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Assessment of Lead Exposures during Abrasive Blasting and Vacuuming in Ventilated Field Containments: A Case Study

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Abstract

Painting contractors have struggled with implementation and assessment of lead exposure controls leading to persistently elevated blood lead levels in this high-risk group of workers. The objective of this study was to assess the intensity of lead exposures based on commonly used air velocities inside field containment structures during abrasive blasting and vacuuming. Exposures were assessed over 14 days from April to July 2021 at a tainter gate and bridge lead paint removal project. Personal air samples, skin wipes, air velocity readings, and blood lead samples were collected. The geometric mean (GM) lead exposure for abrasive blasters and vacuumers was ≥4 × the OSHA Lead Permissible Exposure Limit (PEL) of 50 μg/m^3. There was high variability in the personal lead exposures (Geometric standard deviation (GSD) 4.0 - 5.0). The GM hand wipe exposures exceeded a Dermal PEL of 500 μg/wipe (abrasive blaster 564 μg/wipe and vacuumer 754 μg/wipe). Residual lead was measured on workers' hands in 67% of the post hand washing samples. Air velocities measured inside of the field containments ranged from 107 feet per minute to 229 feet per minute. The effect of air velocity on the concentration of lead on workers' hands after work ($F = 0.58$, $p = 0.35$) and airborne lead concentration was not significant ($F = 0.36$, $p = 0.48$). Six of the eight workers' blood lead levels increased after exposure to lead. There was a non-statistically significant relationship between lead remaining on workers' hands after handwashing and an increase in blood lead level. This is the first study that assessed both ventilation flow rates used in the industrial painting industry and measurements of airborne and dermal (hands) lead exposures. For the projects evaluated, the collected exposure data indicate that air velocities frequently used in the industrial painting industry to ventilate field containment structures did not tend to prevent an increase in worker blood lead and were ineffective for adequately controlling elevated concentrations of airborne lead and preventing contact with workers' hands.

Keywords

Occupational Lead Exposure, Blood Lead, Engineering/Work Practice Controls

1. Introduction

In 1993 OSHA implemented a comprehensive health-based standard requiring employers to institute a series of risk management controls to minimize inhalation and ingestion lead exposures and prevent biological uptake. Like other OSHA health-based standards, it is the employer's responsibility to select feasible engineering controls and work practice controls to achieve compliance [1]. For the first decade after the lead construction standard was enacted, many painting contractors (contractors) had difficulty designing and implementing feasible exposure control methods—as few comparable engineering controls could be adopted from their peers in the general industry. Failure to comply with OSHA's lead requirements resulted in numerous OSHA citations for contractors and persistently elevated blood lead levels among workers in the painting industry [2] [3] [4].

These struggles continue to this day, with contractors having the most OSHA citations for non-compliance with key provisions of the construction lead standard and the largest proportion (29%) of workers exceeding the OSHA medical removal criteria of 50 μg/dl despite advances in engineering control technologies tailored to the painting industry [2] [3] [4] [5]. Abrasive blasters and vacuumers are considered a high-risk exposure group due to exposures that routinely exceed the OSHA lead in construction PEL and experience regular contact to lead 50% to 100% of the work shift [5]. To address the industry exposure controls knowledge gap and assist with the implementation and evaluation of risk management controls, the leading industrial painting trade organization, Steel Structures Painting Council (SSPC), developed a Guidance Document (Guide 6) in the 1990s [6]. The initial guide established minimum air velocity rates within a containment system for contractors to demonstrate the implementation of feasible engineering controls. The SSPC adopted 60 feet per minute (fpm) down draft and 100 fpm cross draft air velocity from the American Conference of Governmental Industrial Hygienists [7] publication Industrial Ventilation, A Manual of Recommended Practice (Figure VS-80-01—Abrasive Blasting Room) for ventilating field abrasive blasting containments. In 2001 SSPC asked OSHA to clarify the agency's meaning of feasible ventilation controls for large field containment structures. SSPC also wanted OSHA to issue a policy memorandum stating if an employer achieved an airflow of 60 fpm when operated in a down-draft or 100 fpm when operated in a cross-draft inside of a containment structure, compliance with the lead standard is established [8]. OSHA issued written clarification stating 60 fpm and 100 fpm were not acceptable as "rule of thumb" flow rates as they were design parameters for "operator visibility" and not appropriate for controlling lead hazards [8]. Despite OSHA's written guidance that default air flows are not suitable for controlling worker lead exposures, there has been widespread adoption of SSPC's suggested air velocities by governmental and private agencies for abrasive blasting containment structures with sparse evidence to support its effectiveness in reducing worker exposure to lead.

Numerous studies have evaluated lead exposure among industrial bridge painters [9] [10] [11] [12]. Still, we could find no study that assessed both ventilation flow rates used in the industrial painting industry and measurements of airborne and dermal (hands) lead exposures—despite the fact industrial ventilation is an important determinant (fixed effect) of worker exposure [13]. The objective of this study was to assess the intensity of lead exposures based on frequently used air velocities inside field containment structures during abrasive blasting and vacuuming.

2. Methods

2.1. Settings

We selected an industrial painting contractor NAICS code 23832 (Industrial Painting code) for this study using our existing contacts within the painting industry. We chose them because of their successful track record implementing OSHA exposure controls during industrial, lead paint removal projects with over 20 years of experience in the industry. The contract work described in this study involved the complete removal of the existing lead-containing paint from steel tainter gates and a bridge. The contractor performed their work from April 2021 to July 2021. They were responsible for erecting a work access platform and containment system (SSPC Class 1A) at both project sites to prevent the release of lead paint into the environment and reduce worker exposures. The work access platform at both sites consisted of cables anchored to the structure's concrete parapet walls with a solid deck fastened to the support cables. Impermeable, coated tarpaulins were used as the containment material for the entire containment system at both project sites.

2.2. Exposure Groups

The contractor employed six workers (4-abrasive blasters/2-vacuumers) at the tainter gate project and two workers (1-abrasive blaster/1-vacuumer) at the bridge project who worked every day inside of the active containment structure during the lead paint removal process. All eight workers volunteered for the study. They were all certified by SSPC as craftsmen in industrial abrasive blasting, painting, and lead paint removal. At each work site, the contractor's support staff included a superintendent, quality control inspector, and a safety officer. The mean age of the study participants was 40 years (range 24 - 54 years), and the mean experience level removing lead paint was 12 years (range 4 - 32 years). They were all male. Six out of the eight workers were smokers. The project safety officer was sampled as a control at each site. The data collected from the project safety officer is not included in the descriptive statistics.

2.3. Work Task Description

Abrasive Blasting

Abrasive blasting entails using compressed air to propel abrasive blast media against a surface (steel structure) to remove the existing coating. Each abrasive blaster on both projects used a new No. 8 nozzle during abrasive blasting. We verified the nozzle pressure using a hypodermic needle pressure gauge. The mean nozzle pressure measured was 110 pounds per square inch (psi). Both projects' abrasive blast media grade was a 30/60 coal slag (expendable abrasive) mix. The existing coating at both locations tightly adhered to the steel structure with a mean thickness of 9 mils.

Vacuuming

A common practice in the industrial abrasive blasting industry is to vacuum the abrasive out of the containment structure while abrasive blasting is taking place to minimize the load the spent abrasive places on the steel structure and after abrasive blasting to complete the removal of all spent debris. For this study, the vacuumers worked on the containment floor using a 3-inch industrial vacuum line that was connected to a 225-horsepower trailer mounted vacuum.

Sampling Strategy

Worker exposure assessments were conducted from April to July 2021 at the two project sites. The exposure assessments were conducted as part of the contractor's planned OSHA compliance sampling. The contractor abrasive blasted and vacuumed the spent blast media for ten days at the tainter gate project and four days at the bridge project. Personal air samples, skin (hand) wipes, and air velocity readings were collected all 14 days that abrasive blasting and vacuuming were conducted.

All workers had their hands wiped at both projects every day of sampling. Air samples were not collected from every worker each day. For the tainter gate project, each day of abrasive blasting, only one of the four abrasive blasters was sampled for airborne lead exposure due to the request of the participating contractor. Every abrasive blaster's personal exposure at the tainter gate project was assessed at least twice. At the bridge project, the one abrasive blaster was sampled every day. Personal air samples for the vacuumers were collected only on the first day of vacuuming at both locations because the workers were unwilling to wear the battery-operated sampling pump for more than one day.

Air Sample Collection

Sixteen personal air samples were collected over the 14-day sampling campaign. One of the ten personal air samples collected during abrasive blasting at the tainter gate project was damaged and could not be analyzed. Personal air monitoring was performed at both projects 8-hours per day. Abrasive blasting was performed for the entire shift on days that abrasive blasting occurred. Vacuuming was performed every day during and after abrasive blasting, approximately 4 to 6 hours per shift.

We collected personal air sampling for lead using 37-millimeter diameter, 0.8 μm pore size mixed cellulose ester membrane filters contained in plastic sampling cassettes. The sampling media was connected with Tygon tubing to calibrated, battery-operated Buck Libra (L-4) personal sampling pumps that maintained a flow rate of (±5)% of the set flow. Airflow rates were set before and checked during and after monitoring to ensure consistent operation. Calibration was conducted with a primary flow calibrator (A.P. Buck—mini buck M-5 bubble meter). A rotameter that was calibrated against the primary flow calibrator was used to verify airflow rates in the field. Sample air volumes were calculated from the average measured flow rate and the duration of the sampling period. The sampling pumps were calibrated at a flow rate of 2.0 liters of sampled air per minute. During personal sampling, the filter cassettes were attached to the worker's shirt at the shoulder (in the worker's breathing zone/outside of the Type CE abrasive blast hood to comply with OSHA mandatory sampling requirements). After air sampling, the samples along with field blanks (one per shipment) were sent to an American Industrial Hygiene Association-accredited laboratory for analysis by ASTM E-1979-17/EPA SW846 7000B. No detectable lead was measured on the field blanks.

Hand Wipe Collection

One hundred and seventy-seven hand wipe samples were collected. Lead Wipe™ wipes were used to measure the concentration of lead on workers' hands each day before work started, at the end of the day before hand washing, and at the conclusion of the workday after handwashing during abrasive blasting and vacuuming. A single wipe was used for each assessment. The researchers donned a clean pair of latex gloves before handling each sample to prevent cross-contamination. We tore open a wipe packet, and the worker removed the wipe. Each worker wiped their palms first and the top surface of both sides of their hands for 30 seconds using normal pressure. At the completion of the sampling, the worker placed the wipe sample into a pre-cleaned centrifuge tube. An unused hand wipe was treated in the same manner as the worker hand wipe samples to serve as a field blank. Each day after sampling was finished, all of the samples were shipped to an American Industrial Hygiene Association (AIHA) accredited lab. The wipe samples were analyzed in accordance with ASTM-E-1979/EPA SW846 7000B. No detectable lead was measured on the field blanks. The contractor's workers used a NIOSH licensed proprietary cleanser called Hygenall© Leadoff™ Foaming Soap (Leadoff™) at the end of the work shift.

Containment Ventilation and Air Velocity Measurements

Ventilation through the tainter gate containment structure was supplied by a 40,000 cubic feet per minute (cfm) dust collector that was placed above the containment structure on a pedestrian bridge. The enclosure was ventilated with 4-20-inch diameter exhaust ducts placed evenly across the top of the containment structure (downdraft). Air supply inlets were provided at the base of each containment structure also evenly spaced. The tainter gate containment volume was approximately 42,029 ft^3 (31 ft. long × 42 ft. wide × 32.28 ft. high). There were 57 air exchanges per hour. The bridge containment volume was approximately 2880 ft^3 (40 ft. long × 8 ft. wide × 9 ft. high). The contractor used a 2000 cfm dust collector to ventilate each tainter gate containment that resulted in approximately 42 air exchanges per hour. The enclosure was ventilated with 2- 20-inch diameter exhaust ducts spaced evenly across the top of the containment structure (cross draft). Air supply inlets were provided at the base of each containment structure also evenly spaced. Cross-sectional airflow measurements taken throughout each containment structure indicated that the airflow through each containment was consistent for the majority of the containment with stagnant area observed in the corners of each containment. We measured the air velocities in feet per minute (fpm) inside of each containment structure using a Dwyer 471B-1 Thermo-Anemometer. We divided each containment structure into five equal sections for sampling purposes. Each day of sampling, we took twenty-five readings in each containment section resulting in 125 air velocity readings per containment structure. In total, 1750 air velocity measurements were taken. The air velocity readings were taken in a cross-sectional area perpendicular to the air flow within each sampling area 5.5 feet above the worker access scaffolding to approximate the air flows in the workers' breathing zone.

We performed smoke tests to observe the air velocity patterns within each containment structure and found minimal turbulence. Observations of the airflow patterns during abrasive blasting and vacuuming confirmed our baseline air velocity patterns. Clear visibility was achieved within the containment structure approximately five minutes after the contractor ended abrasive blasting operations. We also measured negative pressure throughout each containment structure with a Dwyer Series 2000 Magnehelic® Differential Pressure Gage. The overall mean (±SD) negative pressure in each containment was 0.05" water column (±0.01).

Blood Lead Levels

Before exposure on each project and two months afterwards, the contractor involved in the study had their workers' blood drawn (venous blood sample) to measure the concentration of lead as part of their ongoing medical surveillance program. All lead-exposed workers at both sites (n = 8) participated in the BLL testing. Before the de-identified BLL data were made available to the authors, the project study was submitted to the University of South Florida's Institutional Review Board. They reviewed it and determined it was exempt (IRB No. Pro00035891).

Abrasive Blast Media

Both projects used an expendable blasting media (coal slag). Laboratory data provided by the coal slag manufacturer indicated no detectable lead was measured in the abrasive blast media at either site.

Existing Coating

We removed paint samples following ASTM D5702-07(2012) Standard Practice for Field Sampling of Coating Films for Analysis for Heavy Metals as a guide to determine the concentration of lead in the existing coating at both sites. The paint samples were scraped from the substrate. We placed each sample into a pre-labeled Ziploc® plastic resealable bag and labeled, recorded on a chain of custody form. An AIHA accredited laboratory analyzed the paint samples in accordance with EPA method SW846 3050B/6010D. The mean lead concentration in the dry paint film of the tainter gate was 38,150 parts per million (ppm) (weight/weight) and 2400 ppm in the bridge coating.

Exposure Modifiers

Personal protective equipment worn by the abrasive blasters and vacuumers included a Type CE continuous flow (blast hood) respirator with an assigned protection factor of 1000, abrasive blast coverall and leather gloves. The vacuumers wore a Type CE continuous-flow abrasive blast helmet respirator because they worked inside the containment during abrasive blasting. A decontamination trailer that maintained negative pressure within to prevent cross-contamination from the dirty and clean sides was provided at both project sites with a designated clean and dirty side. Smoking and eating was only allowed in a designated areas after handwashing.

OSHA PEL

The effectiveness of the air velocity inside of the containment in controlling lead inhalation exposure was assessed based on comparisons of worker breathing zone exposures to OSHA's 8-hour time weighted average lead exposure limit 50 μg/m^3.

Dermal PEL (*DPEL*)

To estimate the acceptability of lead on workers hands, we converted the lead PEL to a "mass-based dose equivalent" (DPEL) [14].

DPEL − PEL (μg/m^3) × 10 m^3/day inhaled air volume = 50 μg/m^3 × 10 m^3 = 500 μg/shift.

3. Results

The summary statistics (arithmetic mean (am) /standard deviation (sd), geometric mean (gm)/standard deviation(gsd), median) were performed using non transformed data. To check if the normal distribution model fits the study exposure data, a Shapiro-Wilk W test was used. Graphical methods: QQ-Plot chart and Histogram were also used to evaluate the data that further confirmed a log normal distribution. For the skin (hand) wipe samples, the Shapiro-Wilk tests showed a significant departure from normality, $W(59) = 0.812$, $p < 0.001$. For the personal breathing zone air samples, the Shapiro-Wilk tests showed a significant departure from normality, $W(59) = 0.818$, $p < 0.001$. The exposure data (personal and skin (hand) wipes) were lognormally distributed and were log-transformed before all other analyses.

A one-way random effects analysis of variance (ANOVA) model was used to evaluate within-worker and between worker differences. We also evaluated the data using analysis of covariance (ANCOVA) incorporating air velocity as a covariate in a one-way random effects model. Correlation between airflow and personal and hand wipe lead concentrations were also evaluated by regression. We used the Mann-Whitney U test to assess the variability between exposure groups.

The statistical analysis was performed using GraphPad Version Prism 8.3 and R Version 4.1 software [15] [16]. For all samples with a lead concentration less than the lab's detection limit (2 μg/air/5μg/wipe), we used a substitution method calculated by the lab detection limit/2 [17].

The overall mean (±SD) air velocity was 174 feet per minute (±48.3) (range 107 - 229 fpm); 193 feet per minute (±33.5) (range 123 - 229 fpm) for the tainter project; 109 feet per minute (±2.5) (range 107 - 112 fpm) for the bridge project.

Table 1 summarizes the hand wipe and personal air sampling data collected during the study independent of air velocity. Lead was detected in all 59 after-work hand wipe samples collected. Out of the 59 after-work hand wipe samples collected, 7-abrasive blasters and 5-vacuumers samples (20%) exceeded the

Table 1. Full-Shift TWA OSHA personal lead levels during abrasive blasting and vacuuming and personal hand wipe lead levels by work task.

Work Activity	n	AM	SD	GM	GSD	Median	No. Non-Detects	Range
BeforeWork[A] (μg/wipe)								
All	59	10.5	15.4	6.2	2.5	6.0	23	2.5 - 85.7
Abrasive Blaster	42	9.9	13.3	6.2	2.4	6.0	15	2.5 - 69.7
Vacuumer	17	12	20.1	6.1	2.9	4.9	8	2.5 - 85.7
After Work[A] (μg/wipe)								
All	59	383.2	331	274.4	2.4	296.0	-	30.8 - 1520
Abrasive Blaster	42	368.7	322.6	261.0	2.4	301.0	-	30.8 - 1520
Vacuumer	17	419.0	358.7	310.7	2.2	258.0	-	117 - 1250
After Work[B] (μg/wipe)								
All	59	22.1	26.6	10.1	3.7	7.8	22	2.5 - 112.0
Abrasive Blaster	42	21.1	27.4	9.1	3.8	8.0	19	2.5 - 112.0
Vacuumer	17	24.5	25.1	12.7	3.5	7.8	3	2.5 - 74.3
Air Exposure (μg/m^3)								
Abrasive Blaster	13	597.6	610.4	290.1	4.3	380.0	-	29 - 2000
Vacuumer	2	200	70.7	193.6	1.4	200	-	150 - 250

[A]After work for the day—before handwashing; [B]After work for the day—after handwashing with Leadoff™; n = Total number of samples collected.

study established DPEL of 500 μg/wipe. The after-work arithmetic mean exposure for the abrasive blasters/vacuumers was 74%/84% of the DPEL. The 95th percentile point estimate hand wipe exposure values for the abrasive blasters/vacuumers were 1125 μg/1113μg, and the upper tolerance limits were 1704 μg/2137μg.

The abrasive blasting exposure group had the highest lead concentration (1520 μg/wipe) on the workers' hands. The after-work hand wipe sample data indicates the vacuumers' mean (am/gm) exposure was greater than the abrasive blaster exposure group. The within-worker GSD was the major component of the overall variability for each comparison group, suggesting the exposure differences among work tasks were most likely from exposure controls.

The measured airborne lead concentrations for both work tasks were high based on a direct comparison to the OSHA PEL. The geometric mean lead exposure for abrasive blasters was ≥5 × the OSHA Lead Permissible Exposure Limit. There was high variability in the personal lead exposures (GSD 4.0 - 5.0). The 95th percentile personal point estimate exposure value for the abrasive blasters was 3625 μg/m^3, and the upper tolerance limit was 18,554 μg/m^3.

Table 2 summarizes the frequency of lead measured on workers' hands before work and after handwashing. Despite the use of LeadOff^{TM} during handwashing at the end of the workday, 37 (67%) of the 59 samples show lead was present on workers' hands (Table 2). Similarly, 36 (61%) of the 59 samples measured lead on their hands before work started for the day. Two of the workers had lead present before work, and after handwashing every time a hand wipe sample was collected. Six (75%) of the eight workers had lead present on their hands before work started ≥ 50% of the time samples were collected (Table 2). Seven (88%) of the eight workers had lead present on their hands after handwashing at the end

Table 2. Lead concentration of workers hands before and after exposure.

Study Subject	Total no. of samples	Before work no. of samples measured lead	% Before Work	Total no. of samples	After AH no. of samples measured lead	% AH	Handwashing % lead removal efficiency (mean value) (AWH-AW)	Mean Lead concentration μg/wipe AW
1	9	7	78	9	5	56	94.5	450.7
2	10	5	50	10	5	50	92.8	241.5
3	9	5	56	9	5	56	91.8	399.1
4	10	6	60	10	4	40	86.6	243.7
5	7	3	43	7	5	71	95.0	358.1
6	6	2	33	6	5	83	88.2	232.9
7	4	4	100	4	4	100	93.2	644.1
8	4	4	100	4	4	100	93.1	753.8
Total	59	36	-	59	37	-	-	-

AH = After Work Handwashing; AW =After Work.

of the workday ≥ 50% of the time hand wipe samples were collected, suggesting inadequate handwashing. For each study subject, we subtracted the pre-shift lead concentration from the post-shift lead concentration (before handwashing) to measure the burden of occupational exposure. The mean lead concentration for each study subject for all sampling periods is shown in Table 2.

Mean Lead Concentration After Work = the After Work lead on workers' hands minus the before work lead on workers hands.

Exposure Outcomes by Air Velocity

The results of the ANCOVA indicate the effect of air velocity on the concentration of lead on workers' hand after work was not significant (F = 0.58, p = 0.35). Similarly, the effect of the air velocity on the airborne lead concentration was also not significant (F = 0.36, p = 0.48).

Regression models for relationships between air velocity and the 8-hour TWA personal lead concentrations and lead on workers' hands after work are plotted as Figure 1 and Figure 2.

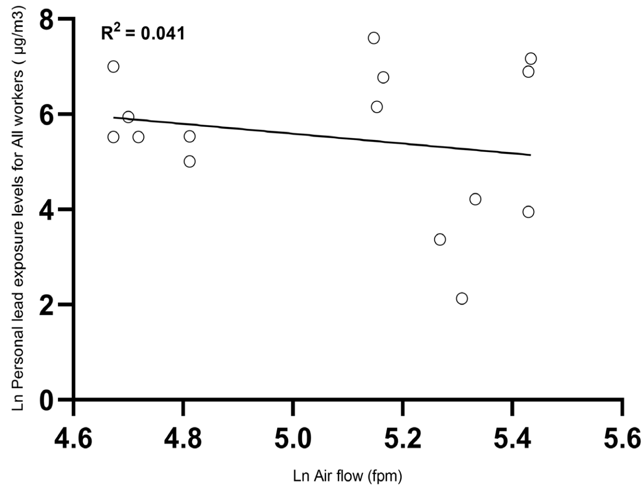

Figure 1. Relationship between Full Shift TWA Personal (OSHA Compliance Samples) measurements and Air Velocity measurements (Abrasive Blasters & Vacuumers).

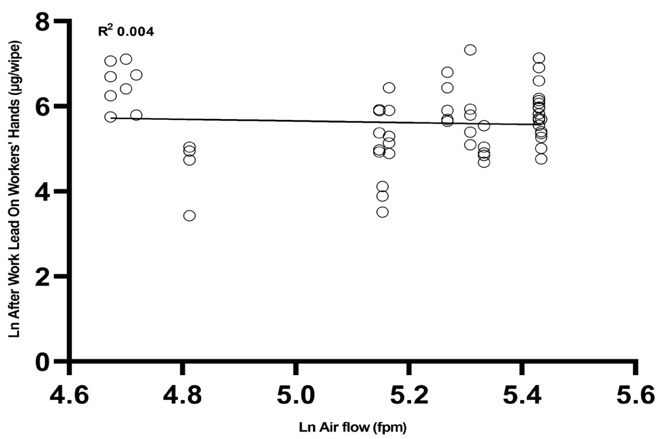

Figure 2. Relationship between After Work Skin (hand wipe) Lead Concentration and Air Velocity (Abrasive Blasters & Vacuumers).

Regression analysis indicate a weak and non-statistically significant ($p = 0.5$) relationship between air velocity and personal air concentration. Likewise, the relationship between air velocity and the after-work skin (hand wipe) lead concentration was weak and non-statistically significant ($p = 0.7$).

Blood Lead Levels

Six of the eight workers' blood lead levels increased after exposure to lead at the worksite (Table 3). The abrasive blaster work classification saw the greatest individual increase between testing periods (10 µg/dl). Amongst the abrasive blasters, there was a mean (±SD) increase in blood lead levels of 5.8 µg/dl (±4.0). The vacuumers' blood lead levels also increased post-exposure with a mean increase of 3.7 µg/dl (±4.1). All blood lead level samples were less than the OSHA mandated level that triggers medical surveillance under the lead standard (40 µg/dl).

Of the eight study subjects, the measured blood lead level increased in six, and did not increase in the other two. These two groups perfectly correspond to project or work site: all six with an increase were at Tainter Gate, while the other two at Bridge either decreased or remained constant.

There were 22 measurements where there was no lead measured after hand washing from all participants ($n = 59$ measurements). All 22 of these measurements came from study subjects whose blood lead level ultimately increased; this was not a feasible predictor for odds of an increase in blood lead level. We also evaluated a linear regression model with an outcome of change in blood lead level, predicted by the mean lead concentration remaining on workers hands after-handwashing. There was a non-statistically significant relationship (positive correlation coefficient 0.48, $p = 0.34$) between lead remaining on a workers' hands after handwashing and an increase in blood lead level.

Table 3. Change in worker blood lead level after exposure.

Study Subject	Work Task	Initial blood lead level µg/dl	Follow up blood lead level µg/dl	Change in blood lead level µg/dl
Tainter Gate				
1	Abrasive Blaster	6	15	9
2[A]	Abrasive Blaster	21	25	4
3	Abrasive Blaster	1	7	6
4	Abrasive Blaster	3	13	10
5[A]	Vacuumer	5	12	7
6	Vacuumer	8	13	5
Bridge				
7	Abrasive Blaster	7	7	No change
8	Vacuumer	13	12	-1

[A]Nonsmoker.

4. Discussion

This is the first study to report the intensity of lead exposures based on commonly used air velocities inside field containment structures during abrasive blasting and vacuuming. For the projects evaluated, the collected exposure data indicate that air velocities frequently used in the industrial painting industry to ventilate field containment structures were ineffective for adequately controlling elevated concentrations of airborne lead and preventing contact with workers' hands. Under the exposure conditions measured during this study, blood lead levels tended to increase despite the use of commonly used industry exposure controls.

The majority of the personal exposure samples exceeded the lead PEL suggesting inadequate engineering controls at both sites. This is supported by the fact that the within-worker GSD was the major component of the samples' overall variability, indicating the exposure differences among work tasks were most likely from poorly performing exposure controls and not individual worker behaviors. As a result, exposure reduction is more likely achieved by improved general ventilation within the containment. There was not a significant difference in personal exposure and the concentration of lead deposited on workers' hands at the air velocities evaluated in this study for either work task.

Overall, the measures of the global association between air velocity and hand wipe, and air velocity with personal air measurements were not significant. More data is needed to gain a better understanding of the relationship between air velocity and lead personal levels and lead on workers hands. Our findings are consistent with previous research conducted by the Federal Highway Administration (FHWA) regarding air velocities inside a field containment system during abrasive blasting [18]. The FHWA found that worker personal lead exposures were not significantly different at air velocities that ranged from 70 fpm to 300 fpm. The FHWA study did not evaluate the concentration of lead on workers' hands. Other research on this topic indicates that despite general ventilation within the containment structure during abrasive blasting and vacuuming, exposures often exceed the lead PEL [5] [10] [11] [19] [20].

Our study results also support OSHA's and other researchers' conclusions that the regularly used air velocities in field abrasive blasting and vacuuming containments are not appropriate for the adequate control of worker exposures [8] [12].

The airborne lead exposures measured during this study support OSHA's engineering controls technological feasibility assessment finding that mechanical ventilation alone is unlikely to reduce exposures to the permissible lead exposure limit (50 $\mu g/m^3$) during abrasive blasting and vacuuming operations [21].

We assessed the concentration of lead on workers' hands for the duration of both projects and found elevated levels of lead deposited on workers' hands. Our findings are important because residual lead on the skin increases the risk of lead uptake by hand-to-mouth ingestion [22]. The concentration of lead measured on the workers' hands in this study is consistent with our previously conducted research on this topic and the research of others [9] [23]. Abbas Virji *et al.* [9] used hand wipes to assess the personal hygiene practices of abrasive blasters and painters working on bridge rehabilitation projects. Abbas Virji *et al.* [9] found elevated lead on abrasive blasters' hands at their lunch break (1192 µg-GM) and the end of the day (447 µg-GM). Similarly, Askin and Volkmann [24] assessed the association between lead on a worker's hands and the uptake of lead at a lead processing facility and found a statistically significant positive correlation coefficient of 0.61 (p = 0.002). The findings from this study also support existing research from Essewin *et al.* [25] on the effectiveness of Hygenall soap in reducing lead on workers hands compared to commonly used soap in the industrial painting industry.

Our assessment of the concentration of lead on workers' hands through the analysis of hand wipes provides evidence for the role work practice controls play in preventing the uptake of lead through ingestion exposure. As the 95th percentile point estimate and upper tolerance limit both exceeded the DPEL for the abrasive blasters and painters, we classified the exposure profile for both work tasks as unacceptable.

It further indicates the ingestion pathway is a major route of exposure among abrasive blasters and vacuumers and underscores the importance of evaluating all routes of exposure to assess the overall risk to worker health. Although OSHA has not established an exposure limit for lead on workers' skin, there is interest in establishing a risk-based limit for dermal exposures in the construction industry that may help reduce exposure and uptake [26].

Workers received intense lead exposure on their hands despite the fact they wore gloves while working inside of the containment. This suggests the workers did not wear their gloves properly, did not follow proper donning and doffing procedures, or a combination of both. According to Evans *et al.* [27], it is common to find a chemical of interest inside workers' gloves as improperly used or maintained PPE limits the protection afforded the wearer. Greater emphasis should be placed on the training of workers on how to wear personal protective equipment properly. The percentage of hand wipe samples that contained lead after hand washing was not a good predictor for odds of an increase in worker blood lead level. Residual lead remaining on the workers' hands after hand-washing was a moderate predictor of increase in worker blood lead level for the tainter gate workers.

Despite a small sample size, our findings are generalizable to other abrasive blasting and painting projects in the industrial painting sector as the adoption of SSPC flow rates across the country has resulted in standardized containment and ventilation systems that have been optimized to meet 60 fpm downdraft and 100 fpm cross draft requirements. In addition, 88% of the contractors in NAICS 23832 employ less than nine employees [28].

5. Conclusions

Personal and hand lead exposures were not adequately controlled using air velocities commonly used in the industrial painting industry resulting in increased blood lead levels in six out of the eight study participants.

Contractors must understand the effectiveness and limitations of the most common engineering control used during abrasive blasting and vacuuming (general ventilation) to reduce worker exposures to prevent uptake. This study provides a basis for further research evaluating the effectiveness of lead exposure controls to improve the understanding of the factors that influence lead exposure and elevated BLLs in the industrial painting industry.

The lack of a PEL dermal dose equivalent to protect workers from lead exposure highlights a current gap in OSHA regulatory policy that needs to be addressed at an organizational level.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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