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Lead exposure in US worksites: A literature review and development of an occupational lead exposure database from the published literature

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Abstract

Background—Retrospective exposure assessment of occupational lead exposure in population-based studies requires historical exposure information from many occupations and industries.

Methods—We reviewed published US exposure monitoring studies to identify lead exposure measurement data. We developed an occupational lead exposure database from the 175 identified papers containing 1,111 sets of lead concentration summary statistics (21% area air, 47% personal air, 32% blood). We also extracted ancillary exposure-related information, including job, industry, task/location, year collected, sampling strategy, control measures in place, and sampling and analytical methods.

Results—Measurements were published between 1940 and 2010 and represented 27 2-digit standardized industry classification codes. The majority of the measurements were related to lead-based paint work, joining or cutting metal using heat, primary and secondary metal manufacturing, and lead acid battery manufacturing.

Conclusions—This database can be used in future statistical analyses to characterize differences in lead exposure across time, jobs, and industries.

Keywords

Lead; occupational exposure; exposure assessment; review; population-based studies

INTRODUCTION

Lead has been widely used across many industries since the beginning of the industrial age because of its low melting point, high malleability, poor electrical conductivity, high density, and chemical stability. An estimated three million US workers were potentially

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exposed to lead in 1998 [ATSDR 2007]. Its continued widespread use is a health concern because lead has been associated with adverse health effects on multiple organ systems including the urinary, nervous, cardiovascular, skeletal, immune, gastrointestinal, and reproductive systems [ATSDR 2007]. Lead is also designated a probable human carcinogen by the International Agency for Research on Cancer [IARC 2006]. In epidemiologic studies, lead exposure has been associated with cancers of the brain, stomach, kidney, lung, and meninges [Boffetta, et al. 2011, IARC 2010, Liao, et al. In Press, van Bemmelen, et al. 2011]; however, these findings have been inconsistent [IARC 2006]. Additional studies are needed to elucidate the relationship between lead and cancer. Because industry-based studies rarely have sufficient numbers of cases for many of these cancer sites, population-based studies can provide a crucial etiologic role.

To aid retrospective exposure assessment efforts to evaluate occupational lead exposure for US population-based studies, we conducted a literature review of exposure monitoring studies of US work sites to identify when, how, where, and at what levels occupational lead exposure has occurred. From the reported lead exposure data and ancillary exposure information in the identified papers, we developed a database of air and blood occupational lead measurements. Here, we provide an overview of the major uses of and exposures to lead in the US workforce, describe the development of the occupational lead database (available from the corresponding author), and briefly summarize the extracted measurements, including weighted-arithmetic means for measurements reported from 1970 onwards. Further statistical evaluations of this data are described separately.

MATERIALS AND METHODS

We identified all papers published on or before December 2010 that reported air or blood lead measurements that had been collected from US work sites that contained information on job or industry by searching the web-based bibliographic databases MEDLINE, Web of Science, Scopus, SciFinder, and NIOSHTIC2 using the search terms 'lead exposure', 'worker', 'occupation', and 'occupational exposure' and by reviewing the citations of the identified papers.

From each paper, we extracted lead measurements, which were primarily reported as summary statistics (including results presented in figures), and corresponding ancillary data. We excluded blood zinc protoporphyrin and free erythrocyte protoporphyrin measurements because these tests are not specific to lead [Baxter and Igisu 2010], pre-employment baseline biologic measurements, post-medical removal biologic measurements, and subsequent reports of data reported in multiple papers.

Air and blood lead concentrations were entered using units of $\mu\text{g}/\text{m}^3$ and $\mu\text{g}/\text{dL}$, respectively, using conversion factor $1.0 \mu\text{mol}/\text{L}=20.7 \mu\text{g}/\text{dL}$. If the number of measurements was provided as a range, the mean number was used in descriptive statistics and analyses. The three air summary statistics reported as below the limit of detection (LOD) were replaced with the LOD/2. Individual measurements in the same job/facility were aggregated. Missing arithmetic means (AM) were calculated from the geometric mean (GM) and geometric standard deviation (GSD) using equation 1. Missing GMs were

assigned the median, if reported. Missing GMs and GSDs were calculated using equations 2 and 3, respectively, if the range was reported, then the AM was calculated using equation 1. If missing the GSD but the GM was available, we assumed a GSD =2.56 [Kromhout, et al. 1993].

$$AM=GM \times \exp \left[\frac{1}{2} \times (\ln(GSD))^2 \right] \quad (1)$$

$$\ln(GM)=\frac{[\ln(\max)+\ln(\min)]}{2} \quad (2)$$

$$\ln(GSD)=\frac{[\ln(\max) - \ln(\min)]}{4} \quad (3)$$

Extracted ancillary data included exposure category, industry, job, task or area description, sample year (if a range, the midpoint was assigned; if missing, assigned publication year minus 2), exposure source, sample type, sampling method, analytic method, type of ventilation used, type of respiratory protection used, whether measurements represented worse case exposure scenarios (e.g., elevated blood lead levels, employee concerns, regulatory violations), whether the work being performed was a lead-based paint removal activity, and whether workplace containment structures were erected. Industry was coded to two-digit 1987 Standard Industrial Classification (SIC) codes [OMB 1987]. For air measurements, we extracted sampler location, whether the sample was task-based or full-shift, sampling duration, and particle size. For blood measurements, we extracted the time of sampling.

Hereafter, we focus on personal air and blood lead measurements because they are considered the preferred measures of personal lead exposure [ACGIH 2001]. To facilitate broad comparisons, we calculated industry-specific weighted arithmetic means (WAM₁₉₇₀, weighted by the number of measurements) for all personal air and blood lead summary statistics collected from 1970 onwards. Personal air WAM₁₉₇₀ calculations were restricted to total suspended particle and inhalable particle samples with sample durations >1 hour and that reported the number of measurements collected. WAMs₁₉₇₀ are reported here only for industries with ≥10 measurements. Statistical modeling of these data is reported separately.

RESULTS

Exposure database

We extracted 1,111 sets of summary statistics representing 27 2-digit SIC codes from 175 studies. The summary statistics represented >7,900 personal air measurements, >5,700 area air measurements, and >19,500 blood measurements (Table I). Personal air and blood lead measurements accounted for 44% and 30% of the summary statistics, respectively. Pre-1970 measurements accounted for 10% of the personal air and 11% of the blood lead summary statistics. Sample duration was <1 hour for 4% of personal air summary statistics and not reported for 36%. Personal air summary statistics were 81% total suspended particle

samples; 59% were collected using closed filter cassettes. Blood collection methods were missing for 67% of the blood lead summary statistics. Analytic methods predominantly used atomic absorption spectroscopy (personal air: 37%; blood lead: 19%), graphite furnace atomic absorption spectroscopy (personal air: 5%; blood lead: 11%), and inductively coupled plasma methods (personal air: 12%; blood lead: none), with analytic methods not reported for 42% of the personal air and 57% of the blood lead summary statistics. A “worst-case” exposure sampling scenario was reported for 13% of the personal air and 18% of blood summary statistics.

Personal air summary statistics were most prevalent for lead-based paint work (34%), manufacturing (25%), joining or cutting metal using heat (10%), and primary and secondary metal production (10%). Blood lead summary statistics were most prevalent for manufacturing (25%), lead-based paint work (20%), and primary and secondary metal production (18%). Lead-based paint removal activities accounted for 27% of the personal air and 10% of the blood summary statistics. Workplace containment structures were reported for 14% of the personal air and 1% of the blood summary statistics. Type of respiratory protection was reported for 61% of personal air and 43% of blood summary statistics. Type of ventilation was reported for 18% of the personal air and 9% of the blood summary statistics.

Lead exposure by activity and industry

A summary of common activities and industries with occupational lead exposure is provided in Table II. Below, we summarize the lead exposure concentrations reported in the published literature, focusing predominantly on personal air and blood lead exposure measurements reported in the literature from 1970 onwards and reported in two or more papers. We provide the full list of 175 papers, indicating which include area air, personal air, or blood lead measurements, in online supplemental materials (Table S1).

Lead-based paint (SIC: various)—Measurements from 1970 onwards related to lead-based paint are summarized in Table III. Overall, the air lead WAM₁₉₇₀ for lead-based paint activities was 348 $\mu\text{g}/\text{m}^3$ (maximum AM 23,300 $\mu\text{g}/\text{m}^3$) based on 138 summary statistics from 26 papers. The blood lead WAM₁₉₇₀ was 14 $\mu\text{g}/\text{dL}$ (maximum AM 99 $\mu\text{g}/\text{dL}$) based on 64 summary statistics from 23 papers. These measurements covered a wide variety of industries, occupations, and activities; however, the majority were collected during lead-based paint removal (abatement) work. The highest air lead WAM₁₉₇₀ (1020 $\mu\text{g}/\text{m}^3$) was observed in the shipyard industry during lead-based paint removal; however, the blood lead WAM₁₉₇₀ was a more moderate 9 $\mu\text{g}/\text{dL}$. In contrast, the highest blood lead WAMs₁₉₇₀ were observed in furniture restoration (30 $\mu\text{g}/\text{dL}$) and lead-based paint removal work in the construction industry (18 $\mu\text{g}/\text{dL}$).

Joining or cutting metals using heat (SIC: various)—Measurements from 1970 onwards related to joining or cutting metal using heat are summarized in Table IV. Overall, the air lead WAM₁₉₇₀ for joining or cutting metals using heat was 727 $\mu\text{g}/\text{m}^3$ (maximum AM 30,000 $\mu\text{g}/\text{m}^3$) based on 57 summary statistics of air measurements from 26 papers. The blood lead WAM₁₉₇₀ was 24 $\mu\text{g}/\text{dL}$ (maximum AM 86 $\mu\text{g}/\text{dL}$) based on 47 summary

statistics from 26 papers. The majority of the measurements were for construction (19 of 57 personal air summary statistics; 27 of 47 blood lead summary statistics) and automobile repair (26 personal air summary statistics; 12 blood lead summary statistics). For construction, the overall personal air lead WAM₁₉₇₀ was 270 $\mu\text{g}/\text{m}^3$ and the blood lead WAM₁₉₇₀ was 24 $\mu\text{g}/\text{dL}$, with the highest WAMs₁₉₇₀ observed in heavy construction and railway construction and the lowest in general construction. For automobile repair, the overall personal air lead WAM₁₉₇₀ was 111 $\mu\text{g}/\text{m}^3$ and the blood lead WAM₁₉₇₀ was 25 $\mu\text{g}/\text{dL}$.

Primary and secondary metal production (SIC 33)—Measurements related to lead exposures in primary and secondary metal production are summarized in Table V. The measurements are sparsely distributed across various metal foundries and smelters. The air WAMs₁₉₇₀ were variable between 4 and 3,100 $\mu\text{g}/\text{m}^3$ and the blood WAMs₁₉₇₀ were all above 30 $\mu\text{g}/\text{dL}$. The highest air lead WAM₁₉₇₀ was reported for primary lead smelter workers (3,100 $\mu\text{g}/\text{m}^3$) and the highest blood WAMs₁₉₇₀ were reported for primary and secondary lead smelter workers (54 and 66 $\mu\text{g}/\text{dL}$, respectively).

Other manufacturing industries (SIC 28, 36, 37)—Lead exposure also occurs in a variety of other manufacturing industries (Table II). However, measurements in the literature were generally limited. Lead-acid batteries have been the largest end use of lead since the 1950s and by 2010 accounted for over 90% of all lead consumed in the United States (USGS <http://minerals.usgs.gov/minerals/pubs/commodity/lead/>), and correspondingly it was the manufacturing industry with the most summary statistics extracted from the literature (Table V). Lead-acid battery production workers' personal air and blood WAMs₁₉₇₀ were 55 $\mu\text{g}/\text{m}^3$ and 42 $\mu\text{g}/\text{dL}$, respectively, based on 89 air summary statistics from 6 papers and 43 blood summary statistics from 8 papers. Industries with measurements from two or more papers included workers manufacturing electric and electronic components, fuel additives, and polyvinyl chloride, with blood lead WAMs₁₉₇₀ of 35, 24, and 41 $\mu\text{g}/\text{dL}$ respectively.

Firing ranges (SIC 79, 92)—For firing ranges, air lead concentrations have been reported in 9 papers and blood lead concentrations have been reported in 11 papers (Table V). Concentrations vary based on whether the lead bullet is jacketed with copper or plastic. Those using unjacketed lead bullets in a firing range had higher air and blood lead WAMs_{1970s} than those using jacketed bullets (334 vs. 32 $\mu\text{g}/\text{m}^3$; 32 vs. 18 $\mu\text{g}/\text{dL}$).

Other work places—Most other activities and industries with occupational lead exposure listed in Table II were evaluated in only a single US study, were based predominantly on area measurements, or were evaluated pre-1970. WAMs₁₉₇₀ based on single studies are provided for the telecommunications, cable recycling, waste incineration, and stained glass production in Table V.

Most airborne lead measurements from leaded gasoline emissions were area rather than personal air measurements (24 vs. 4 summary statistics, respectively; Table I), thus WAM₁₉₇₀ were not calculated. Average area traffic-related air lead concentrations were between 5 and 36 $\mu\text{g}/\text{m}^3$ [Goldsmith and Hexter 1967, Burgess, et al. 1977, Ayres, et al.

1973, Azar, et al. 1975]. Average blood lead concentrations ranged from 2 to 38 $\mu\text{g/dL}$ [Ludwig, et al. 1965, Azar, et al. 1975, Zettner, et al. 1977, Sharp, et al. 1988].

In the agriculture industry, personal air lead concentrations from lead arsenate pesticide exposure in the 1930s and 1940s ranged from 16 to 190 $\mu\text{g/m}^3$ for workers sorting, packing and dumping fruit, from 65 to 2930 $\mu\text{g/m}^3$ for workers thinning and picking apples, and from 210 to 6450 $\mu\text{g/m}^3$ for pesticide mixers and applicators [Farner, et al. 1949, Nelson, et al. 1973].

In the printing industry, only two US exposure studies were identified. These were published in the 1940s and found area air lead concentrations ranging from 12 to 56 $\mu\text{g/m}^3$ during casting operations, 41 to 748 $\mu\text{g/m}^3$ during melting and re-melting operations, and 196 to >50,000 $\mu\text{g/m}^3$ during dross removal and associated cleaning operations [Brandt and Reichenbach 1943, Ruf and Belknap 1940].

DISCUSSION

Our literature review found that published lead exposure measurements from US work sites were plentiful. The resulting occupational lead exposure database represented >7,900 personal air lead measurements and >19,500 blood lead measurements from 175 papers spanning eight decades and 27 2-digit SIC codes. The database is comparable in size and scope to previous efforts to collect occupational exposure measurements to assist retrospective exposure assessment in population-based studies for formaldehyde [Lavoue, et al. 2007, Lavoue, et al. 2006, Lavoue, et al. 2008], solvents [Hein, et al. 2010, Hein, et al. 2008], and suspected lung carcinogens (i.e., silica, asbestos, chromium, nickel, polycyclic aromatic hydrocarbons) [Peters, et al. 2012] and is unique in including blood measurements. The database will serve as a resource for exposure assessors evaluating historical occupational lead exposure in NCI case-control studies to characterize lead exposures across jobs, industries and time periods and is available to other researchers to assist in their exposure assessment and exposure surveillance efforts.

The extracted lead data represented a broad range of activities, occupations, and industries, with a substantial number of measurements found for work involving lead-based paints and joining or cutting metal using heat in the construction and shipyard industries and for lead acid battery manufacturing. Some trades with known lead exposures had little or no measurement data identified in the review, including plumbers, electrical workers, and roofers. Similarly, several industries with known lead use also had limited published measurements, including the heavy equipment, electric, electronics, pigment, printing, ceramic, rubber, and leaded glass industries. For example, the US printing industry had published measurements only for the 1940s despite the continued use of lead type and lead-containing pigments into the mid-1970s.

Other publically available data sources may provide additional lead measurements, as either individual measurements or summary statistics, where data in this database was sparse or missing. For example, previous efforts to extract historical measurement data for reconstructing exposures for population-based studies have also extracted measurements

from health and safety inspections from OSHA and other regulators [e.g., Friesen, et al. 2012, Koh, et al. 2014a, Lavoue, et al. 2008], NIOSH Health Hazard Evaluations [e.g., Hein, et al. 2010, Hein, et al. 2008], and other national, institute, and industry-specific exposure sources [e.g., Lavoue, et al. 2006, Peters, et al. 2012]. In particular, OSHA inspection data have been previously used to characterize lead exposure across time, occupations, and industries [Froines, et al. 1990, Henn, et al. 2011, Okun, et al. 2004], although not specifically for historical exposure reconstruction of lead exposure in epidemiologic studies. Sources of biological measurements are rarer, but one source of blood lead exposure data is the CDC's Adult Blood Lead Epidemiology and Surveillance (ABLES) database, a state-based program funded by NIOSH [CDC, 2009]. The data extracted here and these additional sources vary in the type of ancillary data available and whether the measurements were reported individually or as summary statistics. The comparability of these data sources and the potential for combining multiple sources warrants future evaluation.

The extraction of ancillary data to provide context for the exposure measurements is a strength of this database and is expected to permit future statistical evaluations to identify sources of exposure variability across time, occupations, and industries. For instance, using this database, we recently published a meta-regression analysis that identified the time trends in personal air and blood lead concentrations for several industries [Koh, et al. 2014b]. A limitation, however, is that the availability of the ancillary exposure information varied from reasonably complete to scarce. For example, 61% of the personal air summary statistics had some information on respirator use, but only 19% included information on the type of ventilation used. For blood lead, we found poor reporting of the sampling and analytical methods (67% and 57% not reported, respectively). The lack of reporting of these variables may in part be because this additional information was either not available to the authors or was secondary to the objectives of the original study and consequently was not included in the paper.

The weighted arithmetic means reported here showed some contrasts in lead exposure between industries. Some industries had personal air lead WAMs₁₉₇₀ that were consistently above the airborne 8-hour occupational exposure limits set by OSHA (1971: 200 µg/m³; 1978, non-construction workers and 1993, construction workers: 50 µg/m³) or recommended by the American Conference of Governmental Industrial Hygienists (ACGIH, 2001: 50 µg/m³) [ACGIH 2001, OSHA 2007]. The blood lead WAMs₁₉₇₀ were often observed above the 2001 ACGIH recommended biological exposure index (BEI) for blood lead of 30 µg/dL for average workers and 10 µg/dL for men and women of childbearing potential (e.g., polyvinyl chloride production workers, lead acid battery production workers) but were rarely above the 60 µg/dL limit set by OSHA for mandatory removal. These descriptive statistics represent a starting point for understanding differences in lead concentrations across time and industries that will be examined in future statistical modeling of these data. For instance, statistical modeling will be used to simultaneously characterize time, industry, and occupation differences in exposures for lead exposure activities with sufficient measurements.

The inclusion of blood lead measurements in this database is a significant strength because air and blood lead concentrations are often not strongly correlated [e.g., Pierre, et al. 2002,

Rodrigues, et al. 2009]. The blood lead measurements represent both inhalation and other routes of exposure, such as hand-to-mouth, which can contribute significantly to the absorbed lead dose [Enander, et al. 2004]. Blood lead measurements also account for the effectiveness of use of personal protective equipment and personal hygiene behaviors [ACGIH 2001, Grauvogel 1986], and include non-occupational sources such as lead-contaminated drinking water from lead pipes [IARC 2006]. The blood lead measurements also reflect individual differences in lead absorption rates, which can vary based on the physicochemical characteristics of the lead compounds present [Froines, et al. 1986, Park and Paik 2002, Pierre, et al. 2002, Spear, et al. 1998a, Spear, et al. 1998b], and worker-specific characteristics, including personal hygiene, nutritional status, respiration rate, and kidney function [ATSDR 2007, McGrail, et al. 1995, Rodrigues, et al. 2009]. Moreover, the blood lead measurements represent both recent and past lead exposure from stored lead mobilized from other body compartments, such as soft tissue and bone [Barbosa, et al. 2005].

There are several limitations to the developed database. First, we may not have captured all relevant literature and measurements, despite the additional search of the references of identified papers. Second, we extracted data only from US work sites because the number of US papers was large and the extraction was time-consuming and because our main focus was aiding exposure assessment in US-based NCI case-control studies. It is unclear whether the data are generalizable to other countries; exposure assessment efforts for other populations may require additional data extraction. Third, the measurements were extracted as summary statistics, rather than individual measurements, which requires using modeling approaches that weight the data based on the number of measurements [Hein, et al. 2010, Hein, et al. 2008], meta-analysis regression models [Koh, et al. 2014b], or simulation studies to recreate the individual measurements [Lavoue, et al. 2007]. Fourth, the measurements were collected for a variety of reasons, including worst-case scenarios such as work sites with known blood lead poisoning events, and consequently may not be representative of typical occupational lead exposures for a given industry. Conversely, companies that permit research studies may represent best-case scenarios, utilizing up-to-date control methods. Lastly, dermal and other wipe samples were not extracted because these measurements were rare; however, the blood lead measurements represent multiple routes of exposures.

In summary, the development of this occupational lead exposure database of US measurements provides a valuable resource for historical lead exposure reconstruction and exposure surveillance efforts in the United States. While basic descriptive statistics of the data are provided here as a starting point, this database will be useful for future statistical modeling efforts and may be able to be combined with other lead measurement sources, such as inspection databases, to further characterize lead exposure across jobs, industries and time.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table I

General characteristics of the US lead occupational exposure database summary statistics extracted from the published literature.

Characteristics	Number of Summary Statistics		
	Area N (%)	Personal N (%)	Blood N (%)
Overall	235 (100)	525 (100)	351 (100)
Decade measurements collected			
1930	23 (10)	9 (2)	3 (1)
1940	46 (20)	22 (4)	1 (<1)
1950	13 (6)	17 (3)	19 (5)
1960	6 (3)	5 (1)	16 (5)
1970	30 (13)	40 (8)	78 (22)
1980	30 (13)	175 (33)	144 (41)
1990	61 (26)	195 (37)	71 (20)
2000	26 (11)	62 (12)	19 (5)
Number of measurements in a summary result			
1	31 (13)	100 (19)	22 (6)
2–4	41 (17)	144 (27)	46 (13)
5–9	23 (10)	87 (17)	64 (18)
10–29	36 (15)	69 (13)	92 (26)
30–99	37 (16)	36 (7)	76 (22)
100+	12 (5)	14 (3)	34 (10)
Not reported	55 (23)	75 (14)	17 (5)
Sample collection duration			
< 1 hour	12 (5)	23 (4)	-
1–4 hour	8 (3)	61 (12)	-
> 4 hour	89 (38)	251 (48)	-
Not reported or not applicable	126 (54)	190 (36)	351 (100)
Particle size fraction/physical state			
Total suspended particles	126 (54)	423 (81)	-
PM10	1 (0.4)	-	-
Inhalable	3 (1)	27 (5)	-
Respirable	12 (5)	14 (3)	-
Gas	19 (8)	3 (1)	-
Not reported	74 (31)	58 (11)	-
Sampling method			
Charcoal tube	19 (8)	1 (0.2)	-
Closed filter cassette ^a	87 (37)	309 (59)	-
Cyclone	11 (5)	14 (3)	-
Electrostatic precipitator	26 (11)	16 (3)	-
Impactor	4 (2)	10 (2)	-

Characteristics	Number of Summary Statistics		
	Area N (%)	Personal N (%)	Blood N (%)
Impinger	5 (2)	6 (1)	-
IOMor GSP personal sampler	3 (1)	27 (5)	-
Finger stick	-	-	10 (3)
Venous puncture	-	-	106 (30)
Miscellaneous	18 (8)	2 (0.4)	-
Not reported	62 (26)	140 (27)	235 (67)
Analytic method			
AAS ^b	92 (39)	194 (37)	66 (19)
Graphite furnace AAS	5 (2)	25 (5)	39 (11)
Inductively couple plasma	19 (8)	63 (12)	-
Anodic stripping voltammetry	-	-	34 (10)
Dithizone	17 (7)	10 (2)	4 (1)
Polarographic	8 (3)	11 (2)	-
Miscellaneous	-	2 (0.4)	8 (2)
Not reported	94 (40)	220 (42)	200 (57)
Worst-case exposure sampling scenario			
Yes	25 (11)	67 (13)	63 (18)
No	42 (18)	135 (26)	89 (25)
Not reported	168 (71)	323 (62)	199 (57)
Exposure/industry category			
Lead-based paint work	25 (11)	180 (34)	69 (20)
Joining or cutting metal using heat	28 (12)	53 (10)	37 (11)
Leaded gasoline vehicle emissions	24 (10)	4 (1)	26 (7)
Primary and secondary metal production	56 (24)	53 (10)	64 (18)
Manufacturing	72 (31)	131 (25)	87 (25)
Automotive repair services	4 (2)	30 (6)	17 (5)
Miscellaneous	26 (11)	74 (14)	51 (15)
Lead-based paint removal activities			
Yes	24 (10)	144 (27)	35 (10)
No	211 (90)	381 (73)	309 (88)
Not reported	-	-	7 (2)
Lead-based paint removal containment structure use			
Yes	15 (6)	76 (14)	5 (1)
Partial	-	7 (1)	1 (0.3)
No	65 (28)	64 (12)	60 (17)
Not reported/not applicable	155 (66)	378 (72)	285 (81)
Respiratory protection			
Any use mentioned ^c	21 (9)	214 (41)	62 (18)
None used	61 (26)	105 (20)	86 (25)

Characteristics	Number of Summary Statistics		
	Area N (%)	Personal N (%)	Blood N (%)
Not reported	153 (65)	206 (39)	203 (58)
Ventilation			
Exhaust ventilation	26 (11)	49 (9)	7 (2)
Dilution ventilation	2 (1)	10 (2)	2 (1)
None used	20 (9)	35 (7)	21 (6)
Not reported	187 (80)	431 (82)	321 (91)

AAS, Atomic absorption spectroscopy; IOM, Institute of Medicine; GSP, Gesamtstaubprobenahme or conical inhalable sampler, N, number; PM10, coarse particulate matter with an aerodynamic diameter of 10 microns or less.

^a Includes summary statistics for samples likely collected using a closed filter cassette based on reported OSHA or NIOSH analytical method.

^b Includes summary statistics for samples analyzed by flame AAS and AAS with an unspecified sample vaporization method.

^c Database includes type of respiratory protection if provided in paper.

Table II

Common activities and industries with occupational lead exposure.

Activities**Lead-based paint work** (various industries)

- Lead added to paints commonly used on bridges, railways, industrial metal structures, ship hulls, structural steel, decorative metal structures, vehicle bodies, interior surfaces with increased traffic or wear, and wood and metal furniture and equipment.
- Exterior paints typically have higher lead content (up to 90%).
- Lead dust generated during the removal of lead-based paint and activities that disturb lead-based paint coated surfaces.
- 1971 - Lead-Based Paint Poisoning Prevention Act restricted use of lead-based paint in federally-funded housing and provided funding to identify and eliminate high-risk lead-based paint exposures in homes.
- 1978 - US Consumer Products Safety Commission bans use of >0.06% by weight lead in paints used on consumer products and residences.
- 1992 - Residential Lead-Based Paint Hazard Reduction Act initiated a multi-agency order to begin eliminating lead-based paint exposure in residential housing.

Joining or cutting metals using heat (various industries)

- Lead fumes and dust generated during metal joining or cutting with heat (weld, braze, solder, torch cut) when the metal contains lead or is coated lead-based paint or lead-containing materials.
- Amount of lead fumes increases with increasing process temperature.
- Fine lead oxide dust generated at surface during lower temperature operations such as soldering.

Leaded gasoline vehicle emissions (various industries)

- Lead alkyls (i.e., tetraethyl lead) added to gasoline from the 1920s; lead fumes and dust generated during combustion.
- 1973 - EPA regulations gradually reduce the lead alkyl content in gasoline.
- 1995 - EPA regulations prohibit leaded gasoline for on-road vehicles.

Industries (SIC^{2a})**Agricultural industry (SIC2:01)**

- Lead arsenate insecticides used in orchards until the 1960s; lead dust generated during pesticide application and fruit handling.

Construction industry (SIC2:15–17)

- Lead-containing building materials are common: terne metal roofing and flashing, industrial and gas tank linings, lead pipe caulking, water pipes, soundproofing material, vibration-dampening material, and ionizing radiation shielding.
- Lead dust generated during grinding, sanding, and cutting activities of lead-containing building materials.
- Uncoated metallic lead develops a lead oxide powder coating that can be dislodged when handled.
- 1986 - Safe Drinking Water Act restricts use of lead solder or flux to <0.2% and lead pipes and fixtures to <8%; lead pipes still used in industrial settings for transporting corrosive materials.

Printing industry (SIC2:27)

- Lead alloys commonly used to make type and plates for letterpress printing.
- Lead pigments used in newspaper and magazine color inks.
- Lead fumes and dust generated during melting, pouring, and casting operations; lead dust generated during type and plate trimming and finishing.
- <1900s- Lead used in typeset for letterpress printing.
- 1960s- Newspapers begin replacing hot metal typesetting processes with offset and computer typesetting.
- 1970s- American Newspaper Publisher Association (ANPA) prohibits use of lead pigments in ANPA-approved inks.
- 1980s- Most newspaper lead typeset printing replaced by offset and computer typesetting.

Chemical and allied product manufacturing (SIC2: 28)

- Organic and inorganic lead compounds used during fuel additive manufacture and blending operations and in pigment and paint manufacture.

- Lead compounds were commonly used as PVC plastic stabilizers, rubber compounders and accelerators, and as plastic and rubber pigments.
- Lead dust generated while handling powdered feedstock during blending and compounding operations.

Ceramics industry (SIC2: 32)

- Lead used in ceramic and porcelain glazes and enamels; lead dust generated during powdered lead compound handling and spray application.

Glass making industry (SIC2:32)

- Lead oxides added to crystal, optical, and radiation shielding glass; strips of metallic lead alloy used to hold pieces of stained glass together; lead fumes and dust generated during handling and grinding, engraving, and polishing operations.

Primary and secondary metal production (SIC2:33)

- Lead naturally occurs in metal ores; exposures frequently occur during primary smelting and refining of lead, copper, zinc, and other metals and during the production of metal alloys such as brass, bronze,terne, and leaded steel.
- In secondary refineries, lead can be present in scrap metals; secondary lead refineries predominantly reclaim lead-acid storage batteries.
- Lead fumes and lead oxide dust generated during melting and pouring operations, fire assaying, bag house operations, and scrap metal processing.

Metal product manufacturing (SIC2:34, 35, 38, 39)

- Metallic lead used in the manufacture of lead sheeting, panels, pipes and lead alloy products.
- Lead used in metal heat treatments (e.g., annealing, patenting) and surface treatments (e.g. tinning, electroplating, galvanizing).
- Lead fumes and dust generated when activities such as grinding, sanding, cutting, or burnishing disturb lead-containing materials.

Lead-acid battery manufacturing (SIC2:36)

- Metallic lead plates and lead oxide paste used to form positive and negative metal plates.
- Lead dust generated during plate casting, pasting and assembly operations.

1950s - Lead acid batteries become the largest end use of lead by US industry.

Electric and electronics manufacturing (SIC2:36)

- Lead commonly used in solders and bearings; lead-containing glass used as vitreous enamel coating on electronic components.
- Lead dust generated during dipping, sandblasting, sanding, and soldering operations.

Telecommunications (SIC2:48)

- Lead commonly used as protective lead sheathing around cable wires and in plastic cable coating; lead dust generated during cable splicing and repair and during cable recycling operations.

Waste incineration (SIC2:49)

- Lead-containing products commonly found in the incinerated municipal waste stream, including batteries, lead-based paint- or ink-coated items, electronic devices, leaded glass, and plastics; lead dust generated during contact with lead-contaminated incineration fly ash.

Firing ranges (SIC2:79, 92)

- Lead extensively used in firearm bullets and primer compounds; lead dust generated at the firearm muzzle and as the bullet strikes a surface.
- Lead exposures substantially lower with jacketed bullets.

^aSIC2, 2-digit SIC1987 standardized industry classification code (OMB 1987).

Key references: IARC 2006; EPA 2006; Hamilton 1974, OSHA 2007.

Table III

Lead-based paint: number of papers, summary statistics and measurements of personal air and blood lead concentration for measurements collected in activities associated with lead-based paints by industry (1970), with corresponding weighted arithmetic means (WAMs 1970).

Industry/Activity (SIC 2 ^a)	Personal air ^b					Blood ^b				
	N papers	N summary statistics	N msmt	WAM 1970 (µg/m ³)	AM range (µg/m ³)	N papers	N summary statistics	N msmt	WAM 1970 (µg/dL)	AM range (µg/dL)
All lead-based paint measurements	26	138	2773	348	<1–23300	23	64	2982	14	3–99
Construction (SIC2:15–17)	20	83	2138	300	<1–23300	16	34	2075	16	4–99
Lead-based paint removal work	15	64	1799	314	<1–23300	10	19	1499	18	4–99
Other activities	6	19	339	227	2–420	7	15	576	10	4–32
Shipyard (SIC2:37)	3	44	260	1020	1–3850	3	16	743	9	4–13
Lead-based paint removal work	3	44	260	1020	1–3850	2	13	602	9	5–12
Other activities	-	-	-	-	-	2	3	141	6	4–10
Automobile manufacturing (SIC2:37)	1	1	309	188	188	-	-	-	-	-
Autobody repair (SIC2:75)	1	4	17	20	11–40	1	7	21	11	3–18
Custodial service (SIC2:75)	1	6	49	2	<1–4	1	1	13	5	-
Furniture restoration (SIC2:76)	-	-	-	-	-	2	6	40	30	14–74

AM, arithmetic mean; msmt, measurements; N, number; WAM 1970, weighted arithmetic mean for summary statistics from 1970 onwards.

^a SIC2 refers to the 2-digit 1987 Standard Industry Classification (SIC) codes (OMB 1987).

^b Excludes measurements on office workers.

Joining or cutting metals using heat: number of papers, summary statistics, and measurements of personal air and blood lead concentrations for measurements collected in activities related to welding, brazing, thermal cutting, or soldering by industry (1970), with corresponding weighted arithmetic means (WAMs 1970).

Table IV

Industry/Activity (SIC 2 ^a)	Personal air ^b					Blood ^b				
	N papers	N summary statistics	N msmt	WAM 1970 (µg/m ³)	AM range (µg/m ³)	N papers	N summary statistics	N msmt	WAM 1970 (µg/dL) ^b	AM range (µg/dL)
All joining or cutting metals measurements	26	57	983	727	1–30000	26	47	1793	24	3–86
Construction (SIC2:15–17)	13	19	270	2520	3–30000	12	27	897	24	3–86
Bridge	6	9	94	1340	193–30000	4	7	305	15	3–77
General	2	2	7	20	3–27	1	3	260	5	3–6
Heavy	3	4	112	3620	745–1110	3	7	137	41	7–51
Lead sheet/plate installation or removal	2	2	13	614	270–1160	1	2	34	28	22–34
Railway	1	2	44	3230	230–4360	3	8	161	54	28–86
Electric and electronics manufacturing (SIC2:36)	-	-	-	-	-	1	3	40	33	26–34
Shipyard (SIC2:37)	2	6	25	206	1–367	2	2	34	19	11–38
Automobile assembly manufacturing (SIC2:37)	1	3	508	18	3–19	1	1	5	44	-
Scrap Metal Recycling (SIC2:50)	2	2	15	315	100–560	2	2	26	22	20–27
Automobile repair (SIC2:75)	7	26	125	111	2–1060	7	12	791	25	20–52

AM, arithmetic mean; msmt, measurements; N, number; WAM 1970, weighted arithmetic mean for summary statistics from 1970 onwards.

^a SIC2 refers to the 2-digit 1987 Standard Industry Classification (SIC) codes (OMB 1987).

^b Excludes measurements on office workers.

Table V

Other activities: number of papers, summary statistics, and measurements of personal air and blood lead concentration for activities related to other lead exposures (excludes lead-based paint, joining/cutting metals, leaded gasoline exhaust) by industry (1970), with corresponding weighted arithmetic means (WAMs 1970).

Industry/Activity (SIC 2 ^a)	Personal air ^b					Blood ^b				
	N papers	N summary statistics	N msmt	WAM 1970 (µg/m ³)	AM range (µg/m ³)	N papers	N summary statistics	N msmt	WAM 1970 (µg/dL)	AM range (µg/dL)
Primary and secondary metal production (SIC2: 33)										
Brass foundry	7	6	33	434	54–1600	2	16	166	40	23–66
Bronze foundry	2	12	197	80	12–106	-	-	-	-	-
Copper smelter worker	-	-	-	-	-	1	1	169	33	-
Lead smelter, primary	1	1	203	3100	-	3	4	481	54	29–57
Lead smelter, secondary	3	5	62	248	102–2660	9	30	605	66	36–104
Precious metals refinery, primary	1	5	6	4	2–6	1	4	45	35	19–61
Precious metals refinery, secondary	1	2	2	80	60–100	-	-	-	-	-
Zinc smelter worker	-	-	-	-	-	1	1	194	39	-
Metallurgical laboratory	1	2	18	232	63–340	1	1	20	37	-
Other manufacturing industries										
Automobile assembly (SIC2:37)	1	10	2047	31	3–297	1	9	369	45	33–69
Lead acid battery manufacturing (SIC2:36)	6	89	636	55	2–1980	8	43	7529	42	12–50
Electric and electronics manufacturing (SIC2:36)	-	-	-	-	-	2	2	105	35	32–47
Chemical and allied product manufacturing (SIC2:28)										
Fuel additives	1	2	64	63	19–54	3	5	499	24	19–40
Inorganic lead	-	-	-	-	-	1	1	19	72	-
Pigments	-	-	-	-	-	1	1	36	32	-
Polyvinyl chloride	1	3	57	65	9–251	3	6	84	41	17–127
Firing range (SIC2:79, 92)	9	12	96	303	6–8640	11	27	243	31	6–125
Jacketed bullet use	3	3	10	32	6–135	3	3	13	18	6–31
Unjacketed bullet use	8	9	86	334	12–8640	10	24	230	32	6–125
Other workplaces										
Telecommunications (SIC2:48)	-	-	-	-	-	1	1	90	28	-

Industry/Activity (SIC 2 ^a)	Personal air ^b					Blood ^b				
	N papers	N summary statistics	N msmt	WAM 1970 (µg/m ³)	AM range (µg/m ³)	N papers	N summary statistics	N msmt	WAM 1970 (µg/dL)	AM range (µg/dL)
Cable recycling (SIC2:33)	1	11	23	1580	12–8520	1	5	36	65	31–124
Waste incinerator (SIC2:49)	-	-	-	-	-	1	1	56	11	-
Stained glass production (SIC2:73)	-	-	-	-	-	1	1	12	21	-

AM, arithmetic mean; msmt, measurements; N, number; WAM 1970, weighted arithmetic mean for summary statistics from 1970 onwards.

^a SIC2 refers to the 2-digit 1987 Standard Industry Classification (SIC) codes (OMB 1987).

^b Excludes measurements on office workers.