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Decision rule approach applied to estimate occupational lead exposure in a case-control study of kidney cancer

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Abstract

Background: We developed a systematic, data-driven approach to estimate metrics of occupational exposure to lead to aid in epidemiologic analyses in a case-control study of kidney cancer.

Methods: Probability of exposure to ten lead sources was assigned using decision rules developed from an extensive literature review and expert judgement. For jobs with 50% probability of exposure, we assigned source-specific frequency based on subjects' self-reported task frequencies or means of subjects' job-groups and source-specific intensity estimates of blood lead (µg/dL).

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AUTHORS' CONTRIBUTIONS

All authors contributed to the acquisition, analysis, or interpretation of data for the work. CLC, SJL, and MCF drafted the work and all authors contributed to revising the work critically for important intellectual content and provide final approval of the version to be published; and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

ETHICS APPROVAL AND INFORMED CONSENT

The study was approved by the institutional review boards at the NCI and the participating institutions, and study participants provided informed consent.

DISCLOSURE (AUTHORS)

P. S. is employed by Stewart Exposure Assessments, LLC (Arlington, VA, USA); the remaining authors declare they have no actual or potential competing financial interests.

DISCLOSURE BY AJIM EDITOR OF RECORD

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DISCLAIMER

None.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Results: In our study, 18.7% of employed person-years were associated with high (>80%) probability of exposure to any lead source. The most common medium (>50%) or high probability source of lead exposure was leaded gasoline (2.5% and 11.5% of employed person-years, respectively). The median blood lead attributed to occupational exposure was 3.1 µg/dL.

Conclusions: These rules can aid in future studies after population-specific adaption for geographic differences and different exposure scenarios.

Keywords

decision-rules; exposure assessment; lead; occupational exposure; population-based studies

1 | INTRODUCTION

The breadth of occupations and time periods encompassed in population-based case-control studies make it infeasible to collect measurements of exposures from participants' past workplaces. These studies often rely on expert review of participants' responses to lifetime occupational history questionnaires and more detailed job- or industry-specific questionnaire modules to assign subject-specific exposure estimates, that is, job-by-job review.¹ The rationale for exposure estimates assigned by expert review is rarely published and has often been criticized for its lack of transparency, which makes it difficult to determine the consistency of an expert's assessments over time and job titles or whether review by a different expert would yield similar estimates.^{2,3} An advantage of expert review over generic job-exposure matrices (JEMs) is that this method better accounts for subject-level differences in reported work tasks. However, since there is no mechanism to apply the decision rules of one expert to other studies, expert review is less efficient and reproducible than JEMs. To overcome the limitations of traditional job-by-job expert review, a growing body of research developing and reporting decision rules that systematically link questionnaire responses to exposure estimates has emerged. These systematic decision rule-based approaches have yielded exposure estimates similar to a job-by-job expert review.⁴⁻⁸

Lead is a metal that has been widely used in a variety of industrial settings and has been associated with a multitude of adverse health effects including nervous system, kidney, and liver damage.⁹ Lead exposure has been associated with kidney cancer in some epidemiologic studies,¹⁰⁻¹² but not others.¹³⁻¹⁵ However, the exposure assessment methods of these studies have varied, with several studies using generic JEMs or job-by-job expert review.^{12,14,15}

We developed decision rules to assign estimates of the probability, frequency, and intensity of occupational exposure to lead for participants in the US Kidney Cancer Study (USKC), a population-based case-control study of renal cell carcinoma (RCC). These rules incorporated participants' responses to a lifetime occupational history and for selected jobs, a detailed job- or industry-specific module that asked participants questions regarding work activities involving potential exposure to lead and other suspected carcinogens. The purpose of this article is to describe our systematic, transparent approach in developing and applying the decision rules to estimate occupational exposure to lead for USKC participants to facilitate the exposure assessment process, and to aid other researchers with similar exposure information.

2 | METHODS

2.1 | Study population and occupational information

USKC is a population-based case-control study conducted in Detroit and Chicago, the details of which have been described previously.¹⁶ Briefly, Detroit RCC cases were identified via the Metropolitan Detroit Cancer Surveillance System from February 2002 until July 2006 (white cases) or January 2007 (black cases). Chicago RCC cases were identified in 2003 through a review of pathology reports from 56 hospitals in Cook County, IL. This study included 1217 cases of RCC and 1235 controls frequency matched on sex, age (five-year intervals), and race. The study was approved by Institutional Review Boards at all institutions, and written informed consent was obtained from all participants before interview.

Occupational information was collected from each participant by a computer-assisted personal interview administered in the home by a trained interviewer.¹⁷ Prior to the home visit, participants were mailed a work history calendar asking them to list each job they held for at least 12 months since the age of 16. During the interview, participants used the work history calendar to provide free-text responses to questions that asked the job title, employer name, job start year and stop year, product made or service provided by employer, work frequency, main activities or duties, the tools and equipment used, and the chemicals or materials used. Each individual job a subject held was assigned a four-digit 1980 Standard Occupational Classification (SOC) code¹⁸ and a four-digit 1987 Standard Industrial Classification (SIC) code.¹⁹

Free-text responses to the occupational history triggered additional exposure-oriented occupation/industry-specific modules based on a search for key words linked to 36 occupations or industries; the interviewer selected the most relevant module if the search suggested multiple modules for a job. The generic exposure module was assigned if no other module was suggested by the keyword search or if the interviewer was unsure of which module to assign. To minimize participant burden, a module was asked only if the job was held for a minimum of 3500 working hours, and a maximum of five modules per participant were administered. The modules that directly or indirectly asked about potential lead exposure by source of lead exposure are presented in Supplemental Table S1. These modules are available upon request from the corresponding author. The years of employment coverage were from 1939 to 2007.

2.2 | Exposure assessment

We used a three-phase process depicted in Figure 1 to derive subject-level annual estimates of probability, frequency, and intensity of occupational lead exposure.

2.2.1 | Phase 1: source-specific probability of exposure for each job a

subject held—In the first phase, probability of exposure to ten categories of lead sources was evaluated for each job a subject reported in their work history: paint, gasoline, grinding metal, solder, welding, engine repair, pigments, guns, printing, and “other.” Probability of exposure was defined as the estimated proportion of workers exposed above the general

population background levels. The estimated source-specific lead probability was assigned using the following four-category ordinal scale: none (0 to <5% of workers exposed), low (5% to <50% of workers exposed), medium (50–80% of workers exposed), or high (80% of workers exposed).

We applied time-period and source-specific decision rules using expert judgment based on extensive review of both published and gray literature.²⁰ Two experts with graduate level training and over 15 years of professional experience in occupational hygiene developed consensus-based rules. These source decision rules were developed based on the following components: occupation title (ie, SOC 1980); industry title (SIC 1987); responses from 31 lead-relevant modules (Supplemental Table S1); and variables extracted from free-text of occupational history responses and metal-relevant modules. The systematic extraction of lead-related information from the free-text responses of occupational histories was previously described²¹ and resulted in 110 variables identifying occupations (44 variables), industries (32 variables), and activities (34 variables) with possible lead exposure.²¹

The rules to assign probability of lead exposure were designed to be applied using a hierarchical assignment procedure for each lead source: rules for the highest category were assigned first, then rules for the medium category were applied to jobs that did not meet criteria for high probability, and then rules for the low category were applied to jobs that did not meet criteria for medium or high probability. The decision rules flagged jobs with combinations of variables that could not be assigned a single probability rating because of potential exposure heterogeneity (249 jobs with a module and 674 without a module) for job-by-job review. For example, a machine operator job that included fabricating metal parts as a task would be flagged for review because the types of metals fabricated vary by machine type.

Time-trend modifications to the probability estimates were incorporated to address the gradual removal of lead from products over time. For example, if a subject's job involved exposure to gasoline before 1990, the probability of exposure to lead from gasoline was assigned as high; if that job occurred between 1990 and 1994, probability of exposure was assigned as medium; and if that job occurred after 1995, the probability of exposure to lead from gasoline was assigned as none.

The criteria for assigning a job high probability of exposure for specific sources of lead are presented in Table 1. Full decision rules for expert-based probability assignments to each lead source are reported in Supplemental Table S2. There were no explicit exposure rules that would lead to assignment of high probability of exposure to lead for engine repair or "other" lead sources because these activities were not directly asked about in the modules; however, these sources may have been assigned a high probability during job-by-job review. Probability of exposure to lead via pigments and printing was based on job-by-job review because few subjects reported these tasks and exposure scenarios were highly variable.

Other jobs were also included in the job-by-job review if they met any of the following criteria: (i) jobs assigned the tile setter or electroplating, textile, foundry, printing, dry cleaning/laundry, pulp and paper, ammunition, leather, oil refining, battery manufacturing,

or rubber industry modules and also had possibly lead-exposed jobs (eg, maintenance) or performed possibly lead-exposed tasks (eg, welding); (ii) jobs assigned the chemical industry module if the subject reported working in an area where paints, plastics, or inks were made or was in a possibly lead-exposed job or performed possibly-exposed tasks; and (iii) jobs assigned the teacher module if the subject was an art, chemistry, or trades. All jobs with source-specific ratings of “none” for all 10 source categories, but that included positive identification of a variable in the occupational history identifying a possibly lead-exposed occupation or task that was not otherwise covered by decision rules were also reviewed individually.

2.2.2 | Phase 2: source-specific frequency and intensity for each job a subject held with medium or high source-specific probability of exposure—

Annual source-specific frequency and intensity estimates were assigned for a job only when the source-specific probability estimate was medium or high (50% of workers exposed). This phase comprised assigning frequency and intensity estimates to 706 jobs reported by subjects without modules and 2050 jobs reported by subjects with a module.

The sources of frequency information were prioritized as: (i) the number of hours the subject reported for a given lead activity from the module responses; (ii) the job-means of the module responses applied to jobs with missing frequency; and (iii) expert judgment when job-means were not available. Expert judgement was used to assign frequency estimates for lead exposure from engine repair and gasoline because the frequency of these activities and exposures were not asked in the modules. If the assigned source-specific frequency was less than 0.5 h per week, we lowered the source-specific probability to low (5% to <50%) and did not assign an exposure intensity.

Source- and time-specific intensity estimates of occupational lead exposure were based on blood lead concentration because the half-life of lead in blood is approximately 1 month²²; thus blood lead generally represents a measure of average internal lead dose for recent exposures. Source-specific base intensity estimates of blood lead ($\mu\text{g/dL}$) for the year 1980 (unless otherwise noted) were assigned after conducting a comprehensive review of published blood lead measurements that included estimates of arithmetic means (weighted for the number of measurements) reported by 351 sets of summary statistics²⁰; industry-specific temporal evaluations²³; more detailed statistical analysis of a subset of data associated with activities disturbing materials painted with or containing lead²⁴; and lead source-specific statistical analyses when sufficient blood lead measurements were available.

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The 1980 base intensity estimate, the associated time trend, and the source of these estimates (published data vs expert judgment) for each lead source are presented in Table 2. Time-trend estimates were based on industry- and time-specific meta-regression models using a database of published blood lead estimates for most sources.^{23,24} Time-trends were held constant at the 1975 value for years prior to 1975 due to limited blood lead data from earlier time periods. Whenever possible, expert judgment of intensity estimates was based on extrapolation from similar scenarios with published blood lead measurements.

Job-by-job review was used to assign base intensity and frequency estimates for jobs with medium or high probability of lead exposure from “printing,” “pigments,” and “other” lead sources (122 jobs). Additionally, an expert reviewed the base intensity and frequency estimates for 30 jobs with a module and 162 jobs without a module when, compared to jobs in the same occupation group, the frequency or intensity estimate was above the 75th percentile of the occupation group estimates or when an atypical module response was observed.

For each occupational lead source, the source-specific blood lead concentration attributed to occupation for each year y , and from each occupational source s was calculated as described below in Equation 1. Equation 1 subtracts the annual median population-level blood lead estimate predicted from NHANES data (Supplemental Table S3), which we considered to be environmental lead exposure, from the occupation or activity-specific blood lead estimate.

$$\begin{aligned} \text{Concentration}_{sy}(\mu\text{g/dL}) = & \left[\left(\text{Base Intensity Estimate for 1980s } (\mu\text{g/dL}) \right. \right. \\ & \times \text{Time Trend modifier}_y \left. \right) \\ & - \text{NHANES Median Blood Lead Estimate}_y \left. \right] \\ & \times \left[\frac{\text{\#Hours Performing Activity}}{40 \text{ Hours/Week}} \right] \\ & \times \frac{\text{\# Weeks per Year}}{52 \text{ Weeks}} \end{aligned} \quad (1)$$

For example, if a subject who completed the welding module reported welding in a general construction industry job in 1979 for 5 h a week, the estimated blood lead concentration from the welding would be as follows, assuming a 1980 base intensity estimate of 13 $\mu\text{g/dL}$ (Table 3) and a NHANES median blood lead estimate of 10 $\mu\text{g/dL}$ (Supplemental Table S2):

$$\begin{aligned} \text{Concentration}_{\text{welding},1979}(\mu\text{g/dL}) &= [(13 \times 1.06) - 10] \times [5/40] \\ &= 0.47\mu\text{g/dL} \end{aligned}$$

For each year, a total annual lead concentration attributed to occupation was calculated by summing all source-specific annual concentration estimates.

Phase 3: subject-specific exposure metrics—The annual source-specific and total lead concentration metrics for each job held were integrated to develop subject-level lead exposure metrics. Overall probability of lead exposure for each job and calendar year was assigned as the highest probability rating from any source for each subject.

For participants with 50% overall probability of lead exposure the following metrics were assigned: *duration of exposure (years)*, defined as the sum of the number of years worked at each job with an exposure probability 50%; *maximum lead exposure* ($\mu\text{g/dL}$), defined as the highest estimated annual blood lead concentration attributed to occupation from all jobs with an exposure probability 50%; *cumulative exposure* ($\mu\text{g/dL}$): defined as the sum of estimated annual blood lead concentrations attributed to occupation from all jobs with an exposure probability 50% weighted by the years in each job; and *average yearly exposure* ($\mu\text{g/dL/year}$), defined as cumulative exposure divided by duration of exposure. We also

calculated the exposure metrics described above based only on jobs with a high (80%) probability of exposure. All exposure metrics incorporated a five-year lag. Metrics incorporating a 10- and 15-year lag were also developed for epidemiologic sensitivity analyses.

3 | RESULTS

Of the 11 991 jobs reported by the participants, 7024 jobs (59%) triggered one of 31 modules that contained questions directly or indirectly related to lead exposure. The generic exposure module was applied to the largest number of jobs (4749, 40%) (Supplemental Table S1). The generic exposure module included several questions regarding lead activities, of which 4–12% of the jobs given this module had affirmative responses (Table 3) that led to questions regarding the frequency and type of activity. Medium or high probability of lead exposure was assigned to 2588 of the 11 991 jobs (22%), which was attributable to one source for 1978 jobs (16%), two sources for 156 jobs (3.7%), and three or more sources for 156 jobs (1.3%) (not shown).

The numbers of employed person-years by source-specific probability of lead exposure are presented in Table 4. The most common medium or high probability source of lead exposure was leaded gasoline (2.5% and 11.5% of employed person-years respectively). Solder and paint were also common sources of high probability of lead exposure (4.1% and 3.5% of employed person-years). In our study, 18.7% of employed person-years were associated with high probability of exposure to any lead source. Of employed person-years with a medium or high probability of exposure, the median blood lead attributed to occupational exposure was 3.1 µg/dL above background. Thirty-seven percent of person-years with medium/high exposure probability and 41% with high exposure probability occurred prior to 1975 and did not incorporate time-changes in lead exposure intensity.

Percentiles of source-specific annual intensity estimates are also presented in Table 4. Pigments were associated with the highest median intensity of exposure above background among jobs with a medium or high probability of exposure (12.4 µg/dL) and grinding with the highest median intensity of exposure above background among jobs with a high probability of exposure (10.5 µg/dL). Lead exposure from guns was associated with both the lowest median intensity of exposure above background for medium and high or only high probability sources (0.8 µg/dL in both instances).

4 | DISCUSSION

We used a systematic method to develop estimates of probability, frequency, and intensity of 10 categories of occupational lead exposure sources individually and combined, in a population-based case-control study. Our approach using participants' responses to job/industry-specific modules allowed us to identify participants conducting various lead-related work tasks and to capture subject-specific variability in the frequency of those tasks with the intention of reducing exposure misclassification to improve on estimates based on generic JEMs. Our data-driven decision rules are transparent and reproducible and may result in less or similar bias from exposure misclassification than job-by-job assessment alone.

Furthermore, these rules will be useful in sensitivity analyses of exposure-disease associations.

Our approach was similar to previous decision rule-based exposure assessment efforts.^{4-6,25-28} We prioritized data-driven estimates and individual-level data wherever possible like Park et al and Friesen et al's assessment of occupational exposure to metalworking fluids.^{25,28} A unique feature of this effort was that we developed decision rules to assign exposure estimates separately for 10 categories of lead exposure sources (ie, paint, gasoline, grinding metal, solder, welding, engine repair, pigments, guns, printing, and "other"), which were then combined into an overall lead estimate for each job a participant held. Additionally, we based intensity estimates on blood lead measurements from the published literature,²³ which accounts for multiple routes of exposure (eg, inhalation, dermal, and ingestion) and effectiveness of personal protective equipment and personal hygiene practices.²³

Probability estimates were based on information extracted from both the occupational history responses and job- and industry-specific module information. This is one of the few studies to systematically incorporate variables extracted from free-text occupational history responses in addition to the job-specific modules in a programmable decision rule process.^{4,25} This free-text information has been traditionally only used in job-by-job review. We have previously reported that systematic extraction of variables from occupational history responses identified an additional 9–14% possibly exposed jobs than considering occupation title and industry alone,²¹ a procedure that often has been used when applying generic JEMs. However, we believe this method identified, at best, only the most common and frequently occurring tasks, tools, and chemicals for a job²¹ and is thus more specific than sensitive.

Frequency estimates were based on participants' module responses wherever possible or median job group responses when more detailed information was not available. This data-driven approach limited the amount of expert review required, while providing subject-specific estimates or group estimates specific to this population. Furthermore, using group-based assignment approaches has previously been reported to follow a Berkson error structure that is unlikely to bias risk estimates.²⁹ We observed a higher prevalence of exposure to lead than in other studies (eg, 6% ever exposed in study by van Bemmelen et al³⁰ compared to our 48% (all subjects), which could be because our study took place in cities that were part of the US manufacturing core. However, our exposure assessment method identified subjects who participated in a low frequency of lead-related activities. This approach enables the exclusion individuals with nominal exposures from the referent group. In addition, we accounted for subject-specific frequency of exposure for those completing modules, which identified additional contrast in exposure that would be masked by solely applying population-level patterns, thus reducing exposure misclassification.

Intensity estimates were based wherever possible on statistical models derived from a comprehensive review of 351 summary statistics of blood lead measurements collected over multiple decades.^{20,24} Measures of lead in air and blood have been reported to be poorly correlated in occupational settings.^{31,32} This method allowed us to consider multiple routes of exposure beyond inhalation, account for changes in workplace behaviors over time (eg,

increasing use of protective equipment), account for variability in physicochemical characteristics of the lead exposure (eg, particle size, lead compound present), which influences solubility in bodily fluids,³³ and identify source-specific levels of exposure.

We used expert judgement to transparently account for within-job heterogeneity in probability, frequency, and intensity of exposure of jobs obtained from the detailed module responses that could not have been captured using generic JEMs or analyses by job title, industry, or duration. We had a systematic approach for assigning jobs for job-by-job review to account when necessary for within-job heterogeneity or rarely occurring exposure scenarios. Our approach estimated lead exposure metrics separately for ten sources, with 16% of jobs having one source with 50% probability and 5% of jobs having two or more sources. This source-specific method simplified the application of programmable decision rules and the aggregation of exposure from multiple sources that would otherwise be conducted one at a time in a job-by-job review. We have developed several metrics that can be used in epidemiologic sensitivity analyses, including investigation of sources with 80% probability of lead exposure, source-specific lead exposure metrics, and consideration of 10- and 15-year lags.

Our decision rule process was time-consuming to develop but using our rules will be less time and resource intensive than a job-by-job expert review in future studies of lead exposure that have incorporated questions about participants' work tasks. These decision rules can also be used by researchers to design questions to evaluate lead exposure in future population-based studies. However, our study setting was Detroit, MI, and Chicago, IL in the United States; thus, our approach would require adaptation for geographic differences, decade differences, and exposure scenarios not found in this population before application to other study settings. Exposure assessments in settings other than the United States may require additional data extraction from relevant literature. Similarly, time-trend modifications and population-level blood lead estimates may require different approaches depending on the study setting. In addition, the subject-level probability and intensity estimates developed for this study could also be aggregated to derive median estimates for a lead JEM that could be used in studies without more detailed work task information, in a similar manner to the development of CANJEM from previously made job-by-job exposure assignments for a variety of agents.³⁴

There are limitations of our method that should also be considered. The decision rules were based on self-reported work activities and their frequency, which is an improvement upon self-reported exposure checklists, but may still be subject to some recall bias; however, the exposure assessment process was conducted blind to case-control status. The blood lead data used to derive estimates of exposure intensity were not specific to participants' workplaces and the decision rules were based on determinants that could be easily recalled by participants. Similarly, the process relied on participants' recall of workplace activities and their frequency, oftentimes decades after employment.

Furthermore, since we did not monitor participants' workplaces directly, did not validate the estimates of blood lead, and had no information on other important determinants (eg, protective equipment, ventilation controls) that would raise or lower the assigned blood lead,

the absolute values should be interpreted with caution. The emphasis should be on relative differences within the study population. Our estimates of blood lead were extracted from the published literature as summary statistics rather than individual measurements, which requires the use of statistical modeling to account for within and between study variability in exposure.²³ The reasons for measurement of blood lead varied and, while known occurrences of blood poisoning events and other worst-case events were omitted, the extracted measurements may not be representative of typical workplace exposures.²⁰ The half-life of lead in blood is 30 days, but stored lead in bone is released over time into the blood stream.³⁵ Thus, published measures of blood lead may reflect historic exposures in addition to job/industry/activity/decade that they were associated with in the databases.

Additionally, our method does not distinguish organic from inorganic lead. Finally, before 1975 we assigned the same intensity values as in 1975; thus, earlier exposures may be underestimated. While it is unlikely that the rank order of exposure intensity estimates would be impacted by this limitation, we can explore the impact of alternative time trend patterns on exposure-response associations in future etiologic analyses.

In conclusion, we describe a framework for estimating probability, frequency, and intensity of occupational lead exposure for 10 lead sources in a case-control study. We systematically used published blood lead summary measurements and applied a hierarchical, data-driven approach that utilized individual-level module data and transparent decision rules wherever possible and applied job-by-job review when necessary. Our approach accounted for some of the likely within-job heterogeneity that would not have been identified using generic JEMs or estimates based on job title, industry, or duration alone. The decision rules presented here may assist other researchers in efficiently assessing lead exposure in epidemiologic studies with similarly detailed occupational information or in job-by-job review, as well as aid researchers in developing occupational questions for lead exposure in future studies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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FIGURE 1.
Schematic of lead exposure assignment decision process

TABLE 1

Decision rules for high source-specific probability of lead exposure assignment

Source ^a	Time-period modification ^b	Task or job ^c	Applicable modules
Paint	Manufacturing industries affected by 1978 lead paint ban ^d 1980–1989 = Medium; 1990+ = Low	Job = Painter and/or Task (MOD, OH) = Paint, strip paint, use/mix/test paint	Any
Gasoline	1990–1994 = Medium; 1995 + = None	Job= Police/security, Military occupations, driver, gasoline station attendant, or mechanic and/or Task (MOD, OH) = Driving, bystander to vehicle exhaust, fill vehicle with fuel, use gasoline-powered equipment	Any
Grinding metal	NA	Task (MOD) = Grind or machine metal that contained lead	Machinist, generic exposure ^e
Solder	NA	Task (MOD, OH) = Solder, or work near others soldering	Any
Welding	NA	Task (MOD) = Welded leaded steel, brass/bronze	Electrician, handyman, industrial machine repairer, machinist, mechanic, welder, or generic exposure ^e
Guns	NA	Job= Military or Police	Any

Rules for other probability levels are available in Supplemental Table S2.

^aProbability of exposure to lead via pigments and printing were assigned via expert review and do not have explicit decision rules. There were no explicit exposure rules that would lead to assignment of high probability of exposure to lead for engine repair or “other” lead sources.^bAll jobs were assigned a 1980 Standard Occupational Classification (SOC) code [18] and a 1987 Standard Industrial Classification (SIC) code [19]; SIC3 refers to the first three digits and SIC4 refers to the entire code.^cSources of information: OH, occupational history; MOD, module.^dThose manufacturing industries where the US Consumer Products Safety Commission’s 1978 regulation (https://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title16/16cfr1303_main_02.tpl) banning paint containing >0.06% lead on consumer products would apply; SIC3 = 250 252 253 254 259 363 365 367 376 391 393 394 395 396 399 or SIC4 = 3711.^eThe generic exposure module was implemented if an occupational module was not asked, and the interviewer or the interviewer was unsure of which specific module should be selected.

TABLE 2

Decision rules for estimates of occupational lead exposure intensity and frequency

Source	Industry	Base intensity for 1980 $\mu\text{g}/\text{dL}$ (source) ^a	Annual percent change in intensity (1970) ^b
Engine repair	All	20 (AM)	-6%
Welding	Construction/Repair	20 (M1)	-6% (1970-89); -3% (1990)
	Manufacturing transportation and heavy equipment	18 (EX)	-6%
	Ship building, general/other auto repair	25 (M1)	-6%
	Steel structure construction	36 (M1)	-6%
Gasoline			
Driving	All	Base year, 1970: 25 (M2)	0 (<1975); -6% (>1975)
Vehicle exhaust bystander	All	Base year, 1970: 30 (M2)	0 (<1975); -6% (>1975)
Grinding metal	Ship building	15 (M1)	-6%
	Steel structure construction,	19 (M1)	-6%
	Construction/Repair	15 (EX)	-6% (1970-89); -3% (1990)
	Automotive and small engine repair	31 (EX)	-6%
	Manufacturing, transportation, heavy equipment—Machining	19 (EX)	-6%
	Manufacturing, transportation, heavy equipment—Grinding	38 (EX)	-6%
Paint	Construction/Repair	17 (M1)	-6% (1970-89); -3% (1990)
	Manufacturing, transportation, heavy equipment	23 (EX)	-6%
	General/other auto repair,	47 (M1)	-6%
	Steel structure construction, ship building	44 (M1)	-6%
	Other industries	Estimate from most similar industry; else used midpoint of 30(EX)	-6%
Guns	All	29 (M2) outdoor range; $\times 1.6$ for indoor range and no ventilation; $\times 1.2$ for indoor range with ventilation	0% (<1990); -6% (1990)
Solder	General/other auto repair, transport	40 (M1)	-6%
	Manufacturing, transportation and heavy equipment	27 (M2)	-6%
	Electric manufacturing and repair	18 (M1)	-6%
Printing	Construction/Repair	18 (M1)	-6% (1970-1989); -3% (1990)
Pigments	Job-by-job expert review		
	Job-by-job expert review		

Source	Industry	Base intensity for 1980 $\mu\text{g/dL}$ (source) ^a	Annual percent change in intensity (1970) ^b
Other	Job-by-job expert review		

^aBase intensity estimates are estimated blood lead levels ($\mu\text{g/dL}$) per 40-h work week for the year 1980 (unless otherwise noted) and were based on: AM, weighted arithmetic mean from database in Table III of ref.²⁰; M1: Predicted intensity from Locke et al.²⁴; M2: predicted intensity from unpublished literature review; EX, expert qualitative review based on single exposure paper and/or applied expert-based modifier to data from another industry.

^bTime trend estimates were drawn from predicated time trend in Locke et al.²⁴ for all activities except gun range activities which were based on expert judgement.

TABLE 3

Generic exposure module lead-related questions

Question	Answered		Answered yes (%)	Hours per week if yes percentile		
	N	N		25th	50th	75th
Did any of your activities involve the use of chemicals to clean or degrease metal or plastic parts?	4749	571	12	0.50	2.00	6.00
Did any of your activities involve soldering?	4749	210	4.4	0.25	1.00	4.00
Did any of your activities involve welding, burning, or cutting metal?	4749	180	3.8			
On this job, did you ever weld or flame cut?	180	119		0.22	1.00	6.00
On this job, did you ever braze?	180	62		0.04	0.50	1.00
Did any of your activities involve handling pigments, dyes, colored powders, or dust?	4749	316	6.7	0.30	2.00	12.00
Did any of your activities involve grinding or machining metal parts?	4749	232	4.9	0.25	2.00	6.00
Did any of your activities involve contact with gasoline on your job?	4749	467	9.8			
On this job, did you use a gasoline powered piece of equipment?	467	214		1.00	6.00	24.00

Descriptive statistics of source-specific occupational lead exposure of US Kidney Cancer Study participants

TABLE 4

Employed person-years					Estimated annual blood lead attributed to occupation (µg/dL) ^a													
Source	Probability of exposure				Medium or high probability Percentile							High probability Percentile						
	None	Low	%	Medium	%	High	%	25th	50th	75th	95th	max ^b	25th	50th	75th	95th	max ^b	
Grinding metal	77 613	4310	5.1	1952	2.3	530	0.6	1.4	5.1	14.7	36.5	70	3.8	10.5	22.1	50.3	70	
Gasoline	70 982	1620	1.9	2068	2.5	9735	11.5	1.3	2.3	5.0	11.9	22	1.6	2.7	5.7	12.6	22	
Welding	76 955	4976	5.9	1337	1.6	1137	1.4	0.5	1.8	6.1	21.3	70	0.7	1.9	6.7	34.8	70	
Paint	78 701	2026	2.4	691	0.8	2987	3.5	0.2	0.6	2.2	11.6	70	0.2	0.6	2.4	12.4	70	
Engine repair	82 399	178	0.2	1828	2.2			1.2	3.4	6.7	9.5	19						
Solder	76 507	4307	5.1	101	0.1	3490	4.1	0.2	0.4	1.4	6.2	31	0.2	0.4	1.5	6.3	30	
Guns	81908	2229	2.6			268	0.3	0.5	0.8	3.6	9.7	12	0.5	0.8	3.6	9.7	12	
Printing	83 869	126	0.1	87	0.1	323	0.4	5.0	5.7	20.4	32.5	49	5.0	8.5	25.8	32.5	49	
Pigments	84173	206	0.2	26	0.0			9.8	12.4	14.0	15.5	16						
“Other”	76 758	6928	8.2	562	0.7	157	0.2	4.5	6.1	8.0	14.9	49	5.3	6.8	12.2	34.4	49	
Highest	51834	12 435	14.7	4319	5.1	15 817	18.7	1.0	3.1	7.8	19.3		0.2	1.6	4.8	14.0		
Total concentration								0.8	2.7	7.9	24.3	70	0.5	2.2	5.7	16.1	70.0	

^aEstimated blood lead concentration subtracts the median population-level blood lead estimate estimated from NHANES data.^bHighest possible concentration was 70 µg/dL.