American Journal of Industrial Medicine

WILEY

AMERICAN JOURNAL OF INDUSTRIAL MEDICINE

RESEARCH ARTICLE OPEN ACCESS

Medical Surveillance of Occupational Lead Exposure Using the EPA's Toxics Release Inventory and Adult Blood Lead Epidemiology and Surveillance Program: Illinois, 2016–2023

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Received: 6 February 2025 | **Revised:** 25 April 2025 | **Accepted:** 8 May 2025

Funding: This publication was entirely supported by funding from the National Institute for Occupational Safety and Health (NIOSH) through the Illinois Occupational Surveillance Program (U60OH010905). C.A. receives support from the NIEHS P30 Chicago Center for Health and Environment (CACHET) (P30ES027792).

Keywords: ABLES | lead | lead testing | medical surveillance | TRI

ABSTRACT

Background: Despite existing regulations mandating exposure control, training, and monitoring, many worksites continue to inadequately protect workers from lead exposure. The Environmental Protection Agency (EPA) requires facilities to report lead emissions to the Toxics Release Inventory (TRI), presenting a potential tool for identifying at-risk worksites. Research has demonstrated that facilities responsible for high levels of environmental pollution often have poor occupational hygiene controls.

Methods: We linked EPA's TRI, the Illinois Adult Blood Lead Registry and business employer data. Using generalized estimating equation (GEE) models, we evaluated the relationship between lead emissions and blood lead testing to estimate the number of potentially exposed workers at sites without medical surveillance of lead exposures between 2016 and 2023.

Results: Of 477 Illinois facilities reporting lead emissions, 8.2% ($n = 39$) were above-threshold polluters. Only 3.98% ($n = 19$) reported blood lead testing for 2 or more workers between 2016 and 2023. Average annual on-site emissions were 86 pounds for below-threshold polluters, 2601 pounds for facilities providing medical surveillance, and 16,917 pounds among above-threshold polluters without medical surveillance. Among the 39 above-threshold worksites without medical surveillance, the GEE model estimates that (range low-to-high) 7 to 684 workers annually had positive blood lead levels, and 10 to 256 workers had levels $\geq 25\ \mu g/dL$. The models indicate that the majority of estimated exposed workers would be employed at 15 worksites.

Conclusions: Among facilities reporting above-threshold lead releases, workers rarely received blood lead testing. EPA's TRI data can identify facilities where compliance with the OSHA lead standards is inadequate and can help prioritize worksites for outreach.

1 | Introduction

It has been broadly shown that lead exposure is associated with cardiovascular disease, renal disease, and cognitive impairment in adults [1, 2]. Occupational exposure contributed to 93.7% of lead exposure in adults [3] in the United States and remains a significant public health issue. Data from the Adult Blood Lead Epidemiology and Surveillance (ABLES) program also found that 20.4 adults per 100,000 employed population had elevated blood lead levels, defined as $\geq 10\,\mu g/dL$ [3]. Select industries, including battery manufacturing, construction, remediation/recycling services, and mining, have reported higher rates of employees with elevated blood lead [1, 3]. Previous work also suggests that major environmental polluters may expose their workforces and nearby communities through inadequate administrative and engineering controls [4, 5]. The Occupational Safety and Health Administration (OSHA) lead standard mandates medical surveillance, including blood lead testing, for workers who may be exposed to airborne lead concentrations equal to or exceeding the action level ($30\,\mu g/m^3$ as an 8-h time-weighted average) for more than 30 days. [6]

Collaborations between OSHA and ABLES programs enable targeted workplace inspections and consultations in response to reported elevated blood lead levels among workers [3]. However, despite OSHA regulations, some employers in at-risk industries do not provide blood lead testing or medical surveillance to lead-exposed workers, resulting in these cases being unreported to the ABLES database and potentially leaving workers with unmanaged exposures. To complicate matters, in many states, there are hundreds of worksites that may expose their workers to lead. Because state ABLES programs and enforcement agencies have limited resources, it is difficult to systematically determine if worksites are complying with the OSH Act and are providing exposed workers with mandatory medical surveillance for lead exposures.

Increasingly, it is understood that linking surveillance databases mitigates limitations of using a single database and can provide additional information for occupational health research and surveillance. The Environmental Protection Agency's Toxics Release Inventory (EPA's TRI) is used to monitor facility-level environmental emissions of hazardous substances in the United States, including lead [7]. Given that the ABLES database provides medical surveillance information on adult blood lead testing at the state level [3, 8], linking it with EPA's TRI and employment data can enhance our understanding of whether reported levels of lead emissions and workforce numbers in a facility correspond to blood lead testing among exposed workers. This is critical for risk assessment and can help identify worksites with potentially exposed workers who are not being provided with medical surveillance.

While some studies have described characteristics of workers receiving blood lead testing using data from the ABLES program [2, 8–11], very few linkage studies have been conducted to better characterize whether reporting of blood lead testing to the ABLES program is consistent with both facility-level lead emissions and the number of on-site employees. Moreover, previous research suggests significant underreporting to medical surveillance databases in the United States [12], although this has not been well studied in relation to occupational lead exposure. Previous work also suggests geographical disparities in blood lead levels [13, 14]. Gaps, however, remain in the current literature describing these disparities in relation to environmental lead emissions, which can inform enforcement efforts. In the present study, we linked EPA's TRI, the Illinois Adult Blood Lead Registry (ABLR) and employer data from the Dun & Bradstreet Hoovers Database to evaluate the relationship between lead emissions across various media and blood lead testing to estimate the number of potentially exposed workers at sites without medical surveillance between 2016 and 2023. We sought to identify a truncated list of worksites with potential exposures in their workforce to better inform public health prevention, enforcement, and consultation efforts in a resource-limited environment.

2 | Materials and Methods

2.1 | Environmental Protection Agency's Toxics Release Inventory

The US EPA's TRI is publicly available and provides information on facility-level emissions across various industries such as manufacturing, mining, hazardous waste management, and electric power generation [15]. With the exception of stainless steel, brass, and bronze alloy manufacturing, the EPA requires facilities that manufacture, process, or use lead and lead compounds to report emissions if they are equal to or exceed 100 pounds per year (reporting threshold) due to lead's persistent, toxic, and bioaccumulative properties [7]. Facilities are required to report lead releases into environmental media such as air, water, and soil, as well as any transfers to off-site locations for treatment or disposal. Lead releases include elemental lead and lead compounds, defined as distinct chemical substances in which lead is an integral part of the molecular structure (e.g., lead acetate, tetramethyl lead, etc.) [7]. Some facilities report environmental lead emissions even if they emit less than the 100 pounds reporting threshold. The TRI database includes information on lead emissions in pounds by release media, name of facility reporting emission, North American Industry Classification System (NAICS) codes for facility, reporting year, street address, city, county, ZIP code, and state.

2.2 | Illinois Adult Blood Lead Registry

The Illinois ABLR database is an active state-based surveillance system [8], which provides data to the national ABLES program. Under the Illinois Health and Hazardous Substances Registry Act [16], Clinical Laboratory Improvement Amendments (CLIA)-regulated Illinois laboratories must report all blood lead test results to the State Health Department for residents 16 years of age and older [17, 18]. Blood lead tests regardless of concentration are required to be reported to the State Health Department and are captured in the registry [17]. Limits of detection for lead measurement range between 0.2 and $1.0\,\mu g/dL$ [19]. In addition, blood lead levels above or equal to $25\,\mu g/dL$ are reported directly to OSHA, which can trigger inspections [17]. For each calendar year, we deduplicated blood lead samples reported to ABLR between 2016 and 2023 since workers can undergo multiple tests in a given year. ABLR data for the present analysis included annual counts by facility of all positive blood lead tests (elevated or not) and blood lead levels above or equal to 25 μg/dL (OSHA action level for initiating inspections). The University of Illinois Chicago Institutional Review Board granted an exemption determination for this project, as it did not meet the definition of human subjects research. This determination was based on the use of publicly available data from the EPA Toxics Release Inventory and deidentified records from the Illinois Adult Blood Lead Registry.

2.3 | Dun & Bradstreet Hoovers Database

The Dun & Bradstreet Hoovers database provides comprehensive business and analytics data, including details on facility name, location (street address, city, county, ZIP code, and state), single site and global employee size, and NAICS codes [20]. Information on employment size at a single site was utilized to estimate the average annual number of workers employed at a facility (based on address).

2.4 | Statistical Analysis

We linked the EPA's TRI, Illinois ABLR, and Dun & Bradstreet Hoovers databases using facility name, address, city, county, ZIP code, state, or NAICS codes. Figure 1 describes the classification criteria for facilities engaged in medical surveillance and those with no medical surveillance above or below EPA on-site lead emissions threshold. Facilities with medical surveillance were defined as those reporting lead emissions to EPA's TRI and 2 or more positive lead cases to ABLR through CLIA laboratories for 4 or more years over the 8-year study period. Among facilities with no medical surveillance, above threshold polluters were defined as those reporting ≥100 pounds of on-site lead emissions (EPA reporting threshold) for 4 or more years over the 8-year study period. Otherwise, facilities were classified as below threshold polluters (Figure 1).

We evaluated mean and median [25th and 75th percentiles] lead emissions by release media and year stratified by whether facilities were (1) below threshold polluters without medical surveillance, (2) above threshold polluters without medical surveillance, and (3) facilities in the Illinois ABLR medical surveillance data set that had provided blood lead tests to workers. We also present environmental lead releases across OSHA enforcement area offices to demonstrate disparities of environmental emissions by region in Illinois. OSHA enforcement area offices were assessed based on ZIP Code and county name as follows: Chicago North, Chicago South, Fairview Heights, Naperville area, and Peoria area. Reflecting Illinois manufacturing, we broadly defined industry type using NAICS codes as battery manufacturers, foundries and metal manufacturers, fossil fuel and electric power generation, or other industries.

Of the 19 facilities that ever had medical surveillance cases reported to ABLR, only six companies had consecutive years

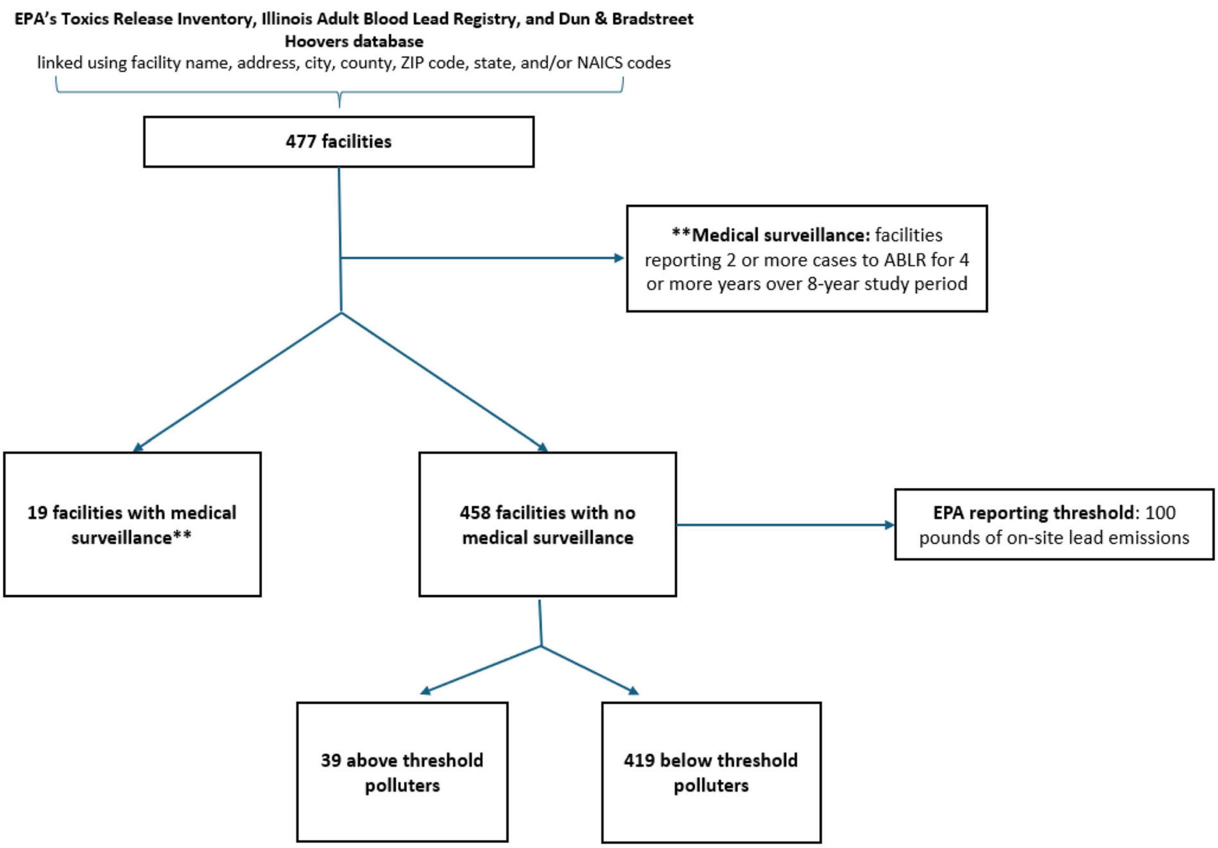

FIGURE 1 | Classification of facilities by medical surveillance and EPA on-site lead emissions threshold.

with workers tested for elevated blood lead levels. Many worksites will have workers with elevated lead levels in 1 year, then have no workers tested the following year, only to have testing resume in a later year. The erratic testing would obscure any relationship between the ABLR and TRI data. For this reason, we restricted the modeling to facilities having medical surveillance with consecutive years of workers tested.

We used multivariable generalized estimating equation (GEE) models with a Poisson distribution to assess relationships between environmental lead emissions across media in pounds (TRI data) and blood lead testing (ABLR data; dependent variable) adjusting for year of testing and emissions report to the EPA and within-facility variation. GEE models are used to generate regression estimates when analyzing variables that were collected across multiple timepoints for the same subject/worksite [21]. This is particularly important since values of variables collected at multiple timepoints may be correlated and will violate the independence assumptions required by traditional regression procedures [21]. For the dependent variable, we developed two separate sets of models using (1) total counts of any positive blood lead tests (deduplicated at the worker level) and (2) counts of unique workers at a facility with blood lead levels equal to or above 25 μg/dL (OSHA action level for initiating inspections). For the independent variable, we separately modeled three parameters of TRI releases (in pounds): total on-site releases, total on-site and off-site releases, and total air releases.

We used model estimates to calculate the annual number of workers potentially exposed to lead at any level, as well as at levels 25 μg/dL or more, among 39 polluting facilities above threshold without medical surveillance that have never reported a blood lead test to the ABLR program. Although worksites varied in employee size, we were unable to estimate the number of employees across facilities for rate calculations over the study period because accurate annual worksite counts of employees were unavailable despite linking employer data from Dun & Bradstreet Hoovers database. We, however, provide estimates of employee size and number of employees with blood lead levels equal to or above 25 μg/dL among facilities with medical surveillance to help contextualize estimates of potentially exposed workers from the GEE models. SAS software (v 9.4; Cary, NC) was used for the statistical analyses.

3 | Results

3.1 | Distribution of Lead Emissions Reported by Illinois Facilities, 2016–2023

Table 1 presents lead emissions reported by Illinois facilities between 2016 and 2023. Lead emissions are presented by release medium and stratified by EPA reporting threshold and medical surveillance. Only 19 (3.98%) of the 477 Illinois facilities reporting lead emissions also submitted blood lead tests for two or more workers during four of the 8 years studied. Among these worksites, seven were identified as above threshold polluters, five in foundries and metal manufacturing, one in battery manufacturing, and one in small arms, ordnance, and ordnance accessories manufacturing. Worksites with active medical

TABLE 1 | Mean, median (25th and 75th percentiles) of lead emissions by release medium and year, stratified by (1) facilities with medical surveillance programs reporting blood lead testing to the Illinois Adult Blood Lead Registry (ABLR), (2) above-threshold polluting facilities without medical surveillance, and (3) below-threshold polluting facilities without medical surveillance.

	Facilities in ABLR medical surveillance		Above threshold polluters without ABLR medical surveillance[a]		Below threshold polluters without ABLR medical surveillance[a]
	N = 19 Mean, median (P25th, P75th)	*p*-value	*N* = 39 Mean, median (P25th, P75th)	*p*-value	*N* = 419 Mean, median (P25th, P75th)
Total on-site and off-site releases	5074.9, 99.5 (1.00, 3132.9)	0.181[b]	27308.1, 3208.2 (711.1, 10380.6)	< 0.0001[c]	1775.4, 0.89 (0.01, 11.1)
Total on-site releases	2600.6, 5.40 (0.08, 115.2)	0.054[b]	16917.1, 438.0 (184.0, 2785.0)	< 0.0001[c]	86.3, 0.02 (0.00, 0.67)
Total air releases	95.8, 4.23 (0.04, 65.3)	< 0.0001[b]	210.2, 110.8 (16.8, 276.0)	< 0.0001[c]	5.25, 0.01 (0.00, 0.40)
Total water releases	34.9, 0.00 (0.00, 0.00)	< 0.0001[b]	15.0, 0.00 (0.00, 14.0)	< 0.0001[c]	0.78, 0.00 (0.00, 0.00)
Total land releases	2470.0, 0.00 (0.00, 0.00)	0.067[b]	16691.9, 0.00 (0.00, 2581.0)	< 0.0001[c]	80.3, 0.00 (0.00, 0.00)

[a] Above-threshold polluters are facilities reporting lead on-site effluent concentrations of 100 pounds or above in 4 or more years of the study period while below-threshold polluters reported lead on-site effluent concentrations below 100 pounds in 4 or more years of the study period between 2016 and 2023.
[b] *p* value comparing average annual lead emission concentration for facilities in ABLR medical surveillance program to below threshold polluting facilities.
[c] *p* value comparing average annual lead emission concentration for above-threshold polluting facilities to below-threshold polluting facilities.

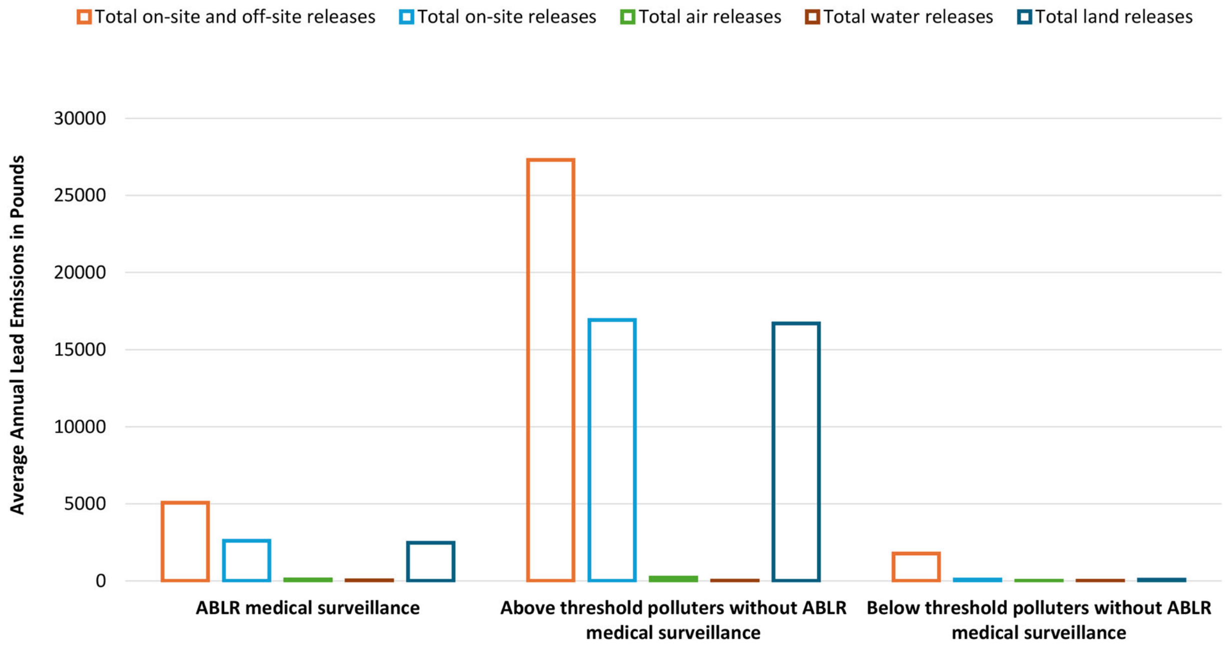

FIGURE 2 | Lead emissions by release medium and ABLR medical surveillance program status.

surveillance of their workforces reported a total of 458,942 pounds of on-site lead emissions over the 8 years studied, with an average annual release of 2601 pounds per facility (Table 1 and Figure 2). Of the 458 facilities who reported one or fewer samples during the 8-year period, eight facilities reported at least one sample per year in less than 4 years during the 8 years studied or participated in medical surveillance for 1 year, while 450 facilities reported no samples to the ABLR medical surveillance system. Among these facilities, 39 (8.2%) were classified as above-threshold polluters, releasing a total of 4,889,041 pounds of lead on-site, with an average annual release of 16,917 pounds per facility (Table 1 and Figure 2) or nearly 7 times higher emissions per year than companies with medical surveillance programs.

In contrast, below-threshold polluters ($n = 419$) who reported one or fewer samples released 215,812 pounds of lead on-site with an average annual release of 86 pounds per facility (Table 1). Overall, average cumulative emissions were higher across various media and year when comparing above- to below-threshold polluters or facilities reporting to the ABLR medical surveillance program, except for emissions to water (Table 1). We also observed declining emissions of total lead compounds and lead-specific emissions released on-site and off-site between 2016 and 2023 (Figure 2). Cumulative pounds of lead compounds emitted declined by 240,557 pounds per year (95% confidence interval [CI]: −314,759, −166,356; $p \leq 0.0001$) while lead-specific emissions declined by 2605 pounds per year (95% CI: −50,637, 45,426; $p = 0.904$).

3.2 | Geographic Disparities in the Distribution of Lead Emissions

There were stark disparities in environmental lead releases across regions corresponding to OSHA area offices. The highest average cumulative lead emissions released on-site and to land were observed in facilities within the jurisdiction of the Fairview Heights district OSHA office, followed by those in the Chicago South and Peoria area offices (Table 2). Facilities within the jurisdiction of the Fairview Heights also reported the highest emissions to air and water. In contrast, facilities within the jurisdiction of the OSHA Chicago North office had the lowest average cumulative lead emissions across various release mediums (Table 2). For example, while average cumulative on-site lead emissions were 78.5 pounds among facilities in the Chicago North OSHA area office; facilities in the Fairview Heights and Peoria OSHA area offices reported average cumulative on-site lead emissions of 16,549 pounds and 7673 pounds, respectively (Table 2).

3.3 | Estimated Number of Potentially Exposed Workers at Worksites Without Medical Surveillance

Based on the GEE model estimates, approximately 7 to 684 workers may have positive blood lead levels, and 10 to 256 workers at levels of 25 μg/dL or higher per year at worksites without medical surveillance (Table 3). As a benchmark, an estimated 623 workers were employed in 2023 among facilities with medical surveillance, and these facilities had an annual average of 15 workers with blood lead levels at or above 25 μg/dL (not shown in tables).

4 | Discussion

In the present analysis, we linked the Illinois Adult Blood Lead Registry, EPA's Toxics Release Inventory database, and workforce data from Dun & Bradstreet Hoovers to examine lead

TABLE 2 | Mean, median (25th and 75th percentiles) of lead emissions as reported to the EPA Toxic Release Inventory by release medium stratified by Occupational Safety and Health Administration (OSHA) enforcement area offices ($N = 477$) in Illinois.

	Chicago north office $N = 108$ **Mean, median (P25th, P75th)**	**Chicago south office** $N = 98$ **Mean, median (P25th, P75th)**	**Fairview heights office** $N = 53$ **Mean, median (P25th, P75th)**	**Naperville area office** $N = 134$ **Mean, median (P25th, P75th)**	**Peoria area office** $N = 84$ **Mean, median (P25th, P75th)**
Total on-site and off-site releases	78.5, 1.84 (0.07, 19.4)	3919.6, 1.40 (0.04, 57.4)	16549.1, 176.5 (1.87, 4530.6)	1075.1, 0.84 (0.00, 15.4)	7672.9, 1.43 (0.01, 211.1)
Total on-site releases	6.15, 0.02 (0.00, 1.00)	1832.9, 0.03 (0.00, 1.00)	12144.3, 8.82 (0.02, 419.0)	78.4, 0.03 (0.00, 1.00)	221.1, 0.15 (0.00, 6.00)
Total air releases	6.12, 0.01 (0.00, 1.00)	27.8, 0.02 (0.00, 1.00)	61.1, 1.35 (0.01, 66.6)	32.7, 0.02 (0.00, 0.68)	41.6, 0.06 (0.00, 5.00)
Total water releases	0.02, 0.00 (0.00, 0.00)	2.23, 0.00 (0.00, 0.00)	20.7, 0.00 (0.00, 0.85)	2.35, 0.00 (0.00, 0.00)	3.58, 0.00 (0.00, 0.00)
Total land releases	0.01, 0.00 (0.00, 0.00)	1802.9, 0.00 (0.00, 0.00)	12062.5, 0.00 (0.00, 0.01)	43.4, 0.00 (0.00, 0.00)	175.9, 0.00 (0.00, 0.00)

Note: Facility-level information on Zip Code and county name were utilized to categorize facilities into OSHA enforcement area offices.

emissions across various media, pollution levels, and rates of blood lead testing in facilities with and without active medical surveillance. Our findings indicated that lead emissions in Illinois were consistently higher across various media and years in facilities with active medical surveillance, compared to facilities reporting environmental lead emissions that were classified as below the EPA lead reporting threshold. However, we identified 39 facilities without active medical surveillance of their workforces that had environmental releases that were nearly 7 times higher than the companies with active medical surveillance programs. We also systematically identified area offices with worksites emitting high levels of lead and highlighted geographic disparities that may contribute to differential worker exposure. Our findings are important for informing OSHA outreach and guiding targeted enforcement strategies. Moreover, we offer a model that could be replicated in other states with a high concentration of lead-exposing industries to support broader occupational surveillance efforts. In addition, the GEE models showed a positive association between environmental lead emissions and the number of workers tested annually and the number with blood lead levels above the OSHA action level. In the facilities without medical surveillance for lead exposure, we estimate there are (range low to high estimates) 7 to 684 workers with positive blood lead levels and 10 to 256 workers with levels 25 μg/dL or higher per year at these facilities. The models indicated that nearly all of these estimated exposed workers are employed at 15 worksites.

Previous studies show that the predominant cause of lead exposure in adults is occupational [2, 3]. Lead concentrations reported in the workplace far exceed those in nearby residential areas and the general population [2, 21]. Likewise, communities with elevated environmental lead exposure often correlate with worksites that have high environmental lead emissions and expose workers [2, 10, 22–25]. Cumulative lead exposure at low to moderate levels ranging from 10 to 20 μg/dL, frequently found in lead-exposed workers, is associated with significant negative health effects such as adverse pregnancy outcomes, and cardiovascular and renal disease [1, 2]. While public health measures like removing lead in paints, gasoline, and consumer products have decreased population levels of lead, occupational exposure remains a significant problem. Our findings suggest that most worksites emitting lead to the environment above threshold reporting levels are not engaged in active medical surveillance and are potentially exposing their workers. In Illinois, 949 workers had blood lead levels ≥ 10 μg/dL in 2015, declining to 734 in 2023, excluding facilities that were not engaged in active medical surveillance [25, 26]. In Illinois, there has been a noticeable decline in work-related lead testing, despite overall laboratory testing remaining stable. In contrast to declining testing, employment in at-risk industries remained relatively constant, and lead emissions either increased or stayed the same. Part of this decline is suspected to involve reduced or cessation of medical surveillance programs by employers following disruptions during the COVID pandemic.

Blood lead measurements derived from active medical surveillance of workers provides information on ongoing lead exposure in the workplace and can inform whether hygiene practices are effective. Our data show that some facilities have had zero workers tested for lead levels in recent years, despite

TABLE 3 | Estimated[a] number of workers[b,c] exposed at worksites without medical surveillance in Illinois, 2017–2023.

	On-site releases		Air releases		On-site and off-site releases	
	Exposed workers with positive blood lead levels per pound of lead released	Exposed workers with blood lead levels 25 µg/dL or more per pound of lead released	Exposed workers with positive blood lead levels per pound of lead released	Exposed workers with blood lead levels 25 µg/dL or more per pound of lead released	Exposed workers with positive blood lead levels per pound of lead released	Exposed workers with blood lead levels 25 µg/dL or more per pound of lead released
Year	N	N	N	N	N	N
2016	645	242	26	~	49	28
2017	364	137	22	~	36	20
2018	664	249	23	~	44	25
2019	560	210	20	~	36	20
2020	684	256	19	~	32	18
2021	579	217	13	~	28	16
2022	476	179	8	~	22	12
2023	366	137	7	~	18	10

[a]Generalized estimating equation (GEE) models were utilized to estimate the number of potentially exposed workers at sites without medical surveillance. GEE models were adjusted for year and within-facility variation. ~ GEE models did not converge.
[b]Range of workers with positive blood lead levels: 7–684 workers.
[c]Range of workers with blood lead levels 25 µg/dL or more: 10–256 workers.

consistent testing in previous years. This occurred despite the TRI data showing that lead emissions across various media remained high, above threshold or unchanged for these facilities. The Illinois ABLER program receives test results even if they are below the limit of detection, and indicates that there are worksites that have never had a worker tested by a CLIA lab. Linking TRI and active medical surveillance databases can, therefore, help identify employers that have stopped testing or never tested their workforce. Importantly, there is an urgent need to understand whether OSHA and other regulatory agencies have adequate resources to ensure effective compliance with lead standard requirements. The strategy described in this manuscript identified 39 worksites out of 477 known facilities using lead in their processes that have high environmental emissions with potentially exposed workers. The GEE models further reduced the list to 15 worksites where nearly all of the estimated exposed workers are employed. Our ABLES program plans to use this information to initiate proactive surveillance and outreach to these worksites by providing free blood lead testing to workers and contacting management at these sites about establishing voluntary medical surveillance programs. If voluntary testing identifies workers with elevated blood lead levels of $\geq 25\ \mu g/dL$, referrals will be made to OSHA, who can require medical surveillance and hygiene controls to better protect these workers.

Many workers are not solely exposed to lead, but to multiple hazardous substances. Workers at these facilities are exposed through inhalation and ingestion of contaminated air and dust, or through dermal contact with contaminated surfaces [1, 6]. Co-exposure to chemical mixtures may interact in synergistic patterns increasing the risk of adverse health outcomes in workers [27, 28]. Worksites with high environmental emissions may also be exposing workers to other toxic chemicals without adequate regulatory protection [29]. While some industries have established standards for specific metals and chemicals [1, 6], medical surveillance and the impact of co-exposure to chemical mixtures in workers at levels that exceed the population average are currently understudied and not fully understood. As an example, in this analysis, many of the above threshold polluters are power generation facilities that are known to release other heavy metals and toxics (e.g., mercury). Thus, the medium of lead emission informs risk management and exposure pathways for workers and nearby residential areas. Active medical surveillance of the workforce, regulatory programming, and employer-based workplace interventions are critical for effectively reducing lead exposure and protecting workers in industries that release lead, irrespective of the exposure medium. Furthermore, medical surveillance and regulatory measures aimed at reducing lead levels in the workplace could also reduce co-exposure to chemical mixtures in the workplace and benefit surrounding communities [30].

The present study is subject to some limitations. First, individual-level factors such as job title, health insurance status, and place of residence which can influence workplace lead testing and blood lead levels were not included in the analysis, as the study focused on facility-level lead emissions and testing. Second, the EPA's TRI does not collect information on lead emissions for all facilities as previously described [7]. Facilities included in the present analysis must manufacture, process, use, and release into the environment certain chemicals above established thresholds, or be classified under NAICS codes specified by the TRI inclusion criteria, and/or have 10 or more full-time employees [7]. Third, the lack of detailed facility-level information, including workforce size, hygiene practices, and administrative controls, all of which may influence lead exposure and the likelihood of lead testing or participation in active medical surveillance. Similarly, the TRI database can miss many facilities where lead exposure occurs, particularly those involved in construction and demolition, as these sectors are not required to report lead emissions to the EPA. Fourth, while we utilized the Dun & Bradstreet Hoovers database [20] to estimate the number of workers at sites engaged in medical surveillance, employment figures can fluctuate over time and may not accurately reflect true worksite employment numbers. The Dun & Bradstreet Hoovers database was also designed for business analytics rather than tracking employment changes across time at individual facilities. Regulatory agencies could address this critical gap in surveillance by mandating information on workforce size. Fifth, we could not use data on lead testing in all facilities since the majority of facilities were not involved in active medical surveillance of their workforce or had erratic testing (gaps in years with no one tested), which affected the inclusion criteria for the modeling. Future studies should leverage data from multiple states or the national ABLES program to better define the relationship between environmental releases and blood lead testing in workers.

5 | Conclusion

Our findings suggest that many worksites that emit lead into the environment, including some exceeding EPA reporting thresholds, do not appear to conduct blood lead testing among their workers. Our state ABLR program has very limited funding. The strategy employed in this analysis identified 15 worksites for outreach, which is manageable given available resources. Beyond local outreach efforts, new approaches are necessary to ensure that workers are better protected from occupational lead exposure. For instance, national medical surveillance policies could be reformed to integrate publicly available lead emissions data, enabling more targeted monitoring of worksites and industries with high potential for worker exposure to lead. A proactive medical surveillance strategy will ensure that workers in high-risk settings are regularly monitored, enabling early detection of elevated blood lead levels and timely interventions to protect worker health.

Author Contributions

Lee Friedman had full access to the data and was involved with conception and design, data analysis, interpretation of data, drafting and revisions of the manuscript, and approval of the final version. Chibuzor Abasilim was involved with conception and design, data analysis, interpretation of data, drafting and revisions of the manuscript, and approval of the final version. Brett Shannon and Dana Madigan were involved in the interpretation of data, drafting and revisions of the manuscript, and approval of the final version.

Acknowledgments

This publication was supported by funding from the National Institute for Occupational Safety and Health (NIOSH) through the Illinois Occupational Surveillance Program (U60OH010905). C.A. receives

support from the NIEHS P30 Chicago Center for Health and Environment (CACHET) (P30ES027792).

Disclosure by AJIM Editor of Record

John Meyer declares that he has no conflict of interest in the review and publication decision for this article.The contents are those of the authors and do not necessarily represent the official views of, nor an endorsement, by CDC/HHS, or the U.S. Government.

Ethics Statement

A claim of exemption was approved for this project by the University of Illinois Chicago IRB (#2023-0908).

Conflicts of Interest

The authors declare no conflicts of interest.

References

1. Agency for Toxic Substances and Disease Registry, *Toxicological Profile for Lead* (U.S. Department of Health and Human Services, Public Health Service, 2020), https://wwwn.cdc.gov/TSP/ToxProfiles/ToxProfiles.aspx?id=96&tid=22.

2. M. J. Kosnett, M. Berenji, A. D. Burton, et al., "ACOEM Position Statement: Workplace Health and Safety Necessitates an Update to Occupational Lead Standard Provisions for Medical Removal Protection, Medical Surveillance Triggers, and the Action Level and Permissible Exposure Level for Lead in Workplace Air: ACOEM Response to OSHA," *Journal of Occupational and Environmental Medicine* 65, no. 3 (2023): 170, https://doi.org/10.1097/JOM.0000000000002774.

3. W. A. Alarcon, S. Davidson, B. Dufour, et al., "Elevated Blood Lead Levels Among Employed Adults—United States, 1994–2013," *Morbidity and Mortality Weekly Report* 63, no. 55 (2016): 59–65, https://doi.org/10.15585/mmwr.mm6355a5.

4. M. Ash and J. Boyce, *Measuring Corporate Environmental Justice Performance* (University of Massachusetts Amherst, Department of Economics, 2008).

5. H. Prechel and L. Zheng, "Corporate Characteristics, Political Embeddedness and Environmental Pollution by Large U.S. Corporations," *Social Forces* 90 (2012): 947–970, https://doi.org/10.2307/41682684.

6. Occupational Safety and Health Administration, "Regulations (Standards - 29 CFR) 1910.1025 - Lead," 2013, https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.1025.

7. United States Environmental Protection Agency, "Toxics Release Inventory Guidance for Reporting Lead and Lead Compounds (Report EPA 745-B-19-020)," 2019, https://ordspub.epa.gov/ords/guideme_ext/guideme_ext/guideme/file/tri%20guidance%20for%20lead%20and%20lead%20compounds%20-%20revised%20march%202019.pdf.

8. E. Szwiec, K. Weems, L. Forst, L. S. Friedman, and T. Shen, "Distributions and Trends in Elevated Blood Lead Levels in Adults—Illinois, 2005-2017," *Illinois Morbidity and Mortality Bulletin* 4, no. 1 (2018): 13–32.

9. L. Rudolph, D. S. Sharp, S. Samuels, C. Perkins, and J. Rosenberg, "Environmental and Biological Monitoring for Lead Exposure in California Workplaces," *American Journal of Public Health* 80, no. 8 (1990): 921–925.

10. D. J. Valiante, S. S. U. Rab, and M. J. Stanbury, "Lead Hazard Surveillance Using an Environmental Reporting Database," *Applied Occupational and Environmental Hygiene* 12, no. 11 (1997): 769–772, https://doi.org/10.1080/1047322X.1997.10387761.

11. K. H. Gelberg and A. Fletcher, "Adult Blood Lead Reporting in New York State, 1994-2006," *Public Health Reports* 125, no. 1 (2010): 103–110, https://doi.org/10.1177/003335491012500114.

12. K. M. Fagan and M. J. Hodgson, "Under-Recording of Work-Related Injuries and Illnesses: An OSHA Priority," *Journal of Safety Research* 60 (2017): 79–83, https://doi.org/10.1016/j.jsr.2016.12.002.

13. V. Zartarian, A. Poulakos, V. H. Garrison, et al., "Lead Data Mapping to Prioritize US Locations for Whole-of-Government Exposure Prevention Efforts: State of the Science, Federal Collaborations, and Remaining Challenges," *American Journal of Public Health* 112, no. S7 (September 2022): S658–S669, https://doi.org/10.2105/AJPH.2022.307051.

14. V. G. Zartarian, J. Xue, A. G. Poulakos, et al., "A U.S. Lead Exposure Hotspots Analysis," *Environmental Science & Technology* 58, no. 7 (February 2024): 3311–3321, https://doi.org/10.1021/acs.est.3c07881.

15. United States Environmental Protection Agency, "Toxics Release Inventory Program," 2019, https://www.epa.gov/enviro/data-downloads.

16. Illinois Health and Hazardous Substances Registry Act [410 ILCS 525], Section 2310-365 of the Civil Administrative Code of Illinois [20 ILCS 2310/2310-365], the Developmental Disability Prevention Act [410 ILCS 250], and the Lead Poisoning Prevention Act [410 ILCS 45], "Subpart D: Occupational Disease Registry. Section 840.300 and 840.305 (Source: Amended at 36 Ill. Reg. 8379, Effective May 18, 2012)." https://www.ilga.gov/Commission/jcar/admincode/JCARTitlePart.asp?Title=077&Part=0840.

17. State of Illinois Department of Public Health, "Annual Report Illinois Health and Hazardous Substances Registry July 2022 Through June 2023," 2023, https://dph.illinois.gov/content/dam/soi/en/web/idph/publications/idph/data-and-statistics/epidemiology/hazardous-substances/fy23-ihhsr-annual-report.pdf.

18. Centers for Disease Control and Prevention, "Clinical Laboratory Improvement Amendments," 2024, https://www.cdc.gov/clia/php/about/index.html.

19. E. J. Pacer, C. D. Palmer, and P. J. Parsons, "Determination of Lead in Blood by Graphite Furnace Atomic Absorption Spectrometry With Zeeman Background Correction: Improving a Well-Established Method to Support a Lower Blood Lead Reference Value for Children," *Spectrochimica Acta, Part B: Atomic Spectroscopy* 190 (April 2022): 106324, https://doi.org/10.1016/j.sab.2021.106324.

20. Dun & Bradstreet, *Search & Build a List* (Company Size, 2024), https://app-hoovers-dnb-com.proxy.cc.uic.edu/search/company.

21. A. E. Hubbard, J. Ahern, N. L. Fleischer, et al., "To GEE or Not to GEE: Comparing Population Average and Mixed Models for Estimating the Associations Between Neighborhood Risk Factors and Health," *Epidemiology* 21, no. 4 (2010): 467–474, https://doi.org/10.1097/EDE.0b013e3181caeb90.

22. D. H. Koh, S. J. Locke, Y. C. Chen, M. P. Purdue, and M. C. Friesen, "Lead Exposure in US Worksites: A Literature Review and Development of an Occupational Lead Exposure Database From the Published Literature," *American Journal of Industrial Medicine* 58, no. 6 (2015): 605–616, https://doi.org/10.1002/ajim.22448.

23. K. B. Egan, R. J. Tsai, and S. O. Chuke, "Integrating Childhood and Adult Blood Lead Surveillance to Improve Identification and Intervention Efforts," *Journal of Public Health Management and Practice* 25, no. Suppl 1 (2019): S98–S104, https://doi.org/10.1097/PHH.0000000000000872.

24. National Academies of Sciences, Engineering, and Medicine, *A Smarter National Surveillance System for Occupational Safety and Health in the 21st Century* (The National Academies Press, 2018), https://doi.org/10.17226/24835.

25. P. J. Seligman and W. E. Halperin, "Targeting of Workplace Inspections for Lead," *American Journal of Industrial Medicine* 20, no. 3 (1991): 381–390.

26. National Institute for Occupational Safety and Health,"Lead in the Workplace: Trends in Workplace Lead Exposure," 2024, https://www.cdc.gov/niosh/lead/data/index.html.

27. Y. Wang, M. Qiao, H. Yang, et al., "Investigating the Relationship of Co-Exposure to Multiple Metals With Chronic Kidney Disease: An Integrated Perspective From Epidemiology and Adverse Outcome Pathways," *Journal of Hazardous Materials* 480 (2024): 135844, https://doi.org/10.1016/j.jhazmat.2024.135844.

28. M. Koszewicz, K. Markowska, M. Waliszewska-Prosol, et al., "The Impact of Chronic Co-Exposure to Different Heavy Metals on Small Fibers of Peripheral Nerves. A Study of Metal Industry Workers," *Journal of Occupational Medicine and Toxicology* 16, no. 1 (2021): 12, https://doi.org/10.1186/s12995-021-00302-6.

29. Occupational Safety and Health Administration, "Directives: OSHA Instruction; National Emphasis Program-Lead," 2008, https://www.osha.gov/enforcement/directives/cpl-03-00-009.

30. K. B. Egan, R. J. Tsai, and S. O. Chuke, "Integrating Childhood and Adult Blood Lead Surveillance to Improve Identification and Intervention Efforts," *Journal of Public Health Management and Practice* 25, no. Suppl 1 (2019): S98–S104, https://doi.org/10.1097/PHH.0000000000000872.