* mutations in codon 12 is the denominator.

One argument against the oxidative-stress hypothesis of metal-induced carcinogenesis is that high, cytotoxic doses of metals (e.g., mM range) are often required to induce oxidative damage while much lower doses induce tumors (Paustenbach *et al.* 2013, Beyersmann and Hartwig 2008). However, as mentioned above, G to T transversions in mouse and rat lung tumors induced by cobalt sulfate and/or cobalt metal are characteristic of oxidative damage. Further, sub-toxic doses of cobalt nanoparticles induced oxidative stress and cell transformation in mouse embryo fibroblasts (Annangi *et al.* 2014, Sighinolfi *et al.* 2014) and oxidative stress and DNA damage in human lung epithelial (A549) cells (Wan *et al.* 2012). It has been suggested that oxidative stress is not the sole cause of cobalt-induced carcinogenicity but may contribute in a potentiating manner (Beyersmann and Hartwig 2008).

### 6.2.3 HIF stabilization and hypoxia mimicry

Oxygen homeostasis in mammals is tightly regulated in order to provide sufficient oxygen levels to body tissues and cells while minimizing production of ROS (Bracken *et al.* 2003). HIFs are heterodimers composed of a labile α subunit and a stable β subunit and are the primary transcriptional regulators that mediate the cellular response to hypoxia (Davidson *et al.* 2015, Galanis *et al.* 2008, Salnikow *et al.* 2004, Zhang *et al.* 2014, Befani *et al.* 2013, Forooghian *et al.* 2007). The α subunit is post-translationally regulated by oxygen and is rarely detectable at normal oxygen tension, while the β subunit, also known as aryl hydrocarbon receptor nuclear translocator (ARNT), is constitutively expressed. There are three known isoforms of the α subunit (HIF-1α, HIF-2α, and HIF-3α) in humans and mammals; however, the HIF-1α subunit is the most widely studied (Zhang *et al.* 2014, Wolff *et al.* 2013, Forooghian *et al.* 2007, Bracken

*et al.* 2003). HIF-1α and HIF-2α share significant structural homology and function and are expressed in multiple tissues and cell types in response to hypoxia (Befani *et al.* 2013). Less is known about HIF-3α; however, it is a transcriptional target of HIF-1α (Tanaka *et al.* 2009). Most studies with cobalt investigated its effects on HIF-1α; however, Befani *et al.* (2013) reported that cobalt stimulated HIF-1-dependent gene expression in two human liver cancer cell lines but inhibited HIF-2-dependent gene expression. Therefore, the following discussion is limited to HIF-1α.

#### Cobalt-induced HIF stabilization

HIF-1 overexpression and enhanced transcriptional activity are linked to cancer initiation and progression. There is strong experimental support that cobalt is a potent inducer of HIF-1α activation. Cobalt metal particles, cobalt chloride, and cobalt sulfate heptahydrate promote a hypoxia-like state *in vivo* and *in vitro*, even with normal molecular oxygen pressure, by stabilizing HIF-1α (Nyga *et al.* 2015, Galán-Cobo *et al.* 2013, Gao *et al.* 2013, Saini *et al.* 2010b, Saini *et al.* 2010a, Galanis *et al.* 2009, Qiao *et al.* 2009, Xia *et al.* 2009, Beyersmann and Hartwig 2008, Maxwell and Salnikow 2004). Further, Wang and Semenza (1995) demonstrated that HIF-1 induction either from hypoxia or cobalt chloride treatment was indistinguishable with respect to DNA binding specificity and contacts with target DNA sequences.

Evidence for cobalt-induced HIF-1 stabilization has been demonstrated in several human cell lines, including cancer cell lines (Fu *et al.* 2009, Ardyanto *et al.* 2008, Wang and Semenza 1995). Cobalt chloride-induced hypoxia also increased the invasiveness of one primary breast cancer cell line (Fu *et al.* 2009). Human A549 lung adenocarcinoma cells exposed to cobalt chloride overexpressed Cap43, a hypoxia-regulated gene (Salnikow *et al.* 2000). Increased expression of Cap43 was reported in tumors and serum of lung cancer patients compared to adjacent normal tissues and may be predictive of tumor angiogenesis and poor prognosis (Azuma *et al.* 2012, Wang *et al.* 2012). Permenter *et al.* (2013) investigated gene expression and intracellular protein abundance in two rat liver cell lines exposed to cobalt chloride. Many genes, proteins, and pathways were modulated, which were mainly due to induction of a hypoxia-like response and oxidative stress. These data were consistent with gene expression profiling in hypoxia signaling in human hepatocellular carcinoma (Hep3B) cells exposed to cobalt chloride (Vengellur *et al.* 2005). Cobalt nanoparticles and ions also induced a time-dependent increase in HIF-target genes and expression of proinflammatory cytokines in the U937 human monocytic cell line (Nyga *et al.* 2015).

Under normal oxygen conditions, the iron-containing oxygen-sensing enzymes (prolyl hydroxylases) and an asparagine hydroxylase that hydroxylate specific proline or asparagine residues in the HIF-1α subunits (Maxwell and Salnikow 2004). Hydroxylated HIF-1α binds to a multiprotein complex that contains the von Hippel-Lindau (VHL) tumor suppressor. VHL acts as part of an ubiquitin ligase complex resulting in rapid ubiquitination and proteolysis of HIF-1α. Under hypoxic conditions, HIF-1α subunits are not hydroxylated, and consequently the protein is stabilized and translocates to the nucleus where it binds with a HIF-1β subunit. The response to hypoxia includes increased red blood cell production, blood vessel growth and increased blood supply to tissues, and increased anaerobic metabolism. Cobalt affects the function of several genes and enzymes responsible for posttranslational modification of HIF-1α such as prolyl hydroxylases and VHL (Davidson *et al.* 2015). Possible mechanisms by which cobalt ions

activate HIF-1 include replacing iron in the regulatory prolyl hydroxylases or depleting intracellular ascorbate (a cofactor for prolyl hydroxylase activity), thus, deactivating these enzymes (Davidson *et al.* 2015, Qiao *et al.* 2009, Maxwell and Salnikow 2004, Salnikow *et al.* 2004). Kang *et al.* (2006) reported that metal-induced (cobalt or nickel) HIF-1α stabilization was reversed in human lung carcinoma A549 cells when the cells were treated simultaneously with iron and metal ions. Oxidative stress does not appear to be a primary mechanism of cobalt-induced HIF activation. Salnikow *et al.* (2000) found that while cobalt and nickel produced oxidative stress in A549 cells, activation of HIF-1-dependent genes was independent of ROS formation. Although the mitochondria are a main target of cobalt toxicity and generate ROS that trigger hypoxia-induced transcription, cobalt activates hypoxia-induced transcription via a mitochondria-independent mechanism (Karovic *et al.* 2007, Chandel *et al.*1998). In a study with rat hepatocytes, lysosomes were shown to be the source of ROS formation with redox transition metals (including cobalt), while the mitochondria were the source of ROS formation for non-redox or poor redox cycling transition metals (Pourahmad *et al.* 2003). Nyga *et al.* (2015) also reported evidence that HIF-1α stabilization in human macrophages treated with cobalt metal nanoparticles or cobalt ions occurred via an ROS-independent pathway.

**Hypoxia mimicry**

HIF-1α is present in almost all human and animal cells and its activation has a central role in the transcriptional regulation of more than 100 hypoxia-responsive genes (including genes encoding for multiple angiogenic growth factors (e.g., VEGF), erythropoietin synthesis, endothelin, glucose transporters, inflammatory factors, and regulation of apoptosis and cell proliferation) that allow for cell survival at low oxygen pressure (Gao *et al.* 2013, Simonsen *et al.* 2012, Saini *et al.* 2010b, Saini *et al.* 2010a, Greim *et al.* 2009, Beyersmann and Hartwig 2008, Wang and Semenza 1995). The evidence suggests that HIF-1α is a major regulator of the adaptation of cancer cells to hypoxia and may contribute to tumor development and progression by decreasing both repair and removal of mutated cells, selecting for cells with genetic instability, reducing *p53* transcriptional activity, evading growth arrest checkpoints, and inducing apoptosis resistance (Greim *et al.* 2009, Ardyanto *et al.* 2008, Hammond and Giaccia 2005, Maxwell and Salnikow 2004, Lee *et al.* 2001).

HIF-1α overexpression, stabilization, and transcriptional activation is found in more than 70% of human cancers (e.g., breast, ovarian, cervical, prostate, brain, lung, head and neck) and is associated with poor clinical outcomes (Cheng *et al.* 2013, Galanis *et al.* 2009, Galanis *et al.* 2008, Maxwell and Salnikow 2004, Paul *et al.* 2004). Greim *et al.* (2009) also identified hypoxia and HIF activation as a relevant mechanism for pheochromocytoma in rats. Further evidence for a role of HIF-1 in cancer is as follows: (1) enhanced glycolytic and angiogenic activities are hallmarks of many tumors and are consequences of HIF-1 activation, (2) immunolabelling for HIF-1α subunits confirms there is a common activation in solid tumors, (3) genetic studies comparing tumor growth with and without HIF-1 have generally shown that tumors without specific HIF subunits have decreased vascularization and growth, (4) a number of pathways implicated in cancer progression increase activation of the HIF-1 pathway in normoxia and hypoxia, and (5) as described above, the VHL tumor suppressor protein is required to regulate HIF-1 (Maxwell and Salnikow 2004). VHL loss of function results in constitutive HIF activation and an increased risk of developing cancer and is evident in people with VHL disease. VHL disease is a hereditary cancer syndrome that is caused by inactivation of the VHL protein (Ben-

Skowronek and Kozaczuk 2015). This disease is characterized by the development of multiple vascular tumors including pheochromocytomas, pancreatic islet cell tumors, renal cell tumors, retinal and central nervous system hemangioblastomas, and others. Loss of the VHL protein results in elevated levels of HIF and leads to increased production of VEGF, platelet-derived growth factor (PDGF), transforming growth factor α (TGF-α) and other hypoxia-responsive transcripts that promote cell growth and angiogenesis. HIF also contributes to overproduction of tyrosine hydroxylase and catecholamines in pheochromocytomas.

### 6.3 Other biological effects

In addition to the biological effects discussed in Section 6.2 and illustrated in Figure 6-2, different forms of cobalt ions induce similar biological effects that may or may not be related to carcinogenicity. The effects of chronic exposure to cobalt and cobalt compounds on the respiratory system in humans and experimental animals are well documented (IARC 2006, ATSDR 2004, IARC 1991). Effects include a spectrum of inflammatory and proliferative changes including respiratory irritation, diminished pulmonary function, asthma, alveolar epithelial hyperplasia and metaplasia, squamous metaplasia, and interstitial fibrosis. Respiratory effects have been observed in workers employed in cobalt refineries, hard-metal workers, diamond polishers, and ceramic dish painters.

Potential mechanisms for these endpoints might be some of the modes of action discussed in Section 6.2 as well as other cobalt-related biological responses. Oxidative damage and inflammatory events are characteristics of fibrosing alveolitis (hard-metal lung disease) and lung cancer and there is some evidence that lung fibrosis is a risk factor for lung cancer (IARC 2006). Lung injury may be due in part to cobalt-induced apoptosis which is primarily mediated via loss of mitochondrial membrane potential and release of cytochrome c and apoptosis-inducing factor (AIF) (Battaglia *et al.* 2009, Karovic *et al.* 2007, Pulido *et al.* 2003, Araya *et al.* 2002). Cobalt also competes with essential divalent metal ions (e.g., calcium, copper, zinc, iron, manganese, and magnesium) for absorption, specific receptor activation, and ion channel transport (Paustenbach *et al.* 2013) and interferes with a number of iron-containing proteins such as the iron regulatory protein 1 (IRP1)/iron response element (IRE) system and various iron-sulfur cluster proteins that are important for maintaining iron homeostasis, energy production, metabolism, gene expression, DNA/RNA processing and repair, and defense against oxidative stress (Davidson *et al.* 2015, Sheftel *et al.* 2009, Li *et al.* 2006). Thus, disruption of iron homeostasis could potentially lead to numerous adverse health effects, including cancer.

### 6.4 Synthesis

Cobalt metal and several cobalt compounds induce similar carcinogenic effects in experimental animals. The mechanisms of cobalt-induced neoplasms are not completely understood but the available data provide strong support that intracellular cobalt ions are the principal toxic entity. Cobalt ions are actively transported inside the cell via metal ion transport systems while cobalt particles with low solubility are readily taken up by cells via endocytosis. Once inside the cell, cobalt particles are partially solubilized at the low pH within lysosomes and release cobalt ions that can react with various cytoplasmic and nuclear proteins and lipids and possibly DNA. Mechanistic data provide strong support that inhibition of DNA repair, oxidative stress, and activation of HIF-1α likely contribute to cobalt-induced neoplastic development and progression. All of these mechanisms are relevant to humans.

# 7 Overall Cancer Evaluation and Preliminary Listing Recommendation

This section brings forward and integrates the evaluations of the human, animal, and mechanistic and other relevant data, applies the RoC listing criteria, and reaches a preliminary listing recommendation.

***Preliminary listing recommendation***

"Cobalt and cobalt compounds that release cobalt ions *in vivo*" are reasonably anticipated to be human carcinogens based on sufficient evidence from studies in experimental animals and supporting mechanistic data. Mechanistic data indicate that the release of cobalt ions *in vivo* (whether from soluble or poorly water-soluble compounds and particles) is a key event for cobalt-induced carcinogenicity.

Mechanistic data (discussed in Section 6) formed the basis for the approach for grouping cobalt and cobalt compounds that release cobalt ions *in vivo* as a class (Section 7.1). The scientific data supporting the conclusion of sufficient evidence of cobalt and cobalt compounds that release cobalt ions *in vivo* from studies in experimental animals is discussed in Section 7.2, and the conclusions from the cancer studies in human studies is briefly summarized in Section 7.3.

## 7.1 Cobalt and cobalt compounds that release cobalt ion *in vivo* as a class

Chemical grouping describes a general approach for considering more than one chemical at the same time for hazard assessment or regulatory purposes. Chemicals whose physicochemical and/or toxicological properties are likely to be similar or follow a consistent pattern, usually as a result of structural similarity, may be considered as a group, or category of substances (OECD 2014, ECHA 2009). One of the primary advantages of grouping is that every chemical within the group does not necessarily require testing for every endpoint. Where scientifically justifiable, chemicals and endpoints that have been tested can be used to fill in the data gaps for the untested chemicals and endpoints. Obviously, only a limited number of cobalt compounds have been tested for one or more of the endpoints evaluated in this monograph. Therefore, a group approach is proposed and the following sections are based on data reviewed in the previous sections of this document that are relevant to the proposed group listing.

Mechanistic data informed the approach for grouping cobalt and cobalt compounds that release cobalt ions *in vivo* as a class. The key events involve cellular uptake of cobalt, intracellular release of cobalt ions from particles, intracellular concentrations and distribution, immediate and downstream molecular effects (discussed below and illustrated in Figure 6-1), and tumor formation. Thus, physicochemical properties, toxicokinetics, mechanistic data and other relevant data were used to identify and compare the chemical and biological properties and events that were relevant to cobalt-induced carcinogenicity to determine if a group listing for cobalt and cobalt compounds that release cobalt ions *in vivo* was warranted. These endpoints are compared for several cobalt compounds in Section 7.1.4 and Table 7-1 and discussed below.

In addition to the mechanistic data, other data relevant for chemical grouping include the following:

- Physicochemical properties and toxicokinetics (Section 7.1.1)
- Overview of the major modes of action (7.1.2)
- Toxicological effects related to a common functional group (i.e., the cobalt ion) (Section 7.1.3)
- Overall synthesis (Section 7.1.4).

### 7.1.1 Physicochemical properties and toxicokinetics

Physicochemical properties and toxicokinetic data for cobalt metal and various cobalt compounds were presented in Sections 1 and 3. Solubility, particle size, bioavailability, and cellular uptake and retention affect toxicity. These data show the following general rank order for aqueous solubility: cobalt(II) salts > cobalt metal > cobalt oxides. Bioaccessibility, defined as the availability of a metal for absorption when dissolved in artificial body fluids, is often used as an *in vitro* surrogate for bioavailability testing (Stopford *et al.* 2003). Bioaccessibility measurements showed the same general rank order as aqueous solubility at near neutral pH but, in acidic solutions associated with lysosomes (pH 4.5) or gastric fluid (pH 1.5), bioaccessibility was 100% or near 100% for cobalt metal and several cobalt compounds tested including water-soluble and poorly soluble compounds indicating that they release cobalt ions in solution (see Table 1-1).

As discussed in Section 3, a number of factors affect cobalt absorption. This is reflected by the fact that absorption of cobalt compounds following oral exposure varies widely but soluble forms are better absorbed than insoluble forms. Inhalation studies also indicate better absorption and shorter retention in the respiratory tract of soluble forms compared to insoluble forms. Thus, cobalt particles with low solubility (e.g., cobalt oxides) are retained in the lungs for long periods and represent a continuing source of exposure. Although cobalt metal has low aqueous solubility, NTP's chronic inhalation study showed that lung clearance in rats and mice was similar to that observed for soluble cobalt sulfate heptahydrate. Cobalt concentrations and tissue burdens increased with increasing exposure concentrations in all tissues examined, indicating systemic exposure; however, normalized tissue burdens increased only in the liver.

Although soluble cobalt compounds are better absorbed, cellular uptake mechanisms for particles also are important (see Section 6.1). Thus, cellular uptake of poorly soluble cobalt particles via endocytosis/phagocytosis can result in intracellular dissolution within the lysosomes and release of cobalt ions. *In vitro* studies of cobalt metal and cobalt oxide particles generally show that intracellular cobalt ion release is responsible for toxicity as opposed to extracellular dissolution. These studies demonstrated that direct particle contact with the cultured cells was required for cellular uptake and intracellular ion release and toxicity, while cells that were exposed only to extracellular ions dissolved from the particles were not affected. In contrast, cobalt ions readily form complexes with proteins and low molecular weight components and must first saturate binding sites in the extracellular milieu and on cell surfaces before entering the cell via metal ion transport systems. Solubility, particle size, and particle surface area also affect elimination from the body. Elimination of cobalt particles and ions is multiphasic with fast, intermediate, and slow phases; however, soluble compounds are cleared faster with a smaller fraction of the dose retained long term.

### 7.1.2 Mechanistic and other relevant data

Although the mechanisms of cobalt-induced carcinogenicity are not completely understood, three biologically plausible modes-of-action have been identified and were reviewed in Section 6. These include (1) genotoxicity and inhibition of DNA repair, (2) ROS and oxidative damage, and (3) stabilization of HIF-1α. Cobalt ions can replace zinc ions in the zinc finger domains of DNA repair proteins, thus altering their catalytic activity, and *in vitro* assays consistently show genotoxic effects (primarily clastogenic) in mammalian cells exposed to a wide range of cobalt compounds. Cobalt is a redox-active transition metal and *in vitro* studies show that cobalt particles and ions can induce ROS in mammalian cells with cobalt metal and cobalt oxide particles having a greater effect than ions. Evidence of oxidative stress and oxidative damage also were shown in *in vivo* studies. Finally, HIF-1α stabilization is well established for cobalt. Although most studies used cobalt chloride to promote a hypoxia-like state, cobalt metal nanoparticles were also shown to have this effect. HIF-1α plays a central role in the transcriptional regulation of more than 100 hypoxia-responsive genes and is a major regulator of the adaptation of cancer cells to hypoxia. Although there were some differences in the degree of toxicity or biological response among cobalt metal particles, cobalt oxide particles, and cobalt ions the modes of action are relevant for all of these cobalt forms.

### 7.1.3 Toxicological effects and key events

*In vivo* studies in humans and experimental animals consistently show that cobalt and cobalt compounds induce a similar spectrum of inflammatory, fibrotic, and proliferative lesions in the upper respiratory tract. Toxicological effects of cobalt are attributed primarily to the cobalt ion; however, *in vitro* studies indicate that direct toxic effects of cobalt particles also contribute. Relevant toxic effects reviewed in this document include carcinogenicity in humans and experimental animals, genetic and related effects (*in vitro* and *in vivo*), oxidative stress (*in vitro* and *in vivo*), and cytotoxicity (*in vitro*). Although not completely understood, cellular uptake mechanisms and intracellular release of cobalt ions and their distribution are important factors.

Cobalt metal and cobalt compounds exhibited similar carcinogenic effects in animals and similar genotoxic and cytotoxic effects *in vitro*. Inhalation studies with cobalt sulfate or cobalt metal primarily induced lung tumors (although tumors distal to the lung were found for cobalt metal) while injection-site tumors were induced following subcutaneous, intraperitoneal, intramuscular, or intratracheal administration of various cobalt particles and compounds. *In vitro* assays show that cobalt metal and cobalt compounds induce genetic damage and inhibit DNA repair. *In vivo* genotoxicity data were mostly conducted with cobalt chloride and were positive for aneuploidy, micronucleus formation, and chromosomal aberrations; cobalt acetate caused DNA damage in the lung and several other tissues. *In vitro* cytotoxicity assays were consistent in reporting dose-related effects for cobalt metal particles, cobalt oxide particles, and cobalt ions. In general, metallic cobalt particles induced cytotoxicity, ROS formation, genotoxicity, and carcinogenicity to a greater extent than cobalt ions while cobalt oxide particles with low solubility were less cytotoxic than cobalt ions but induced higher levels of ROS (see Table 6-1). Many studies (both *in vitro* and *in vivo*) have reported evidence that cobalt induces oxidative stress, particularly when complexed with endogenous chelators such as glutathione or anserine. In addition, mutations in lung tumors induced by cobalt sulfate or cobalt metal included G to T transversions that are characteristic of oxidative damage.

### 7.1.4 Overall synthesis

Several biological endpoints were identified from physicochemical, toxicological, and mechanistic data for cobalt metal, cobalt chloride, cobalt sulfate, and cobalt oxides (CoO and Co3O4). These cobalt forms were the most studied and included both soluble and poorly soluble forms (see Table 7-1 for synthesis of available information). Data for two cobalt oxides, CoO and Co3O4, were combined because both are both poorly water-soluble, enter cells by endocytosis and release Co ions in the lysosomes and induced similar biological effects (e.g., genotoxicity and cytotoxicity). Although data was not available for all endpoints for each oxide, overall the mechanistic data support the inclusion of both oxides in the class of cobalt compounds that release ions *in vivo*.

Symbols (i.e., −, +) in Table 7-1 are used to indicate the overall evaluation for the various endpoints and cobalt forms. These data provide justification for the proposed group approach and are consistent with the OECD (2014) and ECHA (2009) guidelines for chemical grouping. Thus, biological properties of cobalt compounds that are not included in this table may be inferred by comparing with an analogous cobalt compound within the table.

**Table 7-1. Comparison of chemical and biological properties of cobalt metal and cobalt compounds**

| Endpoint | Soluble cobalt salts | | Cobalt metal | Poorly soluble cobalt compounds |
|---|---|---|---|---|
| | $CoCl_2$ | $CoSO_4$ | Particles | CoO and/or $Co_3O_4$ |
| Bioacessibility | | | | |
| Lysosome | + | + | + | + |
| Gastric | + | + | + | + |
| Cellular uptake | + | + | + | + |
| Cytotoxicity | + | + | + | + |
| ROS | + | ND | + | +[a] |
| HIF-1α stabilization | + | + | + | +[b] |
| DNA repair inhibition | + | ND | + | ND |
| Genotoxicity *in vitro* | + | + | + | + |
| Genotoxicity *in vivo* | + | ND | –[c] | ND |
| Animal carcinogenicity | | | | |
| Lung | ND | + | + | +[d] |
| Other | ND | +[e] | +[f] | ND |
| Injection site[g] | + | ND | + | +[d] |

ND = No data, + = positive, – = negative.
[a]Positive ROS for $Co_3O_4$ but negative (one study) for CoO.
[b]Positive HIF-1α for $Co_3O_4$; no data for CoO.
[c]Limited number of studies.
[d]Positive for CoO; no data for $Co_3O_4$.
[e]Adrenal gland.
[f]Adrenal gland, pancreatic islet cell, mononuclear cell leukemia, and kidney (equivocal).
[g]Includes subcutaneous, intramuscular, intraperitoneal, and intrathoracid injection or implantation studies.

### 7.2 Evidence of carcinogenicity from studies in experimental animals

There is sufficient evidence for the carcinogenicity of cobalt and cobalt compounds that release cobalt ions *in vivo* (collectively referred to as cobalt) in experimental animals based on increased incidence of malignant and/or a combination of malignant and benign neoplasms at several tissue sites in rats and mice by different routes of exposure. Inhalation exposure to cobalt caused dose-related increases in the incidence of lung neoplasms (mainly alveolar/bronchiolar adenoma and carcinoma) in male and female mice and rats, adrenal gland (benign and malignant pheochromocytoma) in male and female rats, hematopoietic system (mononuclear-cell leukemia) in female rats, and pancreas (islet-cell adenoma or carcinoma combined) in male rats. (Evidence is insufficient to differentiate between a direct and indirect cause of adrenal gland neoplasms from cobalt exposure.) Tumors of the pancreas (islet-cell carcinoma) in female rats and kidney (adenoma or carcinoma combined) in male rats may have been related to exposure to cobalt metal. The increased tissue levels of cobalt reported in treated animals support the likelihood that the tumors (e.g., mononuclear-cell leukemia and pancreatic cancers) observed distal from the site of exposure resulted from systemic exposure to cobalt. Injection-site tumors (such as sarcoma, histiocytoma, rhabdomyofibrosarcoma, or fibrosarcoma) were observed in rats exposed to different forms of cobalt by parenteral administration (such as intramuscular, subcutaneous, intraperitoneal injection).

Both lung and injection-site tumors were induced in rodents by different forms of cobalt, including cobalt metal, and soluble (e.g., cobalt sulfate or cobalt chloride) and poorly soluble cobalt compounds (cobalt(II) oxide). Data are summarized in Table 7-2. A comparison of the inhalation studies conducted by NTP of cobalt metal and cobalt sulfate suggests that cobalt metal was more toxic and carcinogenic at a similar cobalt concentration as evidenced by the incidence and spectrum of lung neoplasms and the extent of systemic lesions. This is consistent with mechanistic studies showing that cobalt metal has a greater effect on ROS than cobalt ions.

**Table 7-2. Carcinogenic effects of cobalt metal and cobalt compounds in experimental animals**

| | Soluble cobalt salts | | Cobalt metal | Poorly soluble cobalt compounds |
|---|---|---|---|---|
| **Animal Neoplasms** | $CoCl_2$ | $CoSO_4$ | particles | CoO |
| Lung | ND | + | + | + |
| Adrenal gland | ND | + | + | ND |
| Pancreatic islet cell | ND | − | + | ND |
| Mononuclear cell leukemia | ND | − | + | ND |
| Kidney | ND | − | ± | ND |
| Injection site sarcomas | + | ND | + | + |

ND = no data, + = positive; – = negative, ± = equivocal

### 7.3 Evidence of carcinogenicity from studies in humans

There is inadequate evidence from studies in humans to evaluate the association between exposure to cobalt and cobalt compounds that release cobalt ions *in vivo* and cancer. The data relevant to the evaluation were from studies of five independent cohorts of workers in

variousindustries that focused on lung cancer and two case-population case-control studies (see Section 3) Although almost all the cohort studies reported approximately a doubling of the risk of lung cancer from exposure to various cobalt compounds, it is unclear that the excess risks were due to exposure specifically to cobalt, because of potential confounding from exposure to known lung carcinogens or other limitations (such as concerns about unexposed groups) which complicate the interpretation of the results. In addition, the studies had limited sensitivity to detect a true risk because of small number of cases, crude exposure assessment, or concern about healthy worker related effects.

Increased risks of esophageal cancer were found in the two population-based case-control studies; however, cobalt exposure was assessed in a single sample of toenail clippings taken at or several months after diagnosis of esophageal cancer. Based on data on reproducibility of measurements of metals in toenails, cobalt has low to intermediate within-person reliability, suggesting that a single sample is less than ideal. Measurements of nail cobalt reflect an integrated exposures that occurred 12 to 18 months prior to clipping, raising the question about whether cobalt levels taken in toenails close to, and in many cases after cancer diagnosis, reflect the relevant period of exposure for long latency cancer.

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# Glossary

**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.

**Analysis bias:** A bias arising from inappropriate data assumptions, models, or statistical methods used to evaluate findings, exposure-response relationships, latency, or confounding.

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

**Apoptosis:** Cell deletion by fragmentation into membrane-bound particles, which are phagocytosed by other cells.

**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).

**Aroclor 1254-induced liver:** Liver tissue treated with the polychlorinated biphenyl mixture Aroclor 1254 used as a source of S9 fraction for mutagenic and genotoxic effects testing.

**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.")

**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.

**Chemical Data Reporting Rule:** Chemical Data Reporting (CDR) is the new name for Inventory Update Reporting (IUR). The purpose of Chemical Data Reporting is to collect quality screening-level, exposure-related information on chemical substances and to make that information available for use by the U.S. Environmental Protection Agency (EPA) and, to the extent possible, to the public. The IUR/CDR data are used to support risk screening, assessment, priority setting and management activities and constitute the most comprehensive source of basic screening-level, exposure-related information on chemicals available to EPA. The required frequency of reporting currently is once every four years.

**Co-exposures:** substances to which study participants are exposed that can potentially confound the relationship between the exposure and disease.

**Cochran-Armitage trend test:** A statistical test used in categorical data analysis when the aim

is to assess for the presence of an association between a variable with two categories and a variable with *k* categories. It modifies the chi-square test to incorporate a suspected ordering in the effects of the *k* categories of the second variable.

**Comet assay:** The comet assay evaluates DNA damage by measuring DNA migration in single cells using gel electrophoresis. Migration of DNA is directly related to DNA strand length: the smaller the strands (produced by breaks in the DNA, i.e., damage), the further the DNA will migrate from the nucleus in an electric field.

**Confounding bias and potential confounders:** A bias arising when the comparison groups under study (e.g., exposed versus unexposed, or the cases versus controls) have different background risks of disease (Pearce *et al.* 2007), in effect mixing the association of interest with the effects of other factors. Potential confounders can include any co-exposures or risk factors associated with both the exposure and the disease, and that are not part of the disease pathway.

**Conversion factor:** A numerical factor used to multiply or divide a quantity when converting from one system of units to another.

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

**Differential misclassification bias:** A bias that arises when the probability of being misclassified differs across groups of study subjects. The effect(s) of such misclassification can vary from an overestimation to an underestimation of the true value.

**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.

**Dominant lethal mutation assay:** The dominant lethal assay identifies germ cell mutagens by measuring the ability of a chemical to penetrate gonadal tissue and produce embryonic death due to chromosomal breakage in parent germ cells.

**Ecological study:** A study in which the units of analysis are populations or groups of people rather than individuals.

**ELISA assay:** Enzyme-linked immunosorbent assay; a sensitive immunoassay that uses an enzyme linked to an antibody or antigen as a marker for the detection of a specific protein, especially an antigen or antibody.

**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.

**Exposure-response gradient:** describes the change in effect caused by differing levels of exposure (or doses) to a chemical or substance.

**FDA Good Laboratory Practice Regulations:** A quality system codified by the U.S. Food and Drug Administration that prescribes operating procedures for conducting nonclinical laboratory studies that support or are intended to support applications for research or marketing permits for products regulated by the Food and Drug Administration.

**Fisher's exact test:** The test for association in a two-by-two table that is based on the exact hypergeometric distribution of the frequencies within the table.

**Follow-up:** Observation over a period of time of a person, group, or initially defined population whose appropriate characteristics have been assessed to observe changes in health status or health-related variables.

**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.

**Genotoxic:** The property of a chemical or agent that can cause DNA or chromosomal damage.

**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.

**Information bias:** a bias arising from measurement error. Information bias is also referred to as observational bias and misclassification (see differential and non-differential misclassification bias). When any exposure, covariate, or outcome variable is subject to measurement error, a different quality or accuracy of information between comparison groups can occur.

**Integration of scientific evidence across studies:** the final step in the cancer assessment that assigns greater weight to the most informative studies to reach a preliminary listing recommendation.

**Job exposure matrix (JEM):** a tool used to assess exposure to potential health hazards in occupational epidemiologic studies by converting coded occupational data (usually job titles) into a matrix of possible levels of exposures to potentially harmful agents, reducing the need to assess each individual's exposure in detail.

**Lagging:** Statistical methods that weight exposure times in order to account for prolonged induction and latency periods, particularly in occupational epidemiology studies.

**Latency and prolonged induction:** The induction period is the time required for a cause to lead to the disease process (regardless of symptoms); the latent period is the time between the

exposure and clinical manifestation of the disease. Especially important when considering cancer outcomes.

**Left truncation:** This bias can occur when workers hired before the start of the study, and thus exposed and at risk for disease, do not remain observable at the start of follow-up. The remaining prevalent workers may be healthier and not representative of all workers hired before the start of the study.

**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.

**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 nuclear-like bodies 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.

**Mutagenic:** Capable of inducing genetic mutation, e.g., a genotoxic substance or agent that can induce or increase the frequency of mutation in the DNA of an organism.

**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 Health and Nutrition Examination Survey:** A program of studies designed to assess the health and nutritional status of adults and children in the United States. The survey is unique in that it combines interviews and physical examinations.

**Nondifferential misclassification bias:** arises when all classes, groups, or categories of a variable (whether exposure, outcome, or covariate) have the same error rate or probability of being misclassified for all study subjects. In the case of binary or dichotomous variables nondifferential misclassification would usually result in an 'underestimation' of the hypothesized relationship between exposure and outcome.

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

**Octanol/water partition coefficient (log *K*ow):** A measure of the equilibrium concentration of a compound between octanol and water.

**One-compartment model:** A pharmacokinetic modeling approach that models the entire body as a single compartment into which a drug is added by a rapid single dose, or bolus. It is assumed that the drug concentration is uniform in the body compartment at all times and is eliminated by a first order process that is described by a first order rate constant.

**Personal breathing zone:** A sampling area as close as practical to an employee's nose and mouth, (i.e., in a hemisphere forward of the shoulders within a radius of approximately nine inches) so that it does not interfere with work performance or safety of the employee.

**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.

**Point emission:** A release that can be identified with a single discharge source or attributed to a specific physical location.

**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.

**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.

**Proxy:** a substitute authorized to act for the study participant. Often this is a spouse or other family member who may consent to be interviewed, offering information about the participant.

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

**QUOSA:** A collection of scientific literature management software and services for researchers and information professionals in the life sciences and related scientific and medical areas designed to retrieve, organize, and analyze full-text articles and documents.

**Recall bias:** a bias arising from systematic error in the accuracy or completeness of "recalled" by study participants regarding past events, and usually arises in the context of retrospective case-control interviews or questionnaires. The concern is that those with the disease may search their

memories more thoroughly than unaffected controls to try to recall exposure to various causal factors. This bias is often differential and biases towards an overestimate of effect.

**Reverse causality:** may arise in case-control studies when exposure is measured after disease diagnosis, as the concern is that symptoms or early manifestations of the disease may affect the measured exposure; this is particularly of concern in studies using biomarkers of effect.

**Right truncation:** for right truncated data, only participants or person-time under observation up to a given date are included. Right truncation results in limiting person-time to values that are limited below the given date. Truncation is similar to but distinct from the concept statistical censoring. A truncated sample is similar to an underlying sample with all values outside the bounds entirely omitted, with no count of participants or person-time omitted kept. Alternatively, with statistical censoring, the value of the bound exceeded is known and documented.

**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, and bias can be introduced in either direction.

**Selective reporting:** selective reporting occurs when the effect estimate for a measurement (of exposure or disease) was selected from among analyses using several measurement instruments, reflecting the most favorable result or subcategories.

**Sensitivity:** the proportion of truly diseased persons in the screened population who are identified as diseased by the screening test; or the probability of correctly diagnosing a true case with the test.

**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.

**Specificity:** the proportion of truly nondiseased persons who are so identified by the screening test; or the probability of correctly identifying a non-diseased person with the test.

**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.

**Study sensitivity:** the ability of a study to detect an effect (if it exists) which would include a large number of exposed cases; evidence of substantial exposure (e.g., level, duration, frequency, or probability) during an appropriate window; an adequate range in exposure levels or duration allowing for evaluation of exposure-response relationships; and an adequate length of follow-up.

**Study utility:** the overall utility of a study is based on consideration of the potential for bias (i.e., study quality) and study sensitivity. Serious concerns about study quality will result in lower utility of the study; a high quality study with low sensitivity could also have low utility.

**Surrogate exposure data:** ideally, a study would provide multiple quantitative metrics of each individual's exposure to the substance of interest. However, a surrogate metric correlated with exposure may be used instead of, or in addition to exposure data.

**Time-weighted average:** The average exposure concentration of a chemical measured over a period of time (not an instantaneous concentration).

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

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

**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).

# Abbreviations

| | |
|---|---|
| ACGIH: | American Conference of Governmental Industrial Hygienists |
| ADME: | absorption, distribution, metabolism, and excretion |
| ANOVA: | analysis of variance |
| atm: | atmosphere |
| ATSDR: | Agency for Toxic Substances and Disease Registry |
| bw: | body weight |
| BDL: | below detection limit |
| CA: | chromosomal aberration |
| CASRN: | Chemical Abstracts Service registry number |
| CDC: | Centers for Disease Control and Prevention |
| CDR: | Chemical Data Reporting Rule |
| CI: | confidence interval |
| CIN: | chromosomal instability |
| $cm^2$: | centimeters squared |
| $cm^3$: | centimeters cubed (mL) |
| DLMI: | dominant lethal mutation index |
| DLMR: | dominant lethal mutation rate |
| DNA: | deoxyribonucleic acid |
| dw: | drinking water |
| EPA: | Environmental Protection Agency |
| EQ: | exposure quartiles model |
| EUSES: | European Union System for the Evaluation of Substances |
| Exp.: | exposed |
| F: | female |
| FDA: | Food and Drug Administration |
| FR: | *Federal Register* |
| ft: | feet |

| | |
|---|---|
| FTE: | full-time equivalent |
| FU: | follow-up |
| g: | gram |
| G: | guanine |
| GC/MS: | gas chromatography/mass spectroscopy |
| GI: | gastrointestinal |
| GM: | geometric mean |
| Hb: | hemoglobin |
| HETA: | Health Hazard Evaluation and Technical Assistance |
| HHE: | Health Hazard Evaluation |
| HHS: | Department of Health and Human Services |
| HIC: | highest ineffective concentration |
| HID: | highest ineffective dose |
| HPLC: | high-performance liquid chromatography |
| hr: | hour |
| HWE: | healthy worker effect |
| HWSE: | healthy worker survival effect |
| I: | inconclusive |
| i.m.: | intramuscular |
| i.p.: | intraperitoneal |
| i.v.: | intravenous |
| IARC: | International Agency for Research on Cancer |
| ICD-7, -8, -9: | International Classification of Diseases, Seventh, Eighth or Ninth Revision |
| ICD-O | International Classification of Diseases for Oncology |
| IDLH: | immediately dangerous to life and health |
| in: | inch |
| inj.: | injection |
| JEM: | job-exposure matrix |

| | |
|---|---|
| kg: | kilogram |
| L: | liter |
| LEC: | lowest effective concentration |
| LED: | lowest effective dose |
| LOD: | limit of detection |
| Log $K_{ow}$: | logarithm of octanol/water partition coefficient |
| M: | male |
| $m^3$: | cubic meter |
| MCL: | maximum contaminant level |
| mg: | milligram |
| mL: | milliliter |
| MN: | micronuclei |
| mol: | mole |
| MS: | mass spectrometry |
| N: | number |
| NA | not available; not applicable |
| NCE: | normochromatic erythrocyte |
| NCI: | National Cancer Institute |
| NCTR: | National Center for Toxicological Research |
| ND: | not detected; not determined; not done |
| ng: | nanogram |
| NHANES: | National Health and Nutrition Examination Survey |
| NI: | no information |
| NIEHS: | National Institute of Environmental Health Sciences |
| NIH: | National Institutes of Health |
| NIOSH: | National Institute for Occupational Safety and Health |
| NLM: | National Library of Medicine |
| NOES: | National Occupational Exposure Survey |

| | |
|---|---|
| NOS: | not otherwise specified |
| NPL: | National Priorities List |
| NR: | not reported; none reported |
| ns: | not specified |
| NS: | not significant |
| NT: | not tested |
| NTP: | National Toxicology Program |
| OHAT: | Office of Health Assessment and Translation |
| OR: | odds ratio |
| OSHA: | Occupational Safety and Health Administration |
| P: | probability |
| P-value: | the statistical probability that a given finding would occur by chance compared with the known distribution of possible findings |
| p.o.: | per os (oral administration) |
| PBZ: | personal breathing zone |
| PCE: | polychromatic erythrocyte |
| PEL: | permissible exposure limit |
| ppm: | parts per million |
| ppt: | parts per trillion |
| QSAR: | quantitative structure-activity relationship |
| R: | estimated daily production of adducts |
| r: | correlation coefficient |
| RAHC: | Reasonably anticipated to be a human carcinogen |
| RBC: | red blood cell |
| REL: | recommended exposure limit |
| RNS: | reactive nitrogen species |
| RoC: | Report on Carcinogens |
| ROS: | reactive oxygen species |
| RQ: | reportable quantity |

| | |
|---|---|
| RR: | relative risk |
| RTG: | relative total growth |
| s.c.: | subcutaneous |
| SAFE: | significance analysis of function and expression |
| SCE: | sister-chromatid exchange |
| SD: | standard deviation |
| SEER: | Surveillance, Epidemiology, and End Results Program, NCI |
| SIC: | Standard Industrial Classification |
| SIR: | standardized incidence ratio |
| SMR: | standardized mortality ratio |
| SOCMI: | synthetic organic chemical manufacturing industry |
| SRR: | standardized rate ratio, standardized relative risk |
| SSB: | single-strand break |
| STS: | soft tissue sarcoma |
| TDS: | Total Diet Study |
| TLV-TWA: | threshold limit value time-weighted average |
| $t_{max}$: | time to maximum concentration in plasma |
| TMD: | tail moment dispersion coefficient |
| TRI: | Toxics Release Inventory |
| TSCA: | Toxic Substances Control Act |
| TSFE: | time since first employment |
| UDS: | unscheduled DNA synthesis |
| UK: | United Kingdom |
| US: | United States |
| VOC: | volatile organic compound |
| WBC: | white blood cell |
| WHO: | World Health Organization |
| wk: | week |

wt%: weight percent

yr: year or years

µg: microgram

Part 2

# Draft Cancer Profile

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# Cobalt and Cobalt Compounds That Release Cobalt Ions *In Vivo*

## CAS No. 7440-48-4 (Cobalt metal)

No separate CAS No. assigned for cobalt compounds as a class

Reasonably anticipated to be human carcinogens

## Introduction

The compound cobalt sulfate was first listed in the Eleventh Report on Carcinogens in 2004 as *reasonably anticipated to be a human carcinogen* based on sufficient evidence of carcinogenicity in experimental animals. The listing of cobalt and cobalt compounds that release cobalt ions *in vivo* supersedes the previous listing of cobalt sulfate in the Report on Carcinogens and applies to the class cobalt and cobalt compounds that release cobalt ions *in vivo* as defined below.

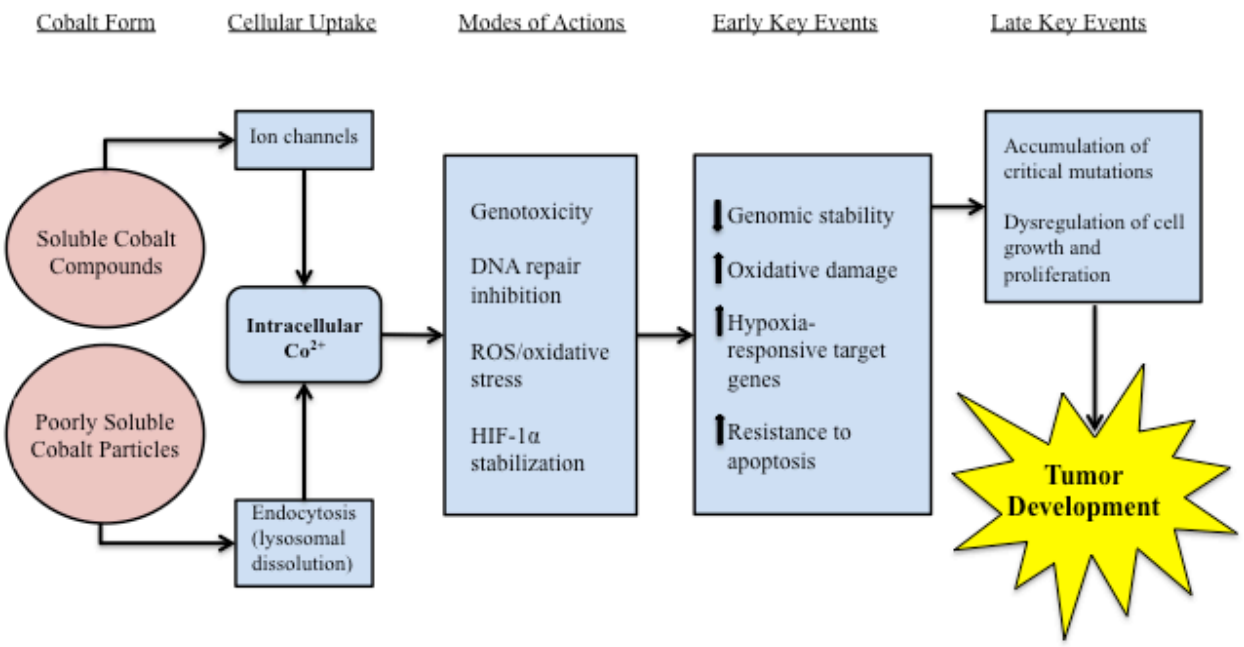
## Carcinogenicity

Cobalt and cobalt compounds that release cobalt ions *in vivo* are *reasonably anticipated to be human carcinogens* based on sufficient evidence of carcinogenicity from studies in experimental animals and supporting data from studies on mechanisms of carcinogenesis. Mechanistic data indicate that the release of cobalt ions *in vivo* is a key event for cobalt-induced carcinogenicity. The available data show that cobalt metal and cobalt compounds that release cobalt ions *in vivo* (regardless of their solubility in water) act via similar modes of action and induce similar cytotoxic, genotoxic, and carcinogenic effects, and that the cobalt ion is largely responsible for the toxicity and carcinogenicity (NTP 1998, 2014, IARC 2006).

Both water-soluble cobalt compounds, which release ions in extracellular fluids, and poorly water-soluble cobalt particles, which release cobalt ions intracellularly in lysosomes, are included in this grouping. Evidence for cellular uptake of particles of cobalt metal and poorly water-soluble cobalt compounds and subsequent intracellular release of cobalt ions includes increased intracellular cobalt ion concentrations and cytotoxicity *in vitro* (Ortega *et al.* 2014, Sabbioni *et al.* 2014a, Smith *et al.* 2014, Peters *et al.* 2007) as well as solubility in biological fluids *in vitro* (e.g., gastric and lysosomal fluids), as discussed under "Properties" below. Vitamin $B_{12}$, which is an essential cobalt-containing nutrient, does not meet the criteria for this listing because it does not release cobalt ions as it passes through the body intact while bound to specific carrier proteins (Neale 1990).

### *Mechanisms of Carcinogenesis and Other Relevant Data*

The key events related to toxicity and carcinogenicity are thought to include cellular uptake of cobalt, intracellular release of cobalt ions from particles, and immediate and downstream biological responses related to the proposed modes of action (as shown in the diagram below). The first step in the carcinogenicity or toxicity process is the release of cobalt ions *in vivo*. Water-soluble cobalt compounds release ions into extracellular fluids, and poorly water-soluble cobalt particles release cobalt ions intracellularly in lysosomes.




**Mechanistic events in cobalt carcinogenicity**

Although the mechanism(s) of action for cobalt-induced carcinogenic effects are not completely understood, several key events have been identified that are related to biologically plausible modes of actions and are applicable to all cobalt forms that release cobalt ions *in vivo.* These events include inhibition of DNA repair, genotoxicity, generation of reactive oxygen species (ROS) and oxidative damage, and stabilization of hypoxia-inducible factor 1α (HIF-1α).

Cobalt is clastogenic in mammalian cells and induces DNA strand breaks and chromosome damage *in vitro*. Only a few *in vivo* genotoxicity studies were available, but the results were generally consistent with those of *in vitro* studies. Although the mechanisms of cobalt-induced genetic damage are not completely understood, the literature suggests two possible mechanisms: (1) a direct effect of cobalt(II) ions to induce oxidative damage to DNA, and/or (2) an indirect effect through inhibition of DNA repair (Smith *et al.* 2014, Lison 2015).

Cobalt is also a redox-active transition metal, and *in vitro* studies have shown that cobalt particles and ions can induce ROS in mammalian cells, with cobalt metal and cobalt oxide particles having a greater effect than ions. Evidence of oxidative stress and oxidative DNA damage have been shown in *in vivo* studies in rat kidney, liver, and lung (Kasprzak *et al.* 1994). Also, a higher frequency of G to T transversion mutations in the K-*ras* oncogene (a common mutation associated with oxidative DNA damage) were found in cobalt induced lung tumors in mice and rats compared to spontaneous lung tumors (NTP 1998, 2014, IARC 2006). In addition to directly inducing DNA damage, ROS also activate a number of redox-sensitive transcription factors (e.g., nuclear factor κB, activator protein 1) that have been linked to carcinogenesis because of their role in regulating inflammation, cell proliferation, differentiation, angiogenesis, and apoptosis (Valko *et al.* 2005, 2006, Beyersmann and Hartwig 2008). Thus, ROS may initiate tumor development by mutagenesis and/or promote tumor growth by dysregulation of cell growth and proliferation.

Finally, a well-established biological effect of cobalt is to mimic hypoxia by stabilizing HIF-1α (Maxwell and Salnikow 2004, Greim *et al.* 2009, Saini *et al.* 2010a,b, Galán-Cobo *et al.* 2013, Gao *et al.* 2013, Nyga *et al.* 2015). HIF-1α plays a central role in the transcriptional regulation of more than 100 hypoxia-responsive genes and is a major regulator of the adaptation of cancer cells to hypoxia. HIF-1α overexpression has been linked to cancer initiation and progression and is a common characteristic of many human cancers (Paul *et al.* 2004, Galanis *et al.* 2008, 2009, Cheng *et al.* 2013).

Although most of the toxicological effects of cobalt are attributed to the cobalt ion, direct toxic effects of cobalt particles also contribute, as evidenced by the greater toxicity of cobalt metal than of cobalt sulfate in National Toxicology Program (NTP) rodent bioassays (NTP 1998 2014, Behl *et al.* 2015). Differences in the relative toxicity reported for cobalt particles and ions may be partially explained by differences in cellular uptake mechanisms, a synergistic effect between the particles and metal on ROS production, and differences in intracellular cobalt accumulation and distribution (Peters *et al.* 2007, Sabbioni *et al.* 2014, Smith *et al.* 2014).

### *Cancer Studies in Experimental Animals*

Exposure of experimental animals to cobalt metal or cobalt compounds caused tumors in two rodent species, at several different tissue sites, and by several different routes of exposure. This conclusion is based on studies in rats and mice exposed to cobalt metal (five studies), water-soluble cobalt compounds (two studies with cobalt sulfate and one study with cobalt chloride), and poorly water-soluble cobalt compounds (four studies with cobalt oxide). Studies of cobalt alloys and radioactive cobalt in experimental animals were not considered to be informative because of potential confounding by other carcinogens.

Inhalation exposure of rats and mice to cobalt metal (NTP 2014) or cobalt sulfate (NTP 1998) or intratracheal instillation of cobalt oxide in rats (Steinhoff and Mohr 1991) caused lung tumors (alveolar/bronchiolar adenoma and carcinoma). In addition, inhalation exposure of rats to cobalt metal caused squamous-cell tumors of the lung (primarily cystic keratinizing epithelioma) in females and possibly in males.

In inhalation studies of cobalt metal in rats, tumors were also induced at sites distant from the lung, including tumors of the pancreas (islet-cell adenoma or carcinoma combined) in males and of the hematopoietic system (mononuclear-cell leukemia) in females, indicating a systemic effect (NTP 2014). Increased incidence of neoplasms in the kidney (adenoma or carcinoma combined) in male rats and pancreas (carcinoma) in female rats may have been related to cobalt metal inhalation (NTP 2014). Exposure to cobalt metal or cobalt sulfate induced adrenal gland tumors (benign and malignant pheochromocytoma); which could be caused by direct or indirect mechanisms..

In rats, local injection of cobalt at various anatomic locations caused tumors at the injection sites. Although these studies were less robust than the inhalation studies and sarcomas are common in injection studies in rats on a variety of compounds, the consistency of the tumor types and findings across different cobalt forms provide supporting evidence of carcinogenicity of cobalt. Intraperitoneal or intramuscular injection of the poorly water-soluble compound cobalt oxide caused histiocytoma and/or sarcoma at the injection site (Gilman and Ruckerbauer 1962, Steinhoff and Mohr 1991), and subcutaneous injection of the water-soluble compound cobalt

chloride caused fibrosarcoma (Shabaan *et al.* 1977). Intramuscular or intrathoracic injection of cobalt metal (Heath 1956, Heath and Daniel 1962) or nanoparticles (Hansen *et al.* 2006) caused sarcoma (primarily rhabdomyofibrosarcoma, rhabdomyosarcoma, or fibrosarcoma. In the study of nanoparticles by Hansen *et al*. 2006, no tumors were observed after implantation of substances (e.g., titanium dioxide and silicon dioxide) with the same physical characteristics (i.e., surface to volume ratio) as cobalt, which suggests that the tumors were due to carcinogenic properties of cobalt and not just to a reaction to any physical implant.

A few studies in rodents (Gilman and Ruckerbauer 1962, Jasmin and Riopelle 1976, Wehner *et al.* 1977) found no tumors at certain tissue sites following exposure to the same forms of cobalt that caused tumors in other studies; however, these studies generally lacked sensitivity to detect an effect, because of the use of a less sensitive animal model, shorter study duration, or lower exposure levels.

### *Cancer Studies in Humans*

The data available from studies in humans are inadequate to evaluate the relationship between human cancer and exposure specifically to cobalt and cobalt compounds that release cobalt ions *in vivo*. The data relevant to the evaluation were from studies of five independent cohorts of workers, primarily evaluating lung cancer, and two population-based case-control studies of esophageal and other cancers of the aerodigestive tract, one in Ireland (O'Rorke *et al.* 2012) and the other in the state of Washington (Rogers *et al.* 1993). The cohorts included (1) porcelain painters in Denmark (Tüchsen *et al.* 1996), (2) cobalt production workers in an electrochemical plant in France reported in two publications (Mur *et al.* 1987, Moulin *et al.* 1993), (3) two overlapping cohorts of cobalt–tungsten carbide hard-metals workers in France (Moulin *et al.* 1998, Wild *et al.* 2000), (4) stainless- and alloyed-steel workers in France (Moulin *et al.* 2000), and (5) nickel refinery workers in Norway (Grimsrud *et al.* 2005). Studies of cobalt alloys in humans (primarily joint implants) were not considered to be informative, because the extent of cobalt exposure is unknown and they were not specific to cobalt exposure.

Although increased risks of lung cancer were found in most of the cohort studies, and increases in esophageal cancer were suggested in the two case-control studies, it is unclear that the excess risks were due to exposure specifically to cobalt, because of potential confounding from exposure to known lung carcinogens, or other study limitations. In the cohort studies, hard-metal (Moulin *et al.* 1998, Wild *et al.* 2000) and nickel refinery workers (Grimsrud *et al.* 2005) were also exposed to known lung carcinogens; excess risks were also found among the “unexposed” referent pottery workers; and the excess risk found in an earlier cohort study of cobalt production workers (Mur *et al.* 1987) was no longer present in a later update of the cohort (Moulin *et al.* 1993). In addition, the studies had limited sensitivity to detect a true risk because of small number of cases, crude exposure assessment, or concern about healthy worker related effects.

In the case-control studies, cobalt exposure was assessed in a single sample of toenail clippings taken at or several months after diagnosis of esophageal cancer. Measurements of cobalt in toenails reflect an integrated exposure that occurred 12-18 months prior to clipping, raising the question whether levels found in toenails close to, and in many cases after cancer diagnosis, reflect the relevant period of exposure for long latency cancer.

## Properties

Cobalt and cobalt compounds that release cobalt ions *in vivo* as a class are related largely by their chemical properties, specifically bioavailability.

### *Bioavailability*

Because the carcinogenic and toxic effects of cobalt and cobalt compounds begin with the release of cobalt ions *in vivo*, the bioavailability of cobalt ions is critical for consideration of carcinogenicity. The bioavailability of a metal species can be predicted by its solubility in biological fluids, such as synthetic equivalents of gastric and intestinal fluids (for ingestion exposure); alveolar, interstitial, and lysosomal fluids (for inhalation exposure) and by studies in cultured cells. Results from studies in biological fluids are shown in the table below, along with other chemical and physical properties of cobalt metal and these cobalt compounds. These studies (testing solubility in synthetic biological fluids) have demonstrated that cobalt metal and both water-soluble and poorly water-soluble cobalt compounds can dissolve and release cobalt ions in some biological fluids (Brock and Stopford 2003, Stopford *et al.* 2003, personal communications from CDI on July 21, 2015, and October 19, 2015), suggesting that they will release ions *in vivo*. Although very low values ($\leq$ 2%) for bioavailability have been reported for the sulfide and mixed (II,III) oxide and intermediate values (14% to 55%) for stearate and oxalate under the same test conditions, more sensitive tests (e.g., longer term studies with 0.3 μm particles in culture medium have reported a 50% solubility value for $Co_3O_4$ (e.g., cobalt(II, III)). Moreover, Ortega *et al*. 2014), found that intracellular concentrations of solubilized cobalt ions were similar for $Co_3O_4$ and cobalt chloride in human lung cells, suggesting that $Co_3O_4$ would release cobalt ions *in vivo* Results with other biological fluids, such as serum and intestinal, alveolar, and interstitial fluids, indicate that species of cobalt compound, particle size and surface area, and the pH of the surrogate fluid can all affect the solubility of cobalt in biological fluids.

**Physical and chemical properties for cobalt metal and some cobalt compounds**

| Form[a] | CAS No.[b] | Formula | Molec. weight | Physical form | Density or specific gravity | Water solubility (g/100 cc)[c] | Bioaccessibility (% solubility in gastric/ lysosomal fluids)[d] |
|---|---|---|---|---|---|---|---|
| *Cobalt metal* | 7440-48-4 | Co[e] | 58.9[e] | grey hexagonal or cubic metal[e] | 8.92[e] | 0.00029[i] | 100/100 |
| ***Water-soluble compounds*** | | | | | | | |
| *Sulfate heptahydrate* | 10026-24-1 | $CoSO_4 \cdot 7H_2O$[g] | 281.1[g] | red pink, monoclinic[g] | 1.95[g] | 60.4[g] | 100/100 |
| **Chloride** | 7646-79-9 | $CoCl_2$[h] | 129.8[h] | blue hexagonal leaflets[h] | 3.36[h] | 45[h] | 100/100 |
| *Acetate* (org.) | 71-48-7 | $Co(C_2H_2O_2)_2$[g] | 249.1[g] | red-violet, monocl.[g] | 1.70[g] | 34.8[i] | 98/80[i] |
| *Nitrate* | 10141-05-6 | $CoN_2O_6$[e] | 182.9[e] | red powder or crystals[e] | 2.49[e] | 67.0[i] | 96/100[i] |
| ***Poorly water-soluble compounds*** | | | | | | | |
| *(II) Oxide* | 1307-96-6 | CoO[g] | 74.9[g] | green-brown cubic[g] | 6.45[g] | 0.00049[i] | 100/92.4 |
| (II, III) Oxide | 1308-06-1 | $Co_3O_4$[b] | 240.8[g] | black, cubic[g] | 6.07[g] | 0.00016[i] | 2/2i[i] (50[i]%) |
| 2-Ethylhexanoate (org.) | 136-52-7 | $Co(C_8H_{15}O_2)_2$[g] | 173.7[h] | blue liquid (12% Co)[g] | 1.01[g] | 0.630[i] | 100/100 |
| Carbonate (org.) | 513-79-1 | $CoCO_3$[g] | 118.9[g] | red, trigonal[g] | 4.13[g] | 0.00114[i] | 100/100 |
| Naphthenate (org.) | 61789-51-3 | $Co(C_{11}H_7O_2)_2$[e] | 401.3[e] | purple liquid (6% Co)[g] | 0.97[g] | 0.0293[i] | 100/100 |
| Hydroxide | 21041-93-0 | $Co(OH)_2$[b] | 93.0[g] | rose-red, rhomb[g] | 3.60[g] | 0.00032[g] | 95/98[i] |
| *Sulfide* | 1317-42-6 | CoS[b] | 91.0[g] | reddish octahedral[g] | 5.45[g] | 0.00038[g] | 1/1[i] |
| Oxalate (org.) | 814-89-1 | $CoC_2O_4$[g] | 147.0[g] | white or reddish[g] | 3.02[g] | 0.00322[i] | 37/55[i] |
| Propionate (org.) | 1560-69-6 | $Co(C_3H_5O_2)_2$[e] | 205.1[e] | reddish solid[i] | – | 7.49[i] | 91/94[i] |
| Stearate (org.) | 1002-88-6 | $Co(C_{18}H_{35}O_2)_2$[e] | 625.9[e] | grey solid[i] | – | 0.00705[i] | 14/16[i] |

[a] Cobalt compounds selected for inclusion in the table include those with toxicological data or of commercial importance. All compounds contain Co(II) except where noted. Forms in italics have been tested for carcinogenicity, genetic toxicity, or have mechanistic data; org. = organic compound; all others are inorganic.
[b]SciFinder (2015).
[c]Solubility data were converted to g/100 cc as necessary.
[d]Stopford *et al*. 2003, [e]PubChem 2015, [f]ChemIDplus 2015, [g]CDI 2006, [h]HSBD 2015,[i]Personal communication, CDI, July 21, 2015, October 19, 2015.
[j]Kreyling *et al.* (1990).

The solubility of cobalt compounds in water is largely pH dependent, and cobalt is generally more mobile in acidic solutions than in alkaline solutions (IARC 1991, Paustenbach *et al.* 2013). Sulfates, nitrates, and chlorides of cobalt tend to be soluble in water, whereas oxides (including the mixed oxide, $Co_3O_4$), hydroxides, and sulfides tend to be poorly soluble or insoluble in water (Lison 2015). Organic cobalt compounds can be either soluble, as with cobalt(II) acetate, or insoluble, as with cobalt(II) carbonate and cobalt(II) oxalate (CDI 2006). In addition to low pH, solubilization of some poorly water-soluble compounds in biological fluids may be enhanced in the presence of binding proteins (IARC 2006).

### *Chemical characteristics*

Cobalt (Co) is a naturally occurring transition element with magnetic properties. It is the 33rd most abundant element, making up approximately 0.0025% of the weight of Earth's crust. Cobalt is a component of more than 70 naturally occurring minerals, including arsenides, sulfides, and oxides. The only stable and naturally occurring cobalt isotope is $^{59}Co$ (ATSDR 2004, WHO 2006). Metallic cobalt, Co(0), exists in two allotropic forms, hexagonal and cubic, which are stable at room temperature (IARC 1991, ATSDR 2004, WHO 2006). Cobalt predominantly occurs in two oxidation states, Co(II) and Co(III). Co(II) is much more stable than Co(III) in aqueous solution (Nilsson *et al.* 1985, Paustenbach *et al.* 2013) and is present in the environment and in most commercially available cobalt compounds (e.g., cobalt chloride, sulfide, and sulfate). Co(III) is also present in some commercially available cobalt compounds, including the mixed oxide ($Co_3O_4$) (IARC 1991, Paustenbach *et al.* 2013, Lison 2015) and some simple salts of Co(III) (e.g., $Co_2O_3$). Important salts of carboxylic acids include formate, acetate, citrate, naphthenate, linoleate, oleate, oxalate, resinate, stearate, succinate, sulfamate, and 2-ethylhexanoate.

## Use

Cobalt and cobalt compounds are used in numerous commercial, industrial, and military applications. On a global basis, the largest use of cobalt is in rechargeable battery electrodes; recycling of electronic and electrical waste can result in releases of cobalt to the environment (though more of a global than U.S. concern). In 2012, the reported U.S. consumption of cobalt and cobalt compounds was approximately 8,420 metric tons, the majority used for superalloys (Shedd 2014b). Major uses for metallic cobalt include production of superalloys, cemented carbides, and bonded diamonds. Cobalt nanoparticles are used in medical applications (e.g., sensors, magnetic resonance imaging contrast enhancement, drug delivery), and cobalt nanofibers and nanowires are used in industrial applications. Cobalt compounds are used as pigments for glass, ceramics, and enamels (oxides, sulfate, and nitrate), as driers for paints, varnishes, or lacquers (hydroxide, oxides, propionate, acetate, tallate, naphthenate, and 2-ethylhexanoate), as catalysts (hydroxide, oxides, carbonate, nitrate, acetate, oxalate, and sulfide), as adhesives and enamel frits (naphthenate, stearate, and oxides), and as trace mineral additives in animal diets (carbonate, sulfate, nitrate, oxides, and acetate). U.S. consumption of cobalt and cobalt compounds in 2012 is summarized in the following table.

| End use | Metric tons of cobalt content | Percent of total consumption |
|---|---|---|
| Superalloys | 4,040 | 48.0 |
| Chemicals and ceramics | 2,300 | 27.3 |
| Cemented carbides | 774 | 9.2 |
| Other alloys[a] | 699 | 8.3 |
| Steels | 548 | 6.5 |
| Miscellaneous and unspecified | 63 | 0.7 |

Source: Shedd 2014b.
[a]Includes magnetic, nonferrous, and wear-resistant alloys and welding materials.

The fastest-growing use for cobalt in recent years has been in high-capacity, rechargeable batteries, including nickel-cadmium, nickel-metal hydride, and lithium-ion batteries for electric vehicles and portable electronic devices such as smart phones and laptops (Maverick 2015). Many other uses for cobalt exist, including in integrated circuit contacts and semiconductor production. An emerging area of use is as a key element in several forms of "green" energy technology applications, including gas-to-liquids and coal-to-liquids processes, oil desulfurization, clean coal, solar panels, wind and gas turbines, and fuel cells, and in cobalt-based catalysts for sunlight-driven water-splitting to convert solar energy into electrical and chemical energy.

## Production

Cobalt metal is produced as a by-product from ores associated with copper, nickel, zinc, lead, and platinum-group metals and is most often chemically combined in its ores with sulfur and arsenic (Davis 2000, CDI 2006). The largest cobalt reserves are in the Congo (Kinshasa), Australia, Cuba, Zambia, Canada, Russia, and New Caledonia, with very limited production in the United States in recent years (Shedd 2014a). Except for a negligible amount of by-product cobalt produced from mining and refining of platinum-group metal ores, the United States did not refine cobalt in 2012 (Shedd 2014b). Cobalt has not been mined in the United States in over 30 years (ATSDR 2004); however, a primary cobalt mine, mill, and refinery were being established in Idaho in 2015 (Farquharson 2015). In 2012, 2,160 metric tons of cobalt was recycled from scrap. No cobalt has been sold from the National Defense Stockpile since 2009.

Metallic cobalt and several cobalt compounds are high-production-volume (HPV) chemicals, based on their annual production or importation into the United States in quantities of at least 1 million pounds. Recent volumes of U.S. production, imports, and exports of cobalt metal and HPV cobalt compounds are listed in the following table.

| | Quantity (lb) | | |
|---|---|---|---|
| **Cobalt category** | **Production (2012)** | **Imports (2013)** | **Exports (2013)** |
| Metal (excluding alloys) | 23,384,002 | 16,151,599 | –[a] |
| ***Compounds:*** | | | |
| Acetates | 1 million to < 10 million | 342,918 | 520,996 |
| Carbonates | 1,038,821 | 1,193,856 | –[a] |
| Chlorides | –[b] | 215,661 | 14,304 |
| 2-Ethylhexanoate | 4,294,523 | – | – |
| Hydroxide | 4,709,137 | – | – |
| Oxides | 1 million to < 10 million | 5,300,984[c] | 902,467[c] |
| Propionate | 1 million to < 10 million | – | – |
| Sulfate | 1 million to < 10 million | 1,319,004 | –[a] |

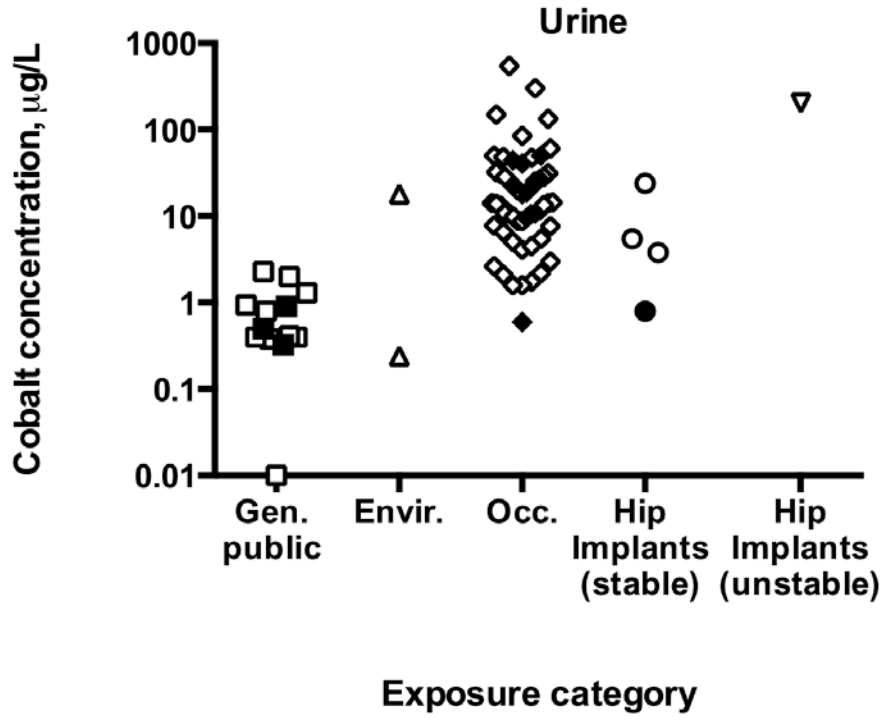
– = no data found.
[a]No specific Schedule B code (i.e., 10-digit classification numbers administered and used by the U.S. Commerce Department to collect and publish statistics on physical goods exported from the United States to another country) identified.
[b]Cobalt chloride production data for 2012 were withheld by the manufacturer.

[c]The reported value is for cobalt hydroxide and oxides combined.

## Exposure

A significant number of people living in the United States are exposed to cobalt, based on several lines of evidence, including biological monitoring data demonstrating exposure in occupationally and non-occupationally exposed populations. Data from the U.S. Environmental Protection Agency's Toxics Release Inventory (TRI) indicate that production- and use-related releases of cobalt compounds have occurred at numerous industrial facilities in the United States.

In biomonitoring studies that measured cobalt in the urine of people exposed to cobalt from various sources, the highest levels generally were due to occupational exposures and failed hip implants; lower levels were due to exposure from normal implants or the environment. Low levels were also observed in the general population (with unknown sources of exposure). The following graph shows the mean or median levels of urinary cobalt for the general public and for groups with known exposures. Data are reported for both U.S. and non-U.S. exposures; occupational and medical implant exposures outside the United States can be informative because of the similar production methods and implant compositions worldwide.




**Urine levels of cobalt for various exposed groups**

Filled symbols = U.S. data; open symbols = non-U.S. data.

Urinary cobalt measurements in the U.S. general public have remained consistent since 1999, with geometric mean values between 0.316 and 0.379 µg/L, according to the National Health and Nutrition Examination Survey (NHANES) (CDC 2015). Urinary cobalt is considered a good indicator of absorbed cobalt (IARC 2006, WHO 2006), especially from recent exposures

(ATSDR 2004). Levels of cobalt in blood (including whole blood, plasma, and serum) show a pattern similar to that for urinary cobalt levels.

### *Occupational exposure*

The primary route of occupational exposure to cobalt is via inhalation of dust, fumes, or mists or gaseous cobalt carbonyl. Dermal contact with cemented carbide (i.e., hard-metal) powders and cobalt salts can result in systemic uptake. Occupational exposure to cobalt occurs during (1) the refining of cobalt, (2) the production of cobalt powders, (3) use in the hard-metal, diamond tool, and alloy industries (including the production and use of these cobalt-containing products), use to make chemicals, pigments, and electronics, and (4) in the recycling of electronics. Workers regenerating spent catalysts may also be exposed to cobalt sulfides. Occupational exposure has been documented by measurements of cobalt in ambient workplace air and in blood, urine, nails, and hair, and lung tissue from workers or deceased workers (IARC 1991, ATSDR 2004, IARC 2006, CDC 2013). The highest levels of cobalt in workplace air are generally for hard-metal manufacture involving cobalt metal powders (1,000 to 10,000 $\mu g/m^3$) (NTP 2009) and for production of cobalt acetate, chloride, nitrate, oxide, and sulfate (IARC 2006).

The National Institute of Occupational Safety and Health (NIOSH) National Occupational Exposure Survey (conducted from 1981 to 1983) estimated that approximately 386,500 workers were potentially exposed to cobalt and cobalt compounds (NIOSH 1990).

### *Surgical implants*

As mentioned above, cobalt implants are a major source of exposure to cobalt in patients receiving orthopedic joint replacements. Most, but not all, hip, knee, and shoulder replacements have at least one articular bearing surface composed of cobalt-chromium molybdenum a alloy. If the bearing surface(s) or modular taper junction(s) of the total joint replacement are composed of CoCrMo alloy, cobalt ions may be released into the body throughout the lifetime of the device (Sampson and Hart 2012, Devlin *et al.* 2013). Implants may fail because of excessive wear or corrosion by body fluids, increasing the levels of cobalt released from the implants (Sampson and Hart 2012). A recommended level of blood cobalt for further clinical investigation and action has been set at 7 μg/L in the United Kingdom (MHRA 2012) and at 10 μg/L in the United States by the Mayo Clinic (2015).

### *Environmental exposure*

Evidence of the potential for environmental exposure to cobalt comes from biomonitoring studies that found elevated levels of cobalt in people who lived near mining operations in Guatemala (Basu *et al.* 2010) and Mexico (Moreno *et al.* 2010). The TRI reported that in 2013, on- and off-site industrial releases of cobalt and cobalt compounds totaled approximately 5.5 million pounds from 723 facilities in the United States (TRI 2014a). Calculations based on media-specific release data from TRI indicate that releases to land accounted for 82% of total releases in 2013. Worldwide, approximately 75,000 metric tons of cobalt enters environment annually (Shedd 1993, CDI 2006) with similar amounts coming from natural sources (40,000 metric tons) and anthropogenic sources (35,000 metric tons) (Shedd 1993, CDI 2006, TRI 2014b).

The average concentration of cobalt in ambient air in the United States has been reported to be approximately 0.4 $ng/m^3$ (ATSDR 2004). Levels can be orders of magnitude higher near source

areas (e.g., near facilities processing cobalt-containing alloys and compounds) reported from outside the United States. The median cobalt concentration in U.S. drinking water has been reported to be less than 2.0 µg/L; however, levels as high as 107 µg/L have been reported (ATSDR 2004). Cobalt concentrations have been reported to range from 0.01 to 4 µg/L in seawater and from 0.1 to 10 µg/L in fresh water and groundwater (IARC 2006). Studies have reported cobalt soil concentrations ranging from 0.1 to 50 ppm. However, soils near ore deposits, phosphate rock, or ore-smelting facilities or soils contaminated by airport or highway traffic or near other source areas may contain higher concentrations (IARC 2006).

#### *Other sources of exposure to the general public*

The general public is exposed to cobalt primarily through consumption of food and to a lesser degree through inhalation of ambient air and ingestion of drinking water; average daily cobalt intake from food has been reported to be 11 µg/day (ATSDR 2004). Although this amount includes cobalt as part of both vitamin $B_{12}$ and other cobalt compounds (ATSDR 2004), green, leafy vegetables and fresh cereals generally contain the most cobalt (IARC 1991), and these plant sources of cobalt do not contain vitamin $B_{12}$. In the 1960s, some breweries added cobalt salts to beer to stabilize the foam (resulting in exposures of 0.04 to 0.14 mg cobalt/kg body weight), but cobalt is no longer added to beer (ATSDR 2004). Higher cobalt intake may result from consumption of over-the-counter or prescription mineral preparations containing cobalt compounds.

Other potential sources of exposure include consumer products and tobacco smoking. Cobalt is present in only a few consumer products, including cleaners, detergents, soaps, car waxes, and a nickel metal hydride battery (5% to 10% cobalt) (ATSDR 2004, HPD 2014). Various brands of tobacco have been reported to contain cobalt at concentrations ranging from less than 0.3 to 2.3 µg/g dry weight, and 0.5% of the cobalt content is transferred to mainstream smoke (WHO 2006). However, urinary cobalt levels (unadjusted for creatinine) for cigarette-smoke-exposed and unexposed NHANES participants for survey years 1999 to 2004 did not differ significantly (Richter *et al.* 2009).

## Regulations

#### *Coast Guard, Department of Homeland Security*

Minimum requirements have been established for safe transport of cobalt naphthenate in solvent naphtha on ships and barges.

#### *Department of Transportation (DOT)*

Numerous cobalt compounds are considered hazardous materials, and special requirements have been set for marking, labeling, and transporting these materials.

#### *Environmental Protection Agency (EPA)*

*Clean Air Act*

*National Emission Standards for Hazardous Air Pollutants:* Cobalt compounds are listed as hazardous air pollutants.

*Clean Water Act*

Cobalt discharge limits are imposed for numerous processes during the production of cobalt at secondary cobalt facilities processing tungsten carbide scrap raw materials.

Discharge limits for cobalt are imposed for numerous processes during the production of cobalt at primary cobalt facilities; for numerous processes during the production of batteries; and for numerous processes during the production of cobalt salts.

Discharge limits for cobalt are imposed for wastewater discharges from centralized waste treatment facilities except discharges and activities exempted in 40 CFR 437.1(b), (c), and 40 CFR 421, Subpart AC.

Cobaltous bromide, formate, and sulfamate are designated as hazardous substances.

*Comprehensive Environmental Response, Compensation, and Liability Act*

Reportable quantity (RQ) = 1,000 lb for cobaltous bromide, formate, and sulfamate.

*Emergency Planning and Community Right-To-Know Act*

*Toxics Release Inventory:* Cobalt and cobalt compounds are listed substances subject to reporting requirements.

Reportable quantity (RQ) = 100 lb for cobalt, ((2,2′-(1,2-ethanediylbis (nitrilomethylidyne)) bis(6-fluorophenolato))(2-)-N,N′,O,O′)- (also called fluomine); = 10 lb for cobalt carbonyl.

Threshold planning quantity (TPQ) = 100 lb for fluomine (solids in powder form with particle size < 100 µm or solution or molten form); = 10,000 lb for all other forms of fluomine; = 10 lb for cobalt carbonyl (solids in powder form with particle size < 100 µm or solution or molten form); = 10,000 lb for all other forms of cobalt carbonyl.

*Federal Insecticide, Fungicide, and Rodenticide Act*

Boiled linseed oil (containing no more than 0.33% manganese naphthenate and no more than 0.33% cobalt naphthenate) is exempt from the requirement of a tolerance when used as a coating agent for *S*-ethyl hexahydro-1*H*-azepine-1-carbothioate. No more than 15% of the pesticide formulation may consist of boiled linseed oil, and this exemption is limited to use on rice before edible parts form.

***Food and Drug Administration (FDA)***

Cobaltous salts are prohibited from use in human food.

All drugs containing cobalt salts (except radioactive forms of cobalt and its salts and cobalamin and its derivatives) have been withdrawn from the market because they were found to be unsafe or not effective, and they may not be compounded.

Chromium–cobalt–aluminum oxide used as a color additive for linear polyethylene surgical sutures used in general surgery must comprise no more than 2% by weight of the suture material, not migrate to surrounding tissue, and conform to labeling requirements in 21 CFR 70.25.

Chromium cobalt-aluminum oxide may be used as a color additive in contact lenses in amounts not to exceed the minimum reasonably required to accomplish the intended coloring effect.

Ferric ammonium ferrocyanide and ferric ferrocyanide used to color externally applied drugs (including those for use in the area of the eye) must not contain more than 200 ppm cobalt (as Co) and conform to labeling requirements in 21 CFR 70.25.

21 CFR 369 contains recommended drug labeling statements for over-the-counter cobalt preparations containing ≥ 0.5 mg cobalt as a cobalt salt per dosage unit and which recommend administration rates of ≥ 0.5 mg per dose and ≥ 2 mg per 24-hour period.

An approved new drug application is required for marketing cobalt preparations intended for use by man.

21 CFR 872, 874, and 888 identify class designations (Class I, II, or III) of various cobalt-containing dental prosthetic device alloys, cobalt-chromium-alloy-based facial prosthetics, and cobalt-chromium-molybdenum orthopedic devices that determine the type of premarketing submission or application required for FDA clearance to market.

Cobalt naphthenate may be used in quantities that do not exceed those reasonably required as an accelerator in the production of cross-linked polyester resins used as articles or components of articles intended for repeated use in contact with food.

Cobalt aluminate may be safely used as a colorant in the manufacture of articles or components of articles intended for use in producing, manufacturing, packing, processing, preparing, treating, packaging, transporting, or holding of food at levels not to exceed 5% by weight of all polymers except in resinous and polymeric coatings complying with 21 CFR 175.300, melamine-formaldehyde resins in molded articles complying with 21 CFR 177.1460, xylene-formaldehyde resins complying with 21 CFR 175.380, ethylene-vinyl acetate copolymers complying with 21 CFR 177.1350, and urea-formaldehyde resins in molded articles complying with 21 CFR 177.1900.

#### *Occupational Safety and Health Administration (OSHA)*

This legally enforceable PEL was adopted from the 1968 ACGIH TLV-TWA shortly after OSHA was established; it may not reflect the most recent scientific evidence and may not adequately protect worker health.

Permissible exposure limit (PEL) (8-h TWA) = 0.1 mg/m$^3$ for cobalt metal, dust, and fume (as Co).

## Guidelines

#### *American Conference of Governmental Industrial Hygienists (ACGIH)*

Threshold limit value – time-weighted average (TLV-TWA) = 0.02 mg/m$^3$ for cobalt and inorganic compounds; = 0.1 mg/m$^3$ for cobalt carbonyl and cobalt hydrocarbonyl.

Biological exposure index (BEI) (end of shift at end of workweek) = 15 µg/L for cobalt in urine.

#### *Consumer Product Safety Commission (CPSC)*

The CPSC has issued guidance regarding the potential hazards of specific cobalt- or cobalt-compound-containing art and craft materials (e.g., glazes, glass colorants, paints, toners, pigments, and dyes) and specific precautions to take when using them.

#### *Environmental Protection Agency (EPA)*

*Regional Screening Levels* (formerly Preliminary Remediation Goals): residential soil = 23 mg/kg; industrial soil = 350 mg/kg; residential air = 0.00031 µg/$m^3$; industrial air = 0.0014 µg/$m^3$; tap water = 6 µg/L.

#### *National Institute for Occupational Safety and Health (NIOSH)*

Recommended exposure limit (REL) (10-h TWA) = 0.05 mg/$m^3$ for cemented tungsten carbide containing > 2% Co (as Co); = 0.05 mg/$m^3$ for cobalt metal dust and fume (as Co); = 0.1 mg/$m^3$ for cobalt carbonyl (as Co) and cobalt hydrocarbonyl (as Co).

Immediately dangerous to life and health (IDLH) limit = 20 mg/$m^3$ for cobalt metal dust and fume (as Co).

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