Trends in Occupational Lead Exposure Since the 1978 OSHA Lead Standard

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Background *The purpose of the study was to evaluate trends in occupational lead exposures throughout U.S. industry after the establishment of the general industry lead standard in 1978 and the construction industry standard in 1993.*
Methods *Lead exposure measurements collected by the Occupational Safety and Health Administration (OSHA) under their compliance and consultation programs were analyzed. Time trends in the distributions of exposure levels were evaluated graphically. Trends in the proportion of exposures above the OSHA permissible exposure limit (PEL) were analyzed using logistic regression models.*
Results *The distribution of lead exposure levels declined over the study time period for general industry, but not for construction. The median exposure levels for general industry facilities decreased five- to tenfold. Logistic regression models reveal statistically significant declines in the odds of a lead exposure exceeding the PEL.*
Conclusions *This study provides evidence for relatively large decreases in lead exposure levels in general industry facilities over time. The study does not provide similar evidence for the construction industry. Given the limited number of years of data available since the implementation of the revised construction standard for lead, re-analysis of lead exposure levels within this industry would be worthwhile when more data become available.* Am. J. Ind. Med. 45:558–572, 2004. *Published 2004 Wiley-Liss, Inc.*†

***KEY WORDS:* lead; exposure; OSHA; regulation; inspection; consultation; trends**

INTRODUCTION

Occupational exposure to lead has been widely recognized as a serious health hazard [National Institute for Occupational Safety and Health, 1978; Landrigan, 1990]. Protection of workers from dangerous levels of lead exposure represents a high priority for the Occupational Safety and Health Administration (OSHA) and has been a major target for regulatory intervention since the inception of OSHA in 1970. OSHA set an initial permissible exposure limit (PEL) for lead in 1971 for both general industry and construction [Occupational Safety and Health Administration, 1971a,b], but revised and updated this limit to provide greater protection for general industry workers in 1978 [Occupational Safety and Health Administration, 1978]. This revised general industry lead standard established a PEL of 50 $\mu g/m^3$ (averaged over an 8-hr workday), a quarter of the previous permissible limit of 200 $\mu g/m^3$. OSHA felt that there was insufficient information to resolve issues raised about the applicability of the standard to conditions in the construction industry, and therefore, excluded the construction industry from coverage under the revised standard [Occupational

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Safety and Health Administration, 1978]. In 1993, however, in partial response to the national goal of the National Institute for Occupational Safety and Health (NIOSH) to eliminate worker exposures leading to blood lead concentrations greater than 25 μg/dl, OSHA revised the PEL down to 50 μg/m^3 for the construction industry [Occupational Safety and Health Administration, 1993].

The purpose of this study was to analyze trends in occupational lead exposure levels throughout U.S. industry after the establishment of the general industry lead standard in 1978 and the construction industry standard in 1993, using data that OSHA has collected as part of its compliance and consultation programs. To date, few studies have examined trends in occupational lead exposure levels in U.S. industries. Froines et al. [1990] examined data from OSHA Integrated Management Information System (IMIS) from 1980 to 1985 and found no consistent decline in the percent of airborne lead samples above the OSHA PEL for four of the five high-risk industries examined. A more recent study of OSHA IMIS data by Gomez evaluated 8-hr TWA personal exposures in the lead battery industry and found an average decline of 5–9% per year in mean exposures for the period 1979–1989 [Gomez, 1997]. A number of other studies have used OSHA compliance inspection (CI) data to assess trends in occupational exposure levels to substances other than lead, including silica [Froines et al., 1986; Stewart and Rice, 1990; Freeman and Grossman, 1995], wood dust [Teschke et al., 1999], perchloroethylene [Gomez, 1997], and iron oxide [Gomez, 1997]. In these studies, the OSHA data were used to describe the magnitude of exposure levels within various industries as well as trends in occupational exposure levels over time. The availability of 8–12 further years of lead exposure data warranted this new investigation into the time trends of occupational lead exposure levels following the adoption of the lead standards.

MATERIALS AND METHODS

Data Structure and Organization

Two main sources of data were used for this investigation: OSHA CI records and OSHA health-consultation (HC) records. The CI records obtained are part of the general OSHA regulation enforcement strategy and include inspection records across virtually all industries (not including the mining industry, regulated by the Mine Safety and Health Administration) with sample measurements for many hazardous substances. Programmed (scheduled) and unprogrammed (inspections due to worker complaints or referrals) are all included. These data were available through OSHA IMIS. The HC records are part of OSHA program to encourage voluntary compliance with safety and health regulations. OSHA provides HC to companies requesting aid in achieving compliance. These HC records contain exposure samples for many substances across a variety of companies and standard industrial classification (SIC) codes.

Data were obtained in the form of multiple data files from the two OSHA sources. Within each set of records, unique record numbers identify both individual inspections/health-consultations and samples. Each record contains information including facility specific data, such as number of employees, location, union status, etc.; the substance sampled; sampling technique; exposure level; citations issued; and sample date. Only personal air samples coded as inorganic lead or lead arsenate samples were included in this analysis.

Data were available for the years 1979–1997 for the CI records and 1984–1997 for the HC records. The following types of sample observations were excluded from the analysis: 4,782 samples obtained from follow-up inspections (deleted to reduce the immediate impact of an inspection on future lead exposures in a particular facility), 1,544 duplicate samples (referencing the same record number), 910 samples not recorded with the appropriate measurement type (time weighted average or TWA), 407 samples not recorded in appropriate units (mg/m^3), and 31 samples for SIC codes below 1500 (agriculture operations not included under the lead standards). The lead samples in the OSHA datasets were coded in mg/m^3; translating the OSHA PEL of 50 μg/m^3 to 0.05 mg/m^3. This unit of analysis (mg/m^3) will be used for the remainder of the study. After the exclusions, the CI records included 10,600 inspections with 34,383 personal air samples for inorganic lead or lead arsenate. The HC records included 4,567 health-consultations with 10,423 personal inorganic lead or lead arsenate air samples. The relatively small number of deletions due to potential coding problems (approximately 6% of the total number of samples from non-follow-up inspections) provides some assurance of the appropriateness of the data given that it is always a concern when using data for purposes other than for what it was originally collected.

Analysis

Analyses of occupational lead exposure levels were performed on two levels due to the nature of OSHA CI and HC. During a single inspection or consultation, multiple personal lead exposure samples may be taken with the number and location of these samples determined at the discretion of the inspector or consultant. Therefore, analysis may be done both at the level of the *individual lead sample* and the *inspection or consultation*; with each inspection or consultation having multiple, potentially correlated, lead exposure samples. Since all samples retained in the data are personal samples, analysis at the sample level provides information on a worker-to-worker basis, whereas analysis at the inspection or consultation level provides information on a facility-to-facility basis.

To identify basic trends, several simple data summaries were created. Graphical plots depicting quantiles of lead exposure levels and the proportion of exposures above the PEL plotted over time were created; in these summaries, each exposure sample was weighted equally. Summary statistics were calculated for the samples within each inspection or consultation and the distributions of the median exposure level per inspection/consultation were displayed separately for each calendar year. The percentage of inspections or consultations with at least one exposure sample above the PEL was also plotted over time. All samples taken within a single inspection or consultation were assigned the beginning date of the inspection/consultation to avoid any inspections or consultations from being counted twice if they spanned two calendar years. While most exposure measurements were below 1 mg/m^3, a few ranged into the thousands, skewing the data. Because of the highly skewed nature of the data, as well as the large number (approximately 40%) of the samples that had non-detectable levels of lead, median exposure levels were used to categorize the central tendency for lead levels per inspection or consultation as opposed to mean exposure levels. Modeling of other quantiles of the exposure distribution (e.g., the 75% centile) did not lead to qualitatively different results and thus the trends in the median exposure levels are the focus of this study.

Logistic regression models for correlated binary data [Liang and Zeger, 1986; Pickles, 2002] using generalized estimating equations (GEE) were developed to assess the odds of observing an exposure above the PEL. The primary predictor variable evaluated was calendar year. The other variables included in the datasets were evaluated as potential confounders. For the CI dataset, these variables included facility size (total number of employees), OSHA region, union status (yes/no), and inspection type (programmed/unprogrammed). For the HC dataset, these variables included facility size, OSHA region, and visit type (initial/training and assistance). Because multiple exposure samples were often collected within a single inspection or consultation, a model that accommodated potential correlation between samples from the same facility was considered. These models were fit using the SAS/STAT software procedure GENMOD [SAS/STAT® User's Guide Version 8, 1999].

The cluster was specified at the inspection or consultation level, allowing for the correlation of samples taken during a single inspection or consultation at a facility. The GEE method [Pickles, 2002] was applied under the assumption that there exists a constant correlation between each pair of responses within any given facility, which creates an exchangeable correlation structure for use in modeling. These models represent the logit of the probability that a sample exceeds the PEL as a linear combination of calendar year and the other variables included in the models. In these models, the effect of the confounders is to shift the response-year relationship (i.e., the model intercept). In unreported analyses in which all of the other variables entered the model as potential effect modifiers of the response-year relationship in addition to being potential confounders, some significant interactions between variables (e.g., facility size) and year were observed. However, with rare exception, the direction of the trend was negative with effect size ranging from no change to estimated annual decrements over 25%. Since the effect was in the same direction (a decline in PEL exceedance probabilities over time), the coefficient associated with year in an additive model can be conceptualized as a pooled or average trend over the other variables. The regression coefficient associated with calendar year, when exponentiated, represents the change in the odds of exceeding the PEL from 1 year to the next when all other variables are held constant. This quantity is the main summary measure employed in the Results Tables.

Using this methodology, models with calendar year and the variables from the datasets as confounders were fit to all general industry inspections and then to data from individual SIC divisions. When many of the divisional models failed to converge, possibly due to small amounts of data in some levels of the variables, reduced models were fit. The reduced model for the CI data contained the significant confounders ($P < 0.05$) of facility size and region, included as a two-level variable. The two-level region variable contrasted western regions (9 and 10) against the rest of the country and was derived from a general industry inspection model containing only calendar year and region as additive predictors. The reduced model for the HC data included the significant confounders ($P < 0.05$) of facility size and visit type. These adjusted models were compared to unadjusted models containing only calendar year to examine the impact of the confounders on observed trends. The models fit for individual four-digit SIC codes were unadjusted since many of the models failed to converge with the presence of any confounders and the inclusion of confounders was shown to have little effect on the trend estimates when comparing the adjusted and unadjusted models for the major SIC divisions.

RESULTS

Descriptive Summaries

Table I describes the number of inspections, number of samples, percent of samples with non-detectable lead levels, and the median lead exposure level by industry division, facility size, and calendar year during the 19 years for which CI data were available. A total of 34,383 lead samples were obtained during 10,600 CI. This included 32,385 samples collected during 9,855 general industry inspections and 1,998 samples collected during 745 construction industry inspections. The overall median lead exposure value for general industry was 0.007 mg/m^3, decreasing from 0.024 in 1979/1980 to <0.0005 in 1997. Note that a median exposure

TABLE I. Description of Inspections, Lead Samples, and Exposure Levels for Industry Divisions, Facility Sizes, and Year for Compliance Inspections

Group	Number of inspections	Number of samples	Non-detectable samples (%)	Median exposure level (mg/m^3)
All compliance inspections	10,600	34,383	40.0	0.007
General industry inspections	9,855	32,385	40.6	0.007
General industry by division				
Manufacturing (SIC[a] 2011–3999)	8,096	28,369	41.0	0.007
Transportation (SIC[a] 4011–4961)	216	551	46.8	0.002
Wholesale (SIC[a] 5012–5199)	323	979	27.3	0.019
Retail (SIC[a] 5231–5999)	134	201	53.7	0.000
Finance (SIC[a] 6011–6733)	6	12	83.3	0.000
Services (SIC[a] 7011–8999)	898	1,737	39.1	0.006
Public administration (SIC[a] 9111–9711)	180	531	35.2	0.004
Non-classifiable establishments (SIC[a] 9999)	2	5	100.0	0.000
General industry by facility size				
1–9 employees	975	1,920	34.2	0.010
10–49 employees	3,571	9,257	41.7	0.007
50–99 employees	1,641	5,312	41.9	0.006
100+ employees	3,668	15,896	40.2	0.007
General industry by year				
1979–1980	1,006	4,620	21.9	0.024
1981–1982	1,124	4,019	29.7	0.012
1983–1984	1,326	4,261	34.3	0.013
1985–1986	1,255	4,091	39.3	0.008
1987–1988	1,209	3,893	43.8	0.004
1989–1990	1,152	3,726	48.3	0.001
1991–1992	1,017	3,003	54.4	0.000
1993–1994	873	2,313	57.6	0.000
1995–1996	663	1,849	57.6	0.000
1997	230	610	57.9	0.000
Construction industry inspections	745	1,998	31.2	0.022
Construction industry by facility size				
1–9 employees	329	828	26.3	0.031
10–49 employees	274	780	31.5	0.030
50–99 employees	65	184	32.1	0.015
100+ employees	77	206	49.0	0.001
Construction industry by year				
1979–1980	38	88	28.4	0.015
1981–1982	29	72	23.6	0.012
1983–1984	48	134	32.8	0.014
1985–1986	63	117	45.3	0.008
1987–1988	72	163	22.7	0.033
1989–1990	102	255	30.2	0.020
1991–1992	125	361	33.8	0.021
1993–1994	122	423	27.7	0.042
1995–1996	97	262	30.9	0.041
1997	49	123	41.5	0.005

A median exposure of 0.000 indicates that the observed value was less than 0.0005 or below the limit of detection.
[a]Range of SIC codes for facilities that received compliance inspections.

of 0.000 in this table indicates that the observed value was less than 0.0005 or below the limit of detection. These samples were recorded as non-detectable in the OSHA data files. Approximately 41% of the general industry lead samples were recorded as non-detectable over the entire time period, increasing from 21.9% in 1979/1980 to 57.9% in 1997. The overall median exposure level for the construction industry was higher than for general industry (0.022 mg/m^3 vs. 0.007 mg/m^3) with fewer samples reported as non-detectable (31.2% vs. 40.6%). The percentage of non-detectable samples for the construction industry increased from 28.4% in 1979/1980 to 41.5% in 1997.

Table II shows similar statistics for the HC data. Throughout the 14-year period for which HC data were available, 10,423 lead samples were collected during 4,567 HC. Of these, 10,139 samples were collected during

TABLE II. Description of Consultations, Lead Samples, and Exposure Levels for Industry Divisions, Facility Sizes, and Year for Health Consultations

Group	Number of consultations	Number of samples	Non-detectable samples (%)	Median exposure level (mg/m^3)
All health consultations	4,567	10,423	30.3	0.003
General industry consultations	4,437	10,139	30.6	0.003
General industry by division				
Manufacturing (SIC[a] 2011–3999)	3,462	8,125	31.5	0.002
Transportation (SIC[a] 4011–4961)	61	151	39.1	0.003
Wholesale (SIC[a] 5012–5199)	134	311	20.6	0.007
Retail (SIC[a] 5231–5999)	91	139	34.5	0.003
Finance (SIC[a] 6011–6733)	8	16	12.5	0.011
Services (SIC[a] 7011–8999)	584	1,138	25.9	0.006
Public administration (SIC[a] 9111–9711)	79	217	31.3	0.004
Non-classifiable establishments (SIC[a] 9999)	18	42	21.4	0.003
General industry by facility size				
1–9 employees	610	1,134	25.6	0.007
10–49 employees	1,722	3,881	28.9	0.003
50-99 employees	877	2,020	31.5	0.002
100+ employees	1,228	3,104	33.9	0.002
General industry by year				
1984–1985	594	1,392	21.5	0.006
1986–1987	675	1,443	28.2	0.005
1988–1989	836	1,923	24.3	0.004
1990–1991	754	1,763	24.8	0.004
1992–1993	595	1,247	36.1	0.002
1994–1995	648	1,562	38.8	0.001
1996–1997	335	809	53.5	0.000
Construction industry	130	284	20.8	0.018
Construction industry by facility size				
1–9 employees	50	99	14.1	0.027
10–49 employees	51	122	23.8	0.019
50–99 employees	13	26	23.1	0.003
100+ employees	16	37	27.0	0.011
Construction industry by year				
1984–1985	20	43	20.9	0.023
1986–1987	25	53	15.1	0.026
1988–1989	27	55	20.0	0.037
1990–1991	5	8	50.0	0.002
1992–1993	18	48	29.2	0.016
1994–1995	22	48	14.6	0.011
1996–1997	13	29	20.7	0.003

A median exposure of 0.000 indicates that the observed value was less than 0.0005 or below the limit of detection.
[a]Range of SIC codes for facilities that received health consultations.

4,437 general industry consultations and 284 samples collected during 130 construction industry consultations. The overall median lead exposure value for general industry consultations was 0.003 mg/m^3, decreasing from 0.006 mg/m^3 in 1984/1985 to <0.0005 mg/m^3 in 1996/1997. Approximately 31% of the general industry lead samples were recorded as non-detectable over the 14-year data collection period, increasing from 21.5% in 1984/1985 to 53.5% in 1996/1997. The overall median exposure level for the construction industry was again higher than for general industry (0.018 mg/m^3 vs. 0.003 mg/m^3) with fewer samples (20.8% vs. 30.6%) reported with a value of non-detectable.

Graphical Summaries

The display of the first, second, and third quartiles of the distributions (depicted as a boxplot) of personal lead exposure levels for both the CI and HC data present a clear negative trend in lead exposure levels over time for general industry (Fig. 1a,b). A steady, five- to tenfold decline in the median and 75th centile exposure values from the beginning to the end of the observed time period can be seen. Plots of the full range of exposure levels versus year are not presented since any relationship is obscured by outlying observations, most notably the small number of observations with values above 30 mg/m^3 (0.47% of the general industry samples and 1.04% of the construction industry samples). The distributions of the per-inspection or per-consultation median lead exposure levels are shown in Figure 1c,d. Again, there is a clear negative trend in lead exposure levels when the median lead exposure level for each inspection or consultation is considered. There was general consistency in the downward trends in lead exposure levels at both the per-sample and per-inspection/consultation level for general industry facilities (Fig. 1a–d).

Figure 2a shows a steady negative trend in the percentage of lead samples from general industry facilities exceeding the PEL over time, subject to small year-to-year variation. The percentage of lead samples obtained during CI that exceed the PEL significantly declined (test of coefficient for annual trend, $P < 0.0001$) from approximately 42% in 1979 to 12% in 1997. For samples obtained during health-consultations, the percentage of samples exceeding the PEL declined from 15% in 1984 to 4% in 1997 (significant at $P < 0.0001$). When considering the percentage of inspections or health-consultations for general industry facilities in

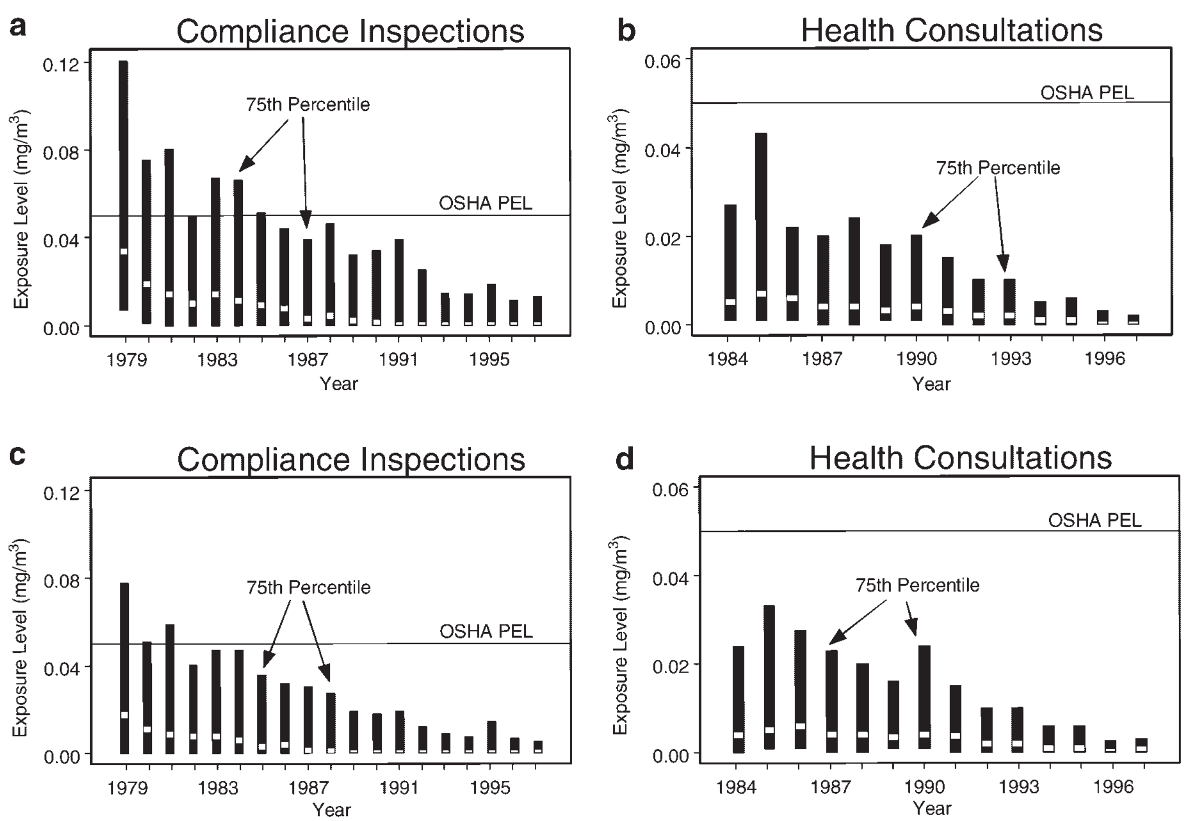

FIGURE 1. **a,b**: Distributions of personal lead exposure samples for general industry facilities over time. **c,d**: Distributions of median lead exposures per inspection/consultation for general industry facilities over time. Inter-quartile ranges are presented. The upper end of the box corresponds to the 75th centile, the lower end of the box corresponds to the 25th centile, and the median is depicted as a white box within the dark box.

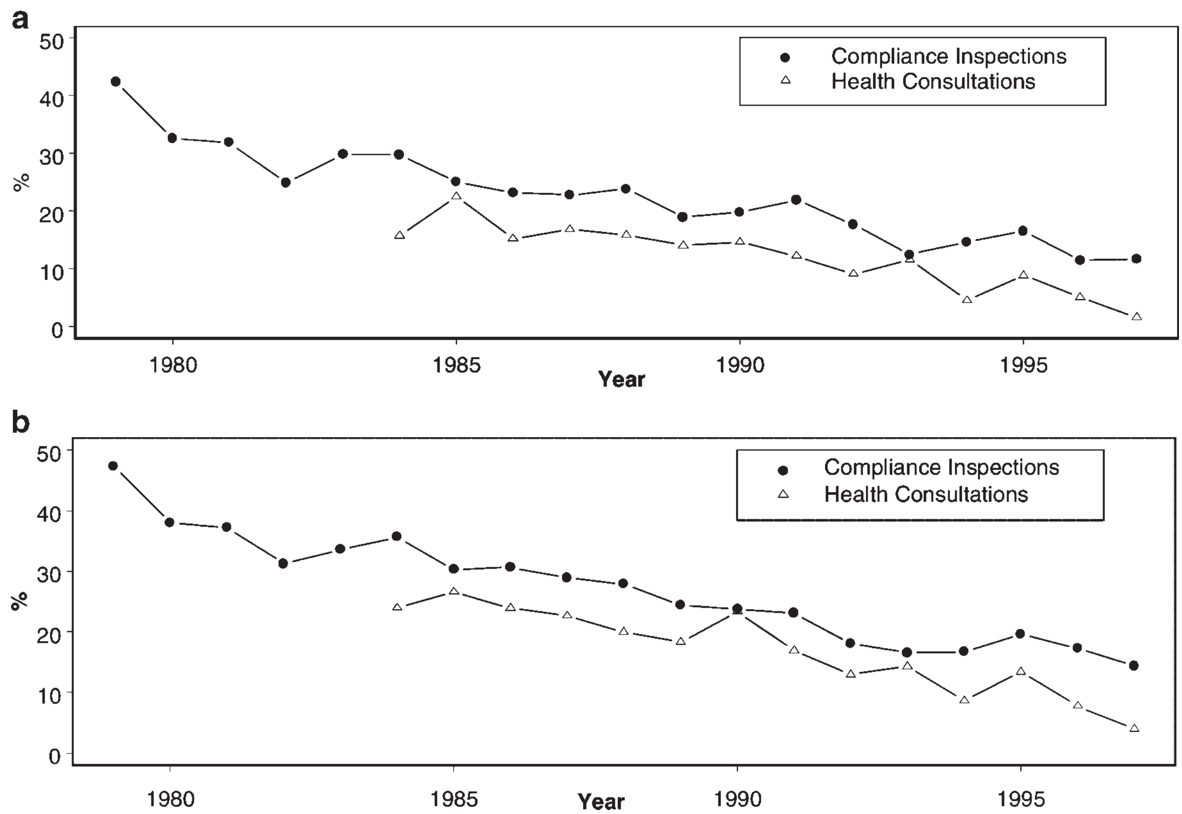

FIGURE 2. **a**: Percentage of general industry samples exceeding the OSHA PEL by year. **b**: Percentage of general industry inspections/consultations with at least one sample exceeding the OSHA PEL by year.

which at least one lead sample exceeded the PEL, a decline from approximately 47% in 1979 to 14% in 1997 was observed for CI ($P < 0.0001$) and from 24% in 1984 to 8% in 1997 for health-consultations ($P < 0.0001$) (Fig. 2b).

To examine whether this downward trend in lead exposure levels occurred within facilities of all sizes, the distributions of the median lead exposure level per general industry inspection and the proportion of general industry inspections with at least one lead exposure sample above the PEL within four facility size categories (<10, 10–49, 50–99, ≥100 employees) were plotted over time. All four facilities size categories showed significant downward trends in lead exposures over time when examining both the percent of inspections with at least one lead exposure sample above the PEL (Figs. 3a–d) and the median exposure levels over time (not shown); however, this decrease was much less pronounced in the smallest facilities (<10 employees). These facilities had large yearly fluctuations in lead exposure levels that may be the result of the small number of facilities of this size inspected per year.

Figure 4a,b illustrate the distributions of lead exposures over time for the construction industry. Only the CI records are summarized here, as there were little construction data available in the HC records. Both the distributions of all personal samples and the per-inspection medians are displayed. There was no decrease in median lead exposure levels over time (1993–1997) for the construction industry either at the per sample or per inspection level. Additionally, exposure levels for the construction industry were, in general, significantly higher than those observed for general industry. A comparison of Figures 1 and 4 highlights the exposure pattern distribution differences between general industry and construction. In many cases, the 75th centile of lead exposure in construction is ten times larger than the 75th centile of lead exposure in general industries. The construction industry also showed more variation in the median exposure levels within the facility size categories (Table I). In the CI data, the median lead level for the smallest facilities (1–9 employees) was 0.031 mg/m^3 for the construction industry and 0.010 for general industry, while the median lead level for facilities with 100 or more employees was 0.001 for construction and 0.007 for general industry.

Logistic Regression

Table III shows the estimated initial probability of a sample exceeding the OSHA PEL for CI conducted in 1979 and HC conducted in 1984 for each level of the variables included in the CI and HC datasets. These estimated initial probabilities can be thought of as the starting point relative to

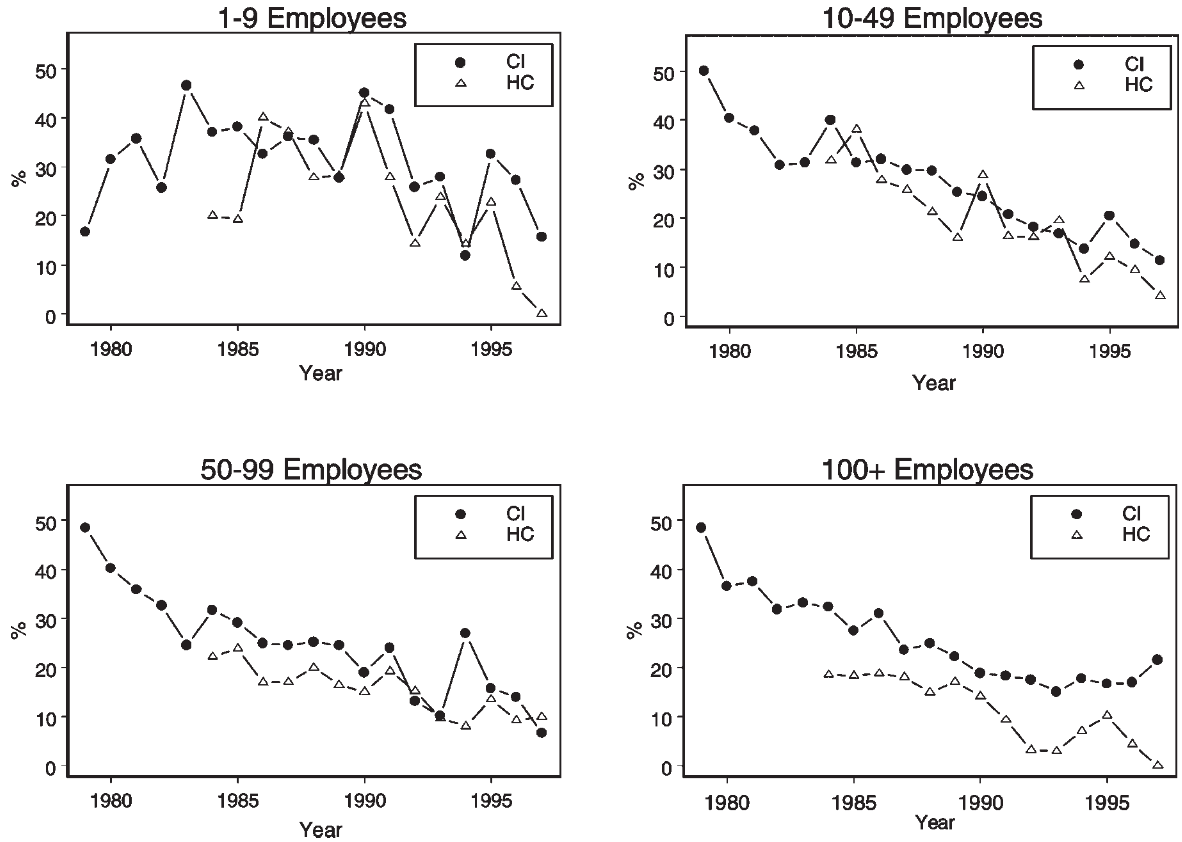

FIGURE 3. Percentage of general industry inspections/consultations with at least one sample exceeding the OSHA PEL by year and facility size.

any change in the odds of a sample exceeding the OSHA PEL. Table III also includes an odds ratio comparing the odds of a lead exposure sample exceeding the OSHA PEL between consecutive years for each level of the variables included in the datasets. This odds ratio should be interpreted as the odds of obtaining a lead exposure sample above the PEL in any given year relative to the preceding year. For example, the odds ratio estimate of 0.9 for establishments with 50–99 employees from the CI data suggests the odds of observing a lead exposure above the PEL declines approximately 10% with the passage of each year. For the CI, there were significant annual declines in the odds of a lead exposure sample exceeding the PEL within all facility size levels, for both unionized and non-unionized facilities, for both programmed and unprogrammed inspections, and for all OSHA regions with the exception of Region 9 and 10, which had non-significant declines. The HC data showed a similar pattern of significant declines in the odds of a lead sample exceeding the PEL for all facility size levels and for both initial and training consultations. Six of the ten OSHA regions showed significant declines, two others had non-significant declines, and the remaining two OSHA regions (6 and 10) had non-significant increases in the odds of a lead exposure sample exceeding the PEL.

Table IV reports the number of samples, number of inspections, and a GEE-generated estimate (and associated *P*-value) of the annual decline in the odds of a sample exceeding the PEL for general industry as a whole and for each SIC division with sufficient data from the CI and HC records (at least 30 inspections or consultations). Parameter estimates with their associated *P*-values and odds ratios for the predictor variable calendar year are given. The odds ratio estimates are presented as both unadjusted odds ratios, where the model included only calendar year, and adjusted estimates. The adjusted model for the CI data included calendar year, facility size, and a two-level region variable while the adjusted model for the consultation data included calendar year, facility size, and visit type. As can be seen in Table IV, the inclusion of confounders had very little effect on the trend estimates. Decreasing odds ratios significant at $P < 0.05$ were observed for the overall category of general industry (OR = 0.92 for the CI data and OR = 0.89 for HC data), as well as for the SIC divisions of manufacturing, transportation, wholesale trade, and services. During the entire time period of observation (1979–1997 for the CI records), the odds of observing a lead exposure above the PEL for general industry facilities decreased approximately 78%. Similar decreases in the odds of a lead exposure exceeding the PEL

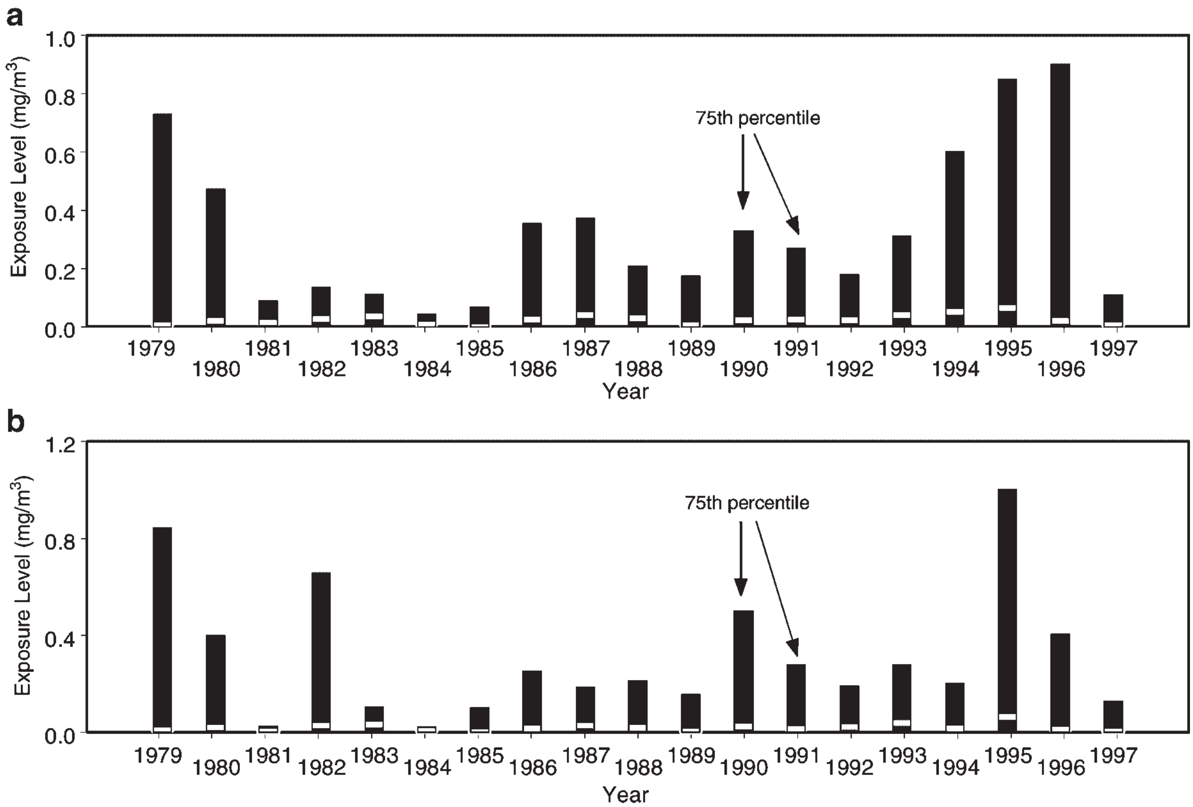

FIGURE 4. **a**: Distributions of personal lead exposure samples for the construction industry. **b**: Distributions of median lead exposures per inspection for the construction industry. Inter-quartile ranges are presented. The upper end of the box corresponds to the 75th centile, the lower end of the box corresponds to the 25th centile, and the median is depicted as a white box within a dark box.

were observed for the other SIC industry divisions ranging from a decrease of 60% for services to 85% for wholesale trade over the 19-year period of observation for the CI data. Only retail trade did not follow this pattern showing a 20% increase in the odds of observing a lead exposure sample above the PEL over the entire period of observation (although the trend was not significant).

Table V provides four-digit SIC specific odds ratios for those general industry SIC codes that had at least 30 inspections during the time period 1987–1997. The SIC specific odds ratios were obtained from unadjusted models containing only calendar year as a predictor variable since the models including facility size and a two-level region variable failed to converge for 30 of the 44 SIC specific categories. Since the inclusion of confounders was shown to have little effect on the trend estimates for the major SIC divisions, the fit of the unadjusted model was reported for the SIC specific analysis. Pre-1987 inspections were not used for this analysis since the SIC coding scheme was revised in 1987; four-digit SIC comparisons across two revisions of the SIC system are very difficult for industries that changed SIC codes between the revisions. Four-digit SIC specific odds ratios were not generated for the HC records due to limited data within most of the four-digit categories.

Thirty-one (70%) of the four-digit SIC codes with sufficient data had odds ratio estimates below one (indicating a decline). Eleven of the 31 SIC codes had statistically significant ($P < 0.05$) decreases in the odds of a lead exposure sample exceeding the PEL; at $P < 0.10$, an additional 4 SIC codes had significant annual declines. Many of the SIC codes with decreases were historically high-risk industries for lead exposure including copper foundries (SIC 3366); non-ferrous foundries (SIC 3369); and storage batteries (SIC 3691). Odds ratio estimates ≥ 1 were observed for 13 (30%) of the SIC codes but none were statistically significantly at $P < 0.05$ and only 1, SIC 3479-coating, engraving, and allied services, had a significant increase at $P < 0.10$.

The shaded four-digit SIC codes in Table V highlight 13 of the general industry SIC codes listed in OSHA July 2001 directive, *National Emphasis Program: Lead* (*NEP:Lead*). The SIC codes listed in this directive are those where high employee lead exposure levels have been demonstrated or which have been known to produce high employee blood lead levels. The *NEP:Lead* was implemented to direct OSHA field inspection efforts to address lead exposures in the workplace. Annual odds ratio estimates of less than 1 were observed for 9 of the 13 SIC codes in the *NEP:Lead* including gray and

TABLE III. Estimated Initial Probability of a Lead Sample Exceeding the OSHA PEL and Annual Relative Odds of a Lead Sample Exceeding the PEL for Models Containing Only the Variable of Interest and Year

		Compliance inspections		Health consultations	
Variable	**Levels**	**Estimated[a] 1979 proportion exceeding PEL**	**Odds ratio[b] (*P*-value)**	**Estimated[a] 1984 proportion exceeding PEL**	**Odds ratio[b] (*P*-value)**
Establishment	1–9	0.32	0.97 (0.01)	0.27	0.93 (<0.01)
Size	10–49	0.34	0.91 (<0.01)	0.27	0.86 (<0.01)
	50–99	0.32	0.90 (<0.01)	0.17	0.91 (<0.01)
	100+	0.26	0.93 (<0.01)	0.15	0.87 (<0.01)
Region	1	0.26	0.94 (<0.01)	0.13	0.96 (0.31)
	2	0.29	0.93 (<0.01)	0.15	0.91 (<0.01)
	3	0.37	0.91 (<0.01)	0.20	0.87 (<0.01)
	4	0.28	0.94 (<0.01)	0.23	0.87 (<0.01)
	5	0.30	0.91 (<0.01)	0.19	0.89 (<0.01)
	6	0.25	0.94 (<0.01)	0.26	1.09 (0.09)
	7	0.39	0.88 (<0.01)	0.20	0.90 (0.02)
	8	0.32	0.87 (<0.01)	0.14	0.92 (0.23)
	9	0.33	0.98 (0.47)	0.33	0.90 (<0.01)
	10	0.37	0.96 (0.07)	0.24	1.01 (0.91)
Two-level region	1–8	0.30	0.92 (<0.01)	N/A	N/A
	9–10	0.36	0.97 (0.04)	N/A	N/A
Union status	Yes	0.30	0.92 (<0.01)	N/A	N/A
	No	0.30	0.93 (<0.01)	N/A	N/A
Inspection type	Programmed	0.33	0.91 (<0.01)	N/A	N/A
	Not programmed	0.28	0.94 (<0.01)	N/A	N/A
Visit type	Initial	N/A	N/A	0.20	0.89 (<0.01)
	Training	N/A	N/A	0.33	0.90 (0.01)

[a]The estimated proportion is derived from the intercept of the fitted model.
[b]Odds ratio represents the odds of a lead sample exceeding the PEL in 1 year relative to the odds of a lead sample exceeding the PEL in the immediately preceding year.

ductile iron foundries (SIC 3321; OR = 0.91), secondary smelting and refining of non-ferrous metals (SIC 3341; OR = 0.97), copper foundries (SIC 3366; OR = 0.92), fabricated plate work (boiler shops) (SIC 3443; OR = 0.90), storage batteries (SIC 3691; OR = 0.91), truck and bus bodies (SIC 3713; OR = 0.74), sporting and athletic goods (3949; OR = 0.64), scrap waste and materials (SIC 5093; OR = 0.92) and amusements and recreation services, not elsewhere classified, which includes shooting galleries and shooting ranges (7999; OR = 0.78). Of the four remaining SIC codes included in the *NEP:Lead* with annual odds ratios ≥1, none were significant.

Two additional analyses were conducted to assess the influence of the non-detectable values on the decreasing trends in lead exposures above the PEL. These analyses were conducted to evaluate whether the increase in the percentage of non-detectable readings over time (from under 20% in 1979 to over 50% in the final years of analysis) was due to something other than actual reductions in lead exposure levels, such as an increase in multiple-metal analyses (which included lead) when lead exposure was not actually suspected. The first analysis evaluated the data for those inspections/consultations where only lead samples were collected, eliminating the potential problem of multiple metal analyses. Both the proportion of samples exceeding the PEL by year and the proportion of inspections or consultations with at least one sample exceeding the PEL by year were evaluated. The same two analyses were performed for both the CI and the HC with all non-detectable samples excluded from the analyses. Table VI shows that significant declining trends remained when the analyses were restricted to those inspections or consultations where only lead samples were collected and for the analyses where all non-detectable values were excluded for both the proportion of samples exceeding the PEL by year and the proportion of inspections or consultations with at least one sample exceeding the PEL by year.

DISCUSSION

Significant decreases in occupational lead exposures for general industry facilities have been seen since 1979 and

TABLE IV. Estimated Annual Relative Odds of a Lead Sample Exceeding the OSHA PEL Based Upon a Logistic Regression Model Using Generalized Estimating Equations

SIC division	Data source	No. inspections/ consultations	No. samples	Unadjusted[b] odds ratio (*P*-value)	Adjusted[c] odds ratio (*P*-value)
General industry	CI	9,855	32,385	0.93 (<0.01)	0.92 (<0.01)
SIC[a] 2011–9999	HC	4,437	10,139	0.90 (<0.01)	0.89 (<0.01)
Manufacturing	CI	8,096	28,369	0.92 (<0.01)	0.92 (<0.01)
SIC[a] 2011–3999	HC	3,462	8,125	0.88 (<0.01)	0.87 (<0.01)
Transportation	CI	216	551	0.94 (0.04)	0.92 (<0.01)
SIC[a] 4011–4961	HC	61	151	0.91 (0.32)	0.89 (0.26)
Wholesale	CI	323	979	0.91 (<0.01)	0.90 (<0.01)
SIC[a] 5012–5199	HC	134	311	0.90 (0.03)	0.91 (0.04)
Retail trade	CI	134	201	1.02 (0.72)	1.01 (0.78)
SIC[a] 5231–5999	HC	91	139	0.99 (0.87)	—[d]
Services	CI	898	1,737	0.95 (<0.01)	0.95 (<0.01)
SIC[a] 7011–8999	HC	584	1,138	0.90 (<0.01)	0.90 (<0.01)
Public administration	CI	180	531	0.92 (0.10)	0.93 (0.17)
SIC[a] 9111–9711	HC	79	217	0.98 (0.72)	0.97 (0.70)

CI, compliance inspection records; HC, health consultation records.
[a]Range of SIC codes for the facilities receiving inspections/consultations.
[b]Unadjusted models measured trend with no other predictors in the models.
[c]Adjusted models for CI measured trend with a four-level facility size variable and a two-level region variable included as confounders. Adjusted models for HC measured trend with a four-level facility size variable and a two-level visit type variable included as confounders.
[d]The — indicates an error in the parameter estimation routine. A parameter estimate is unavailable.

1984 for the CI and HC records, respectively. Trends observed in both the median and 75th centile lead exposure values support this claim. Figure 1a,b show five- to tenfold drops in the median and 75th centile of lead exposures during the observed time periods. This indicates dramatic declines in occupational lead exposures, as measured by samples collected during OSHA inspections for the past two decades and OSHA health-consultations for a period of 14 years.

Weighting each lead sample equally in this manner, however, may distort trends on a per-facility basis. Facilities where more lead samples are taken (large facilities or those with greater potential for lead exposure) might mask a lack of a decline in lead exposures in facilities where fewer samples are taken. The distributions of the median exposure level per inspection or consultation (Fig. 1c,d) show that this is not the case: clear and considerable declines over time can be seen on a per-inspection or per-consultation basis. In addition, the downward trend in both median exposures over time and inspections or consultations with at least one exposure sample above the PEL was observed within facilities of all sizes. However, the downward trend was less pronounced in the smallest facilities, those with fewer than 10 employees.

The decline in lead exposure values observed in this analysis is consistent with the results of an analysis of OSHA IMIS data for the lead battery industry conducted by Gomez in 1997. The Gomez study evaluated 2,111 samples of 8-hr TWA personal exposures to lead in the lead battery industry (SIC codes 3691 and 3692) for the period 1979 to early 1989 and found a decline in mean lead exposures of 5–9% per year.

Analysis of Lead Exposures Exceeding the PEL

To best interpret the results of the categorical analysis of lead exposures, it is first important to discuss the nature and features of performing analyses of these data classified relative to the standard (i.e., exceeding the PEL versus equal to or below the PEL).

- The raw exposure level values are highly positively skewed, with a vast majority of observations below 1 mg/m^3 but with a few values above 30 mg/m^3. The binary characterization (exposure above vs. exposures at or below the PEL) captures this information while preventing these observations from unduly influencing an analysis based upon mean exposures.
- The measurement of lead exposure levels is restricted by the limit of detection of the sampling technique. Froines et al. [1990] excluded all exposure values below the minimum detectable limit, noting that a value of zero may have derived from sampling and analytic error since it is unlikely that workers in many lead industries would

TABLE V. Estimated Annual Relative Odds of a Lead Exposure Sample Exceeding the OSHA PEL for Individual SIC Codes Using Compliance Inspection Data From 1987 to 1997

SIC code	SIC name	No. inspections	No. samples	Odds ratio (*P*-value)
2759	Commercial printing, n.e.c.	30	50	0.95 (0.81)
2851	Paints, varnishes, lacquers, enamels, and allied products	31	55	0.85 (0.25)
3089	Plastic products, n.e.c.	60	137	0.65 (<0.01)
3231	Glass products, made of purchased glass	36	90	0.83 (0.19)
3312	Steel works, blast furnaces, rolling and finishing mills	78	325	0.91 (0.28)
3321	Gray and ductile iron foundries	124	435	0.91 (0.27)
3325	Steel foundries, n.e.c.	37	155	0.83 (0.32)
3341	Secondary smelting and refining of non-ferrous metals	116	706	0.97 (0.62)
3365	Aluminum foundries	40	147	1.00 (0.98)
3366	Copper foundries	118	580	0.92 (0.09)
3369	Non-ferrous foundries, except aluminum and copper	44	145	0.78 (0.05)
3441	Fabricated structural metal	82	216	0.78 (0.03)
3443	Fabricated plate work (boiler shops)	100	315	0.90 (0.21)
3444	Sheet metal work	68	185	0.81 (0.41)
3471	Electroplating, plating, polishing, anodizing, coloring	121	268	1.11 (0.24)
3479	Coating, engraving, and allied services, n.e.c	49	125	1.45 (0.06)
3496	Miscellaneous fabricated wire products	35	95	1.05 (0.65)
3499	Fabricated metal products, n.e.c.	56	151	0.82 (0.34)
3523	Farm machinery and equipment	93	239	0.75 (<0.01)
3531	Construction machinery and equipment	38	151	1.02 (0.84)
3559	Special industry machinery, n.e.c.	41	113	1.49 (0.53)
3585	Air-conditioning, heating, industrial refrigeration equip.	30	77	0.92 (0.55)
3599	Industrial and commercial machinery, n.e.c.	78	174	0.80 (0.02)
3672	Printed circuit boards	61	137	0.47 (<0.01)
3679	Electronic components, n.e.c	65	191	1.23 (0.12)
3691	Storage batteries	99	1,039	0.91 (0.05)
3711	Motor vehicles and passenger car bodies	41	124	0.37 (0.03)
3713	Truck and bus bodies	52	132	0.74 (0.05)
3714	Motor vehicle parts and accessories	117	317	1.08 (0.48)
3715	Truck trailers	64	231	1.00 (0.98)
3731	Ship building and repairing	36	126	1.02 (0.89)
3743	Railroad equipment	45	147	0.94 (0.67)
3949	Sporting and athletic goods, n.e.c.	35	88	0.64 (0.02)
3993	Signs and advertising specialties	46	75	0.90 (0.42)
4953	Refuse systems	34	82	1.00 (0.99)
5093	Scrap and waste material	122	396	0.92 (0.11)
5511	Motor vehicle dealers	38	56	0.89 (0.49)
7532	Top, body, upholstery repair shops, and paint shops	95	165	0.78 (0.04)
7538	General automotive repair shops	49	89	0.73 (<0.01)
7539	Automotive repair shops, n.e.c.	162	308	1.00 (0.95)
7699	Repair shops and related services, n.e.c	57	98	1.07 (0.50)
7999	Amusement and recreation services, n.e.c.	32	69	0.78 (0.02)
8211	Elementary and secondary schools	45	67	0.82 (0.04)
9221	Police protection	59	243	0.90 (0.44)

Shaded SIC codes included in Appendix A of OSHA July 2001, National Emphasis Program: Lead.
n.e.c., not elsewhere classified.

TABLE VI. Alternative Analyses to Assess Effect of Non-Detectable Samples on Declining Trends in Lead Exposures over the PEL

	Full dataset	Inspections with only lead samples	Excluding all non-detectable samples
Model	Odds ratio (*P*-value)	Odds ratio (*P*-value)	Odds ratio (*P*-value)
Proportion of CI samples >PEL by year	0.92 (<0.01)	0.96 (<0.01)	0.97 (<0.01)
Proportion of HC samples >PEL by year	0.90 (<0.01)	0.91 (<0.01)	0.92 (<0.01)
Proportion of CI with at least one sample >PEL by year	0.93 (<0.01)	0.96 (<0.01)	0.97 (<0.01)
Proportion of HC with at least one sample >PEL by year	0.90 (<0.01)	0.93 (<0.01)	0.92 (<0.01)

CI, compliance Inspections.
HC, health consultations.

not have measurable exposures and that a "reported value of zero is not a valid measure of lead exposure where lead is in use." Although based on discussions with OSHA (personal communication), we did not have strong reservations about the accuracy of the samples found to be below the limit of detection, the binary characterization of lead exposure allowed all the data to be used. Samples recorded in the OSHA data as non-detectable for lead exposure were classified as below the PEL.

With this in mind, analysis of trends in the proportions of exposures above the PEL provide clear evidence for declines in occupational lead exposures exceeding the PEL in the OSHA lead standard. Drops in the proportion of lead exposures in exceeding the PEL, seen in Figure 2a, are dramatic: from 42% in 1979 to 12% in 1997 for the CI records and from 15% in 1984 to 4% in 1997 for the HC records. Additionally, Figure 2b provides the percentage of inspections with at least one sample above the PEL by year. In 1979, nearly 47% of all inspections had at least one sample above the PEL, while in 1997 this number decreases to below 14% of all inspections. A decline in the percentage of consultations with at least one sample above the PEL by year was also observed; from 22% in 1984 to 8% in 1997.

The logistic regression models characterize these annual declines along with estimates of the size of this effect. With the exception of the retail sector, annual declines in the odds of an exposure sample exceeding the PEL within large industry divisions (see Table III) range from 5% to 13%. For the overall category of general industry (SICs included 2011–9999), a 8–11% decline per year is seen in both the CI and HC records. The decline in the odds of a lead exposure exceeding the PEL over the entire observed time period (1979–1997 for the CI records) for general industry is nearly 80%.

Similar annual declines were observed for analyses conducted at the four-digit SIC code level. Seventy percent of the four-digit SIC codes examined had annual declines in the odds of a lead exposure sample exceeding the PEL ranging from 3% to 63%. These declines included a number of historically high-risk industries including copper foundries; storage batteries; manufacturing of truck and bus bodies; manufacturing of sporting and athletic goods; and amusement and recreation services.

Exceptions

Exceptions to the consistent downward trends in occupational lead exposures do exist, however. The construction industry showed little to no decreases in exposure levels over the years of data available for this study. Furthermore, exposure levels, in general, are higher for the construction industry than for general industry during the observed time period, as seen in Figure 4a,b. This is potentially reflective of the higher PEL standard in effect for the construction industry until 1993. Considering the relatively recent reduction of the lead PEL for construction, it would be worthwhile to analyze lead exposures within this industry when more data becomes available. In addition, the smallest size general industry facilities (those with <10 employees) showed a less pronounced (although still significant) decline in lead exposure levels over the period of observation. These facilities, however, had lower lead exposure levels at the beginning of the time period and displayed a more variable pattern of lead exposures that may be partially attributed to the smaller number of facilities of this size where data were collected. The retail sector did not show the same pattern of annual declines in the relative odds of a lead sample exceeding the OSHA PEL. Although, the models for this industry division were based on a relatively small number of inspections or consultations. Finally, annual declines in the odds of a lead exposure sample exceeding the PEL were not exhibited for all four-digit SIC codes evaluated including a few historically high-risk industries such as manufacturing of motor vehicle parts and accessories (SIC 3714) and ship building and repair (SIC 3731) which had non-significant increases. In addition, it is important to note that although consistent declines in lead exposure levels have occurred over time for general industry facilities, 12% of the CI samples and 4% of the HC samples still exceeded the OSHA PEL in 1997.

General Comments

There are several potential concerns associated with this analysis. First, the level of clustering used to build the logistic regression models is important to consider. The models presented here cluster at the inspection/consultation level, allowing for the correlation of observations in a given facility during a specific inspection or consultation. There are two other sources of correlation that may be mentioned: different facilities owned by the same company and repeat inspections at the same facility. Identifying these clusters reliably using the available data is difficult. Company names and addresses are often recorded with slight variations (e.g., ‘Co.’ vs. ‘Company’), and phone numbers are often variable (multiple phone lines, changing area codes, etc.); this obscures the connections between multiple facilities owned by a single company and facilities re-inspected over time. One method used to minimize the effect of re-inspections of the same facility was to eliminate all inspections from the dataset coded as follow-up inspections. This eliminated approximately 9% of the inspections in the CI records. However, removing follow-up inspections does not eliminate the potential for unrelated re-inspections of the same facility over time. Therefore, attempts were made to ascertain the potential effects of these sources of correlation by using several clustering variables including company name, address, and phone number. The results slightly increased cluster size and decreased the total number of clusters, but did not substantially affect parameter or standard error estimates.

Second, the influence of samples found to be below the limit of detection of the sampling technique (recorded as non-detectable) should be noted. The trends seen in both the distributions of the individual sample exposure levels and in the logistic regression analysis are partially attributed to the steady increase in the percentage of non-detectable readings over time: from under 20% in 1979 to over 50% in the final years of analysis. However, analyses conducted to address this issue showed that significant declining trends remained when the analyses were restricted to those inspections or consultations where only lead samples were collected and for the analyses where all non-detectable values were excluded.

Finally, the breadth of applicability of these conclusions is debatable. Statistical inference generally requires the assumption of a ‘random sample’ to safely apply the numerical conclusions drawn for the sample to the population as a whole. In this study, the population of interest is U.S. lead-exposed industrial facilities; neither the CI nor the HC records can be seen as a ‘random sampling’ of lead-exposed facilities. They instead represent the population of facilities receiving OSHA inspection or consultation visits where lead samples were collected. However, since OSHA targets those industries where lead exposure is believed to be the greatest, it is reasonable to assume that OSHA has not reduced its targeting of high-risk industries during the observed time period. This assumption was checked for validity: while the overall number of inspections has declined, especially in the last three observed years (1995–1997), there is no evidence of consistent shifts in SIC codes where inspections or consultations were conducted. Thus, there is no evidence that OSHA strategy for targeting high-risk industries has significantly changed during the observed time period. Furthermore, there are no consistent changes over time in the distribution of inspection types (unscheduled, routine, or due to worker complaint), a factor previously shown [Froines et al., 1990] to be significantly associated with exposure levels. Finally, OSHA tends to inspect the most hazardous lead-exposed facilities and samples from the most hazardous job types consistent with its basic goal of reducing occupational lead overexposure. In the presence of this bias, the results of the CI records can be seen as representative of the population of industrial facilities and workers where lead exposure is the greatest potential problem.

The OSHA CI and HC data used for this evaluation provide a valuable resource for understanding trends in occupational lead exposure levels in U.S. industry. The data indicate a decline in occupational lead exposures for general industry facilities since 1979 on the basis of OSHA CI data and 1984 for OHSA HC data. With the exception of the retail trade, declines were observed for the major industry divisions and the majority of the general industry four-digit SIC codes evaluated. However, annual declines were not observed for all general industry four-digit SIC codes including a few historically high-risk industries. A decline was also not observed for the construction industry. Given the limited number of years of data available since the implementation of the revised construction standard for lead, it would be worthwhile to re-analyze lead exposures within this industry when more data becomes available.

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