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Assessment of lead exposure controls on bridge painting projects using worker blood lead levels

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ABSTRACT

A retrospective analysis of worker blood lead levels (BLL) was conducted using blood lead data collected by four bridge painting contractors before and after lead exposure. The objective of the study was to evaluate the effectiveness of exposure controls in preventing elevated blood lead levels (> 25 μg/dl) during bridge painting projects. The contractors selected for the study submitted BLL data for 289 workers representing ten work tasks and 11 bridge painting projects. In total, 713 blood lead levels results were evaluated.

The mean blood lead level for all work classifications combined was 10.9 μg/dl at baseline compared with 14.9 μg/dl after two months of exposure and 15.0 μg/dl after four months of exposure. Two months after initial exposure, 29% of the painters and 35% of the laborers had a 10 μg/dl incremental increase or greater in blood lead level. Likewise, 18% of the painters and 26% of the laborers had a blood lead level greater than 25 μg/dl during the same time. The blood lead levels that exceeded the 25 μg/dL threshold ranged from 30μg/dL-63 μg/dL for painters and 26 μg–56 μg/dL for laborers.

All work tasks with high-intensity exposure (abrasive blaster/painter, abrasive blaster, painter & laborer) experienced an average blood lead level increase that ranged from 0.2 μg/dl to 8.9 μg/dl two months after initial exposure. Blood lead testing conducted after modified exposure controls (two months after the initial follow-up blood testing) were implemented showed a decrease in average blood lead levels (range −0.14 μg/dl to −2.7 μg/dl) for two high-intensity exposure work tasks. In comparison, the other two high-intensity work tasks had moderate increases (range 1 μg/dl to 2.4 μg/dl). The modified exposure controls included an increase in the air velocity inside of the work containment and an administrative control in the form of additional worker training on lead exposure prevention. The reduction in the 95th percentile (point estimate) BLL exposure profile for each exposure group at the 4-month follow-up blood testing period is associated with modified exposure controls.

Ineffective exposure controls were identified through the analysis of worker BLLs. We found two exposure groups (laborer and painter) whose 95th percentile (point estimate) exposure profile was greater than the OSHA construction lead standard's targeted BLL goal (25 μg/dl) during the first two months of exposure. Our research findings provide support for monthly blood lead testing after baseline until blood lead levels are controlled to an acceptable concentration.

1. Introduction

Workers in the industrial painting industry are exposed routinely to a variety of chemical and physical agents that are known to cause adverse health effects from short-term and long-term exposure (CPWR, 2018). To mitigate workplace exposures, OSHA has long relied on its hierarchy of exposure control approach to ensure workers do not suffer health impairment (OTA, 1995). The OSHA lead construction standard exemplifies this preferred risk management framework (OSHA, 1993a). There is a requirement within the lead standard for the implementation of engineering controls as the first line of defense (OSHA, 1993a) - as elimination and substitution are not viable in many construction settings. OSHA anticipated, in some cases, that engineering controls would need to be used in concert with work practice controls and personal protective equipment to reduce workplace lead exposures and to prevent lead intoxication (OSHA, 1993b).

Despite numerous studies that have been performed assessing airborne exposures to lead during abrasive blasting and painting activities, not many have been conducted that evaluate the effectiveness of exposure controls (Flynn and Susi, 2004; Roelofs et al., 2003). A few

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researchers have assessed the effectiveness of implemented lead exposure controls and their impact on worker blood lead levels (Levin et al., 1997; Vork et al., 2001). Vork et al. (2001) observed reduced uptake of lead among exposed workers employed by industrial contracting firms that implemented comprehensive exposure controls (more stringent than the OSHA lead construction standard). Similarly, Levin et al. (1997) also observed a decline in worker uptake of lead as a result of implementing exposure controls.

Because elevated BLLs are known to cause adverse health effects (ATSDR, 2019), a lack of exposure control efficacy data makes the task of developing a focused intervention to reduce workplace lead exposure challenging. For example, recent research suggests that the residual lead measured on worker's hands, at the end of a shift, is likely contributing to elevated BLLs (Guth et al., 2019). The persistence of elevated worker blood lead levels in the construction industry (Alarcon, 2016; OSHA, 2008) underscores the importance of assessing the effectiveness of exposure controls to determine if they are adequate to maintain worker blood lead levels to less than 25 μg/dl.

An essential component of a lead exposure control intervention is biomonitoring (OSHA, 1993b; Schulte and Hauser, 2012). OSHA requires biomonitoring in its lead health standards to supplement the primary standard driven exposure prevention measures (exposure controls) (OSHA, 1993b). A blood lead test serves a useful role in the prevention of lead intoxication by highlighting the need to adjust poor-performing exposure controls (Levin and Goldberg, 2000).

The OSHA BLL testing frequency (every 2-months given a BLL > 40 μg/dl) was established in 1978 in the General Industry lead standard and later served as the blueprint for the follow-up blood lead testing frequency in the construction standard (OSHA, 1978). After considering all of the evidence presented for the proposed frequency of biological monitoring in the General Industry lead standard, OSHA opined that testing worker BLLs every two months was "reasonable and adequately protective" to detect "unacceptable elevations" for workers with BLLs (> 40 μg/dl) (OSHA, 1978). Evidence has started to amass that challenges the adequacy of OSHA's BLL testing frequency in the construction industry for protecting worker's health from lead exposure (Kosnett et al., 2007; Shaffer and Gilbert, 2018).

Research conducted by Levin and Goldberg (2000) and Kosnett et al. (2007) both report OSHA's current blood testing frequency is inadequate to protect worker's health. They also recommend monthly blood testing until exposure controls are determined to be acceptable for the reliable management of blood lead levels among the exposed workers (Kosnett et al., 2007; Levin and Goldberg, 2000). Levin and Goldberg (2000) argue that the incorporation of risk management controls into a construction firm's biomonitoring plan is essential to reduce lead intoxication in the industry. They suggest an incremental increase in BLLs of 10 μg/dl between any testing period should result in an evaluation of the site exposure controls by an industrial hygienist to modify ineffective controls to reduce worker lead exposure (Levin and Goldberg, 2000).

Likewise, many authors have argued that OSHA needs to update its medical surveillance testing requirements to align with the current scientific understanding of adverse health effects workers may suffer at levels much lower than currently allowed under the lead construction standard (Schwartz and Hu, 2007; Shaffer and Gilbert, 2018). In late 2018, the Michigan Occupational Safety and Health Administration (MIOSHA) became the first regulatory agency in the United States to reduce occupational BLLs since 1993 (NSC, 2019). Medical removal for lead-exposed workers in Michigan now occurs at 30 μg/dl compared with the federal removal level of 50 μg/dl (NSC, 2019).

The primary objective of this study was to evaluate the effectiveness of exposure controls in preventing elevated BLLs (> 25 μg/dl) during bridge painting projects. A secondary objective of the study was to evaluate if OSHA's current medical surveillance testing frequency is reliable for the adequate management of worker blood lead levels.

2. Methods

We employed a quantitative nonexperimental study design using retrospective blood lead level data to assess the effectiveness of exposure controls. The BLL data was collected by four bridge paint contractors that were required to collect biological specimens per OSHA mandated lead medical surveillance provisions before exposure to lead (baseline) and after exposure to lead (follow-up) in the workplace to evaluate the effectiveness of risk management controls.

The contractors sent their workers to an occupational health clinic to have their blood sampled for the presence of lead. A nurse obtained the samples by a venous blood draw. The samples were sent to a Clinical Laboratory Improvement Amendments (CLIA)-certified facility and analyzed for the presence of lead by inductively coupled plasma/mass spectrometry. The method detection limit was 2 μg/dl. An occupational physician reviewed the worker BLLs. Afterward, the clinic emailed the BLL results to each contractor.

2.1. Study population

We recruited industrial bridge painting contractors (SIC -1721) for inclusion in this study from January 2019 to August 2019. The painting contractor's workers who removed lead paint from major bridge river crossings were identified using our existing contacts within the industrial painting industry. We elected to study workers in industrial classification (1721) because of the persistence of elevated BLLs among this population combined with the fact OSHA (1993b) assumed many workers in this industry have the potential for intense lead exposure.

Due to the use of retrospective data for this study, it was necessary to select contractors with a successful track record of implementation of OSHA exposure controls during bridge paint removal projects. We developed the following inclusion criteria to ensure comparable experience and technological aptitude among the contractors in implementing lead exposure controls:

- The contractor had to be certified by a third-party agency (SSPC) to conduct hazardous paint removal;
- The contractor had to have at least three years of experience in conducting hazardous paint removal while certified;
- The project specification required the implementation of lead exposure controls;
- The project specification required full containment (SSPC Class 1A) with mechanical ventilation as the engineering control;
- The owner of the bridge had a third-party firm on-site to ensure exposure control implementation and compliance with the project specification requirements;
- The project had environmental support such as decontamination trailers, handwashing facilities and lead warning signs;
- Standard soap and water were used for handwashing;
- The contractor had a trained lead competent person on-site during any lead emission generating activities;
- All workers received lead training, hazard communication, and respiratory protection training;
- Confirmation from the contractor of airborne lead exposures above the airborne PEL of 50 μg/m^3 at the worksite;
- Confirmation from the contractor that they used a CLIA accredited lab for the blood lead level analysis.
- Confirmation from the contractor that worker exposure to lead remained constant over the study period.

During the BLL data collection phase of the study, there were 186 contractors certified by SSPC to remove hazardous paint. Out of the eligible painting contractors, 145 met the inclusion criteria. Four bridge painting contractors that met the study inclusion criteria agreed to participate in the study. All of the study participants were men. No other demographic data was provided by the contractors.

Table 1
Lead exposure by job task.

Exposure by Job Task	
Abrasive Blaster	Equipment Operator
Abrasive Blaster/Painter	Superintendent
Painter	Foreman
Laborer	Quality Control
Competent Person	Rigger

2.2. Study setting

The setting for this study was short-term (2 months–10 months) bridge abrasive blasting and painting projects. Each project included the full enclosure of segments of the bridge with a containment system ventilated with a portable dust collector (45,000 cfm). Based on industry practice, the minimum designed cross-draft air velocity inside of a bridge containment is 100 feet per minute (fpm). All participating contractors reported meeting the designed 100 fpm air velocity. The air velocity was field verified by the contractor's lead competent person before any work was performed inside of an active containment. Periodic air velocity measurements were also conducted by the contractor's lead competent person throughout the duration of the project. The existing paint was removed by abrasive blasting with steel grit as the blast media followed by the application of an industrial coating.

We identified ten individual work tasks from 11 separate bridge painting projects (Table 1). Based on conversations we had with the participating contractors, each worker was placed into a specific exposure group based on their general lead exposure profile, the similarity and frequency of the tasks they performed, the materials being used, work process, and the specific controls in place.

All contractors reported the paint that was removed from the bridge contained lead, and the airborne exposure concentration was greater than 50 μg/m^3 during abrasive blasting operations. For all 11 projects, the contractors reported constant, daily lead exposure for all workers after the baseline BLL testing through the 4-month follow-up testing period.

2.3. Data collection

We created a data collection form to gather information on the work task during exposure, the matching BLL, and whether the blood lead test was a baseline or follow-up measurement. The contractors that participated in the study removed all personal identifiers before the blood lead data was submitted. The contractors emailed their completed data collection forms to the authors.

2.4. Exposure measurement & required testing frequency

The OSHA construction lead standard requires blood lead testing as well as zinc protoporphyrin (ZPP) testing as part of an employer established medical surveillance program (OSHA, 1993a). After the biological monitoring results have been analyzed by the testing laboratory, an occupational physician typically compares the BLL and ZPP test results to reference levels (Table 2) to determine the worker's health risk from exposure. Industrial hygiene professionals use the biological monitoring test results to measure the effectiveness of controls and to also modify poor-performing exposure controls to prevent occupational disease from workplace exposure if the measured blood concentrations exceed safe levels (OSHA, 1993b).

The airborne lead concentration, duration of exposure, and the blood lead concentration drive the biological monitoring testing frequency (OSHA, 1993a, 1993b). There are two phases to medical surveillance in the OSHA lead construction standard, initial (pre-project baseline) and program-based medical surveillance if exposed above the lead Action Level for more than 30 days in a year (OSHA, 1993a, 1993b). Table 3 illustrates the OSHA required testing frequency.

Table 2
Reference blood lead levels.

Agency	(μg/dl)
ACGIH – Biological exposure index (2017)	20
OSHA – Construction lead standard target goal (<)	25
MIOSHA – Medical Removal state of Michigan	30
OSHA – Construction lead standard (maintain ≤) over a worker's career	40
OSHA – Medical removal (construction)	50

Source: (CDC, 2015; NSC, 2019).

2.5. Exposure control modifiers

The contractors supplied personal protective equipment to minimize worker contact and potential lead uptake during project work activities. Table 4 illustrates the personal protective equipment (PPE) worn by exposed workers who participated in the study by work task. Workers in 4 out of the 10 work tasks did not wear respiratory protection. The contractor's competent person used inspection forms (daily) to document the supplied PPE was worn to ensure compliance with the project lead exposure control requirements.

2.6. Exposure intensity by work task (exposure group)

We classified each work task with a specific anticipated airborne exposure by intensity and duration of exposure based on our previous experience evaluating bridge painting contractor's lead exposure during lead paint removal activities. These tasks were categorized as follows:

- High - work tasks with the most intense exposure (> 500 μg/m^3). Routine exposure duration > 50% of the work task.
- Medium-work tasks with less intense exposures than the high classification (50 μg/m^3-500 μg/m^3) experienced for shorter durations. Routine exposure 10% to 50% of the work task.
- Low – work tasks with the least exposure intensity (< 50 μg/m^3). Routine exposure duration < 10% of the work task.

The contractors reported a routine work duration of 10 h.

2.7. Evaluation decision logic

Based on an exposure model used to demonstrate the benefits of a reduced PEL in the development of the lead construction standard, OSHA predicted if the required implemented exposure controls reduced exposures to the PEL (50 μg/m^3), all worker BLLs could be maintained < 25 μg/dl (OSHA, 1993b).

To evaluate if OSHA's lead exposure controls are effective at maintaining worker BLLs < 25 μg/dl, we elected to assess the increase in BLLs between testing periods. We opted not to evaluate if absolute BLLs remained below 25 μg/dl because of the varying BLL concentrations at baseline. For example, there were 27 workers at baseline with a BLL ≥ 25 μg/dl and 10 workers with a BLL that ranged from 20 μg/dl to 24 μg/dl. Thus, multiple workers likely would have had a BLL > 25 μg/dl at the follow-up period after intense exposure.

Measuring the increase in BLLs between the testing periods allowed for the direct measurement of lead uptake and indirectly the effectiveness of the controls associated with exposure on the projects – and not from previous exposure. As a result, to err on the conservative side, we decided for decision logic 1 (Table 5), if the group 95th percentile BLL increase was greater than 25 μg/dl, conclude the exposure controls are not effective at maintaining BLLs less than 25 μg/dl.

Likewise, a common industrial hygiene practice is to determine whether an exposure profile for a similar exposed group is acceptable. If the group 95th percentile exposure profile is not acceptable, an

Table 3
OSHA blood testing frequency.

Baseline If airborne exposure is ≥ 30 μg/m^3 for at least 1 day		Program Surveillance If airborne exposure is ≥ 30 μg/m^3 for at least 30 days/year
The employer must provide initial blood test to exposed workers.	The employer must test exposed workers every two months for the first six months and then every six months afterward.	
If the worker BLL is 40 μg/dL at baseline, the employer must conduct BLL and ZPP testing every two months until two consecutive tests demonstrate BLLs < 40 μg/dL.	If the worker BLL is 40 μg/dL during the program surveillance testing, the employer must conduct BLL and ZPP testing every two months until two consecutive tests demonstrate BLLs < 40 μg/dL.	

Source: (OSHA, 1993a, 1993b).

Table 4
PPE used as an Exposure Control Modifier by Exposure Intensity and Work Task.

Work Tasks	Exposure Intensity	Exposure Control Modifiers
Foreman	Low	Full body tyvek suit; leather gloves
Superintendent	Low	
Competent person	Low	
Quality control	Low	
Rigger	Medium	½ mask air purifying respirator with P-100 cartridges (APF-10); tyvek suit; leather gloves
Equipment operator	Medium	
Abrasive blaster	High	Type CE Continuous Flow (Blasthood) Respirator with (APF-1000); abrasive blast coverall; leather gloves
Abrasive blaster/painter	High	½ mask air purifying respirator with P-100 cartridges (APF-10); tyvek suit; leather gloves
Laborer	High	
Painter	High	

industrial hygiene practitioner can use this information to guide changes in exposure controls (Jahn et al., 2015). To assess the acceptability of the exposure group's 95th percentile BLL profile, we used a Bayesian Decision Analysis Likelihood chart that depicts the probability that the group's true 95th percentile BLL profile is in one of the five listed exposure rating categories (Jahn et al., 2015):

- < 1% of the Biological Exposure Index (BEI)
- Between 1% and 10% of the Biological Exposure Index (BEI)
- Between 10% and 50% of the Biological Exposure Index (BEI)
- Between 50% and 100% of the Biological Exposure Index (BEI)
- > the Biological Exposure Index (BEI)

If the highest probability is > the BEI, it is common industrial hygiene practice to conclude the BLL exposure profile is unacceptable. Changes to exposure controls are typically necessary.

Similarly, we also developed a decision logic to evaluate if the current OSHA frequency of blood testing in the construction industry is reliable for the adequate management of blood lead levels. We incorporated Levin and Goldberg's (2000) suggested incremental increase in BLLs (10 μg/dl) between testing periods into our decision logic as it is a more protective risk management approach than OSHA's current approach of a single BLL ≥ 40 μg/dl before requiring follow-up blood testing (Table 6).

2.8. Data analysis

The statistical analyses of biological monitoring data are necessary to account for the variability in the sample collection and analysis processes as well as to attempt to accurately describe the lead uptake to make an informed decision on the effectiveness of exposure controls.

Descriptive statistical techniques were used to analyze the BLL data using GraphPad version 8.2.1 (2019) and Expostats (2018). A paired *t*-test was used to analyze the worker's mean changes in BLL by work task. Through the use of Expostats' Bayesian analysis tool, we calculated the 95th percentile increase in BLL for each work task and the likelihood that the true 95th percentile BLL (point estimate) in a similar exposure group is > the OSHA construction lead standard's targeted BLL goal (25 μg/dl). We also calculated the % of workers in a given work task with a BLL incremental increase ≥10 μg/dl and the probability that the true proportion of workers with an incremental increase ≥10 μg/dl in an exposure group is ≥ 10%. For the parameter estimates (95th percentile and exceedance fraction) the Expostat software program generates a credible interval instead of a confidence interval. From the authors of the software package: "While not formally equivalent, Bayesian credible intervals are usually interpreted in a similar way as the more traditional confidence intervals" (Expostats, 2018).

BLL distributions were assessed using Expostat's graph entitled Q-Q plot. The BLL data were found to be lognormal. The BLL data were also assessed using the Shapiro-Wilk statistical test. This Shapiro-Wilk test confirmed the Q-Q plot assessment that the BLL data were lognormally distributed. The data were log transformed, and the geometric means and the geometric standard deviations were calculated.

Within worker BLL variability was assessed for the high intensity exposure groups using a one-way random effects ANOVA model. The ANOVA model was fit to log transformed BLL data because the distribution was lognormal. The estimated geometric standard deviations

Table 5
Evaluation Decision Logic (What is the effectiveness of lead exposure control measures in preventing elevated BLLs (> 25 μg/dl)?).

Decision Rule	Decision
If the 95th percentile (90 CL) point estimate increase in BLL for an exposure group (work task) is > than 25 μg/dl between the baseline and any follow-up period	Conclude that project exposure controls are not effective at preventing elevated blood lead levels BLLs (> 25 μg/dl)
If the 95th percentile (90 CL) point estimate increase in BLL for an exposure group (work task) is < than 25 μg/dl between the baseline and any follow-up period	Conclude that project exposure controls are effective at preventing elevated blood lead levels BLLs (< 25 μg/dl)

Table 6
Evaluation Decision Logic (Is the current OSHA frequency of blood testing in the construction industry reliable for the adequate management of blood lead exposures?).

Decision Rule	Decision
If ≥ 10% of a work task experiences an incremental BLL increase ≥ 10 μg/dL between baseline and any follow-up for any work task	Conclude the current OSHA frequency of blood testing in the construction industry is not reliable for the adequate management of blood lead exposures
If < 10% of a work task experiences an incremental BLL increase ≥ 10 μg/dL between baseline and any follow-up for any work task	Conclude the current OSHA frequency of blood testing in the construction industry is reliable for the adequate management of blood lead exposures

$\exp(S_{within\ worker})$ were used to describe the within worker BLL variability.

We also considered the fact that the cohort that is present at the four-month testing period is smaller (n = 141) than at the two-month testing period (n = 283). To determine if the group that was present at four months is different, we calculated the 95th percentile (point estimate) BLL exposure profile for the smaller cohort at the 2-month testing period separately. It could be possible that the smaller group has workers more experienced in personal hygiene practices and compliance with job site safe operating practices. These possible differences could account for a reduction in the very high BLL incremental increases within each group. The 95th percentile (point estimate) BLL exposure profiles were not calculated for the competent person (n = 2), superintendent (n = 1), and equipment operator (n = 1), due to an insufficient number of BLLs.

3. Results and discussion

3.1. Results

Table 7 presents a summary of worker BLLs collected before exposure (baseline) on the projects included in this study. A total of 842 BLLs samples were collected for the study. We assessed only the BLLs (n = 713) from baseline to four months after initial exposure because those were the exposure periods that the contractors reported daily, consistent exposure to lead throughout the workday. Two projects in the study lasted longer than four months, but the contractors reported only sporadic, daily exposure to lead on the two bridge painting projects. Also, there was a significant decrease in the study population (n = 63 at six months, n = 53 at eight months, and n = 13 at ten months of exposure after baseline). As a result, we did not analyze 129 BLL samples from the (6, 8 & 10) month follow-up periods (see Table 8).

3.1.1. Baseline BLL

Elevated BLLs (> 25 μg/dl) were observed in 6 out of the 10 exposure groups. The high-intensity exposure work tasks represented 88% of the BLLs > 25 μg/dl before exposure on the projects (Table 7). For all workers at baseline, 38% (n = 110) had a BLL > 10 μg/dl, and 5% (n = 15) had a BLL > 30 μg/dl. One worker had a BLL > 40 μg/dl at baseline. The maximum worker BLL at baseline was 41 μg/dl. BLLs for all sampling periods were log-normally distributed.

Table 7
Worker BLLs by work task at (baseline).

Work Tasks (Exposure Groups)	N	Mean BLL μg/dl (SD)	GM(SD)	N (%) BLL > 25 μg/dl
All work tasks	289	10.9 (8.4)	8.0 (2.4)	24 (100)
High Exposure Intensity				
Abrasive Blaster	41	11.1 (9.1)	8.1 (2.4)	3 (12.5)
Abrasive Blaster/Painter	103	11.4 (7.8)	9.1 (2.1)	9 (37.5)
Laborer	58	11.7 (10.0)	7.8 (2.7)	7 (29.2)
Painter	51	8.7 (6.7)	6.0 (2.8)	2 (8.3)
Medium Exposure Intensity				
Equipment Operator	6	18.0 (8.6)	16 (1.8)	2 (8.3)
Rigger	9	4.9 (3.3)	3.7 (2.4)	0 (0.0)
Low Exposure Intensity				
Competent Person	3	5.0 (3.6)	4.2 (2.1)	0 (0.0)
Foreman	3	20.7 (11.5)	19 (1.7)	1 (4.2)
Quality Control	11	7.8 (3.7)	6.9 (1.8)	0 (0.0)
Superintendent	4	17.0 (7.1)	16 (1.6)	0 (0.0)

BLL = Blood Lead Level; GM = Geometric Mean; SD = Standard Deviation.
μg/dl = Microgram/Deciliter.

3.1.2. BLLs – 2 months after exposure

The mean BLLs increased by 4 μg/dl ($p < 0.01$) from baseline to the 2- month follow-up for all work tasks combined. Twenty percent of workers in the high-intensity exposure work tasks experienced an incremental increase in BLL > 10 μg/dl (Table 9). Likewise, the high-intensity exposure work tasks also accounted for 88% of the BLL incremental increases of 25 μg/dl (n = 15) or greater during the same time. After two months of lead exposure, 53% of the workers (for all work tasks) had a BLL > 10 μg/dl, 12% (n = 34) had a BLL > 30 μg/dl, 7% (n = 19) had a BLL ≥40 μg/dl, and 2% (n = 5) had a BLL ≥ 50 μg/dl.

The 95th percentile BLL (point estimate) exposure profile for the laborer and painter exposure groups was > than 25 μg/dl (Table 9). The likelihood of the 95th percentile (point estimate) for the laborer and painter exceeding 25 μg/dl is presented in Fig. 1. As a group, 16% of painters had a BLL incremental increase > 25 μg/dl and 29% had a BLL incremental increase of ≥10 μg/dl. Similarly, 9% of the laborers had a BLL incremental increase > 25 μg/dl and 35% had a BLL incremental increase of ≥10 μg/dl. The estimated within worker BLL variability (geometric standard deviation $\exp(S_{within\ worker})$) from baseline to the two-month follow-up period was 2.3 (Painters), 2.3 (Laborers), 1.6 (Abrasive Blaster/Painter), and 1.4 (Abrasive Blaster).

The probability of the abrasive blaster/painter, laborer and painter work tasks having an unacceptable exceedance fraction (≥10%) for a BLL incremental increase ≥ 10 μg/dl is depicted in Fig. 2. All work tasks with high-intensity exposure (abrasive blaster/painter, abrasive blaster, painter & laborer) experienced an average BLL increase that ranged from 0.2 μg/dl to 8.9 μg/dl two months after initial exposure.

For the cohort remaining at 4-months (n = 141), the 95th percentile BLL (point estimate) exposure profile at the 2-month testing period was 8.4 μg/dl (Abrasive Blaster), 11.6 μg/dl (Abrasive Blaster/Painter), 72.6 μg/dl (Painter), 65.7 μg/dl (Laborer), 23.3 μg/dl (Quality Control), and 2.8 μg/dl (Rigger).

3.1.3. BLLs – 4 months after exposure

Two months after the initial follow-up blood testing, two out of the four work tasks (abrasive blaster & abrasive blaster/painter) with high-intensity exposure showed a decrease in average blood lead levels (−0.14 μg/dl to −2.7 μg/dl) while the other two work tasks (laborer and painter) had moderate increases (1 μg/dl to 2.4 μg/dl). For the workers who remained in the study after four months of exposure, there was a mean BLL reduction of 2 μg/dl (N = 141) ($p < 0.01$). The estimated within worker BLL variability (geometric standard deviation $\exp(S_{within\ worker})$) from the two-month follow-up period to the four-month follow-up period was 1.2 (Painters), 1.3 (Laborers), 1.5 (Abrasive Blaster/Painter, and 1.4 (Abrasive Blaster).

After four months of lead exposure, 60% (n = 84) of the workers for all work tasks combined had a BLL > 10 μg/dl, 11% (n = 15) had a

Table 8
All work classifications BLLs.

	Baseline	Mean BLL (SD)	Follow-up 2-months[a]	Mean BLL (SD)	Follow-up 4-months[a]	Mean BLL (SD)
Variable	N (%)		N (%)		N (%)	
All work classifications	289 (100)		283 (100)		141 (100)	
Blood Lead Levels						
≤5 μg/dl	77 (26.6)	3.0 (1.6)	56 (19.8)	3.6 (1.2)	16 (11.3)	3.8 (1.0)
> 5 μg/dl - 10 μg/dl	102 (35.3)	7.9 (1.4)	76 (26.8)	7.9 (1.4)	41 (29.1)	7.9 (1.3)
> 10 μg/dl- 25 μg/dl	86 (29.8)	15.5 (3.8)	108 (38.2)	16.3 (4.2)	62 (44.0)	15.5 (3.9)
> 25 μg/dl	24 (8.3)	32.0 (4.2)	43 (15.2)	38.3 (9.1)	22 (15.6)	35.1 (6.7)

BLL = Blood lead level.
SD = Standard Deviation; μg/dl = Microgram/Deciliter.
[a] After initial exposure.

BLL > 30 μg/dl, 3% (n = 4) had a BLL ≥40 μg/dl. One worker had a BLL ≥50 μg/dl. None of the work tasks exceeded the targeted exceedance fraction of 10% for incremental increases of BLLs > 10 μg/dl; no exposure group's profile at the 95th percentile (point estimate) was ≥25 μg/dl (Table 10).

3.2. Discussion

We used BLLs collected by industrial contractors from 11 bridge painting projects to evaluate the effectiveness of exposure controls and to assess OSHA's medical surveillance testing frequency to determine if it is reliable for the adequate management of worker BLLs. Using 25 μg/dL as the target BLL goal for lead in this study, we compared the increase in BLLs for workers in 10 exposure groups from baseline with two follow-up periods (2-months and 4-months after initial exposure).

3.2.1. Baseline

The contractors reported all of the workers were coming off other lead paint removal projects. It has been our experience working with this population that given the short-term nature of the bridge painting projects, many of the workers who are routinely exposed to lead often skip post job blood lead sampling to find another job. Based on our analysis of the baseline BLLs, overexposure to lead continues to occur among workers in the industrial bridge painting industry. For example, before lead exposure on the projects included in this study, 12% of the workers (n = 34) had a BLL > ACGIH's biological exposure index of 20 μg/dl, 8% of the workers (n = 24) had a BLL > OSHA's targeted BLL goal of 25 μg/dl, and 5% (n = 15) had a BLL > MIOSHA's medical removal level of 30 μg/dl. There was also one worker with a BLL > 40 μg/dl.

3.2.2. BLL - 2-month follow-up

The metric we used to assess the effectiveness of the project exposure controls was the 95th percentile BLL (point estimate) of the work task exposure profile. The 95th percentile (point estimate) for the laborer work task and the painter work task was 1.6 x and 1.5 x greater than the OSHA construction lead standard's targeted BLL goal (25 μg/dl). Using the decision logic developed for this study, the laborer and painter exposure groups, for both cohorts that were analyzed, experienced an unacceptable increase in BLLs from baseline to the 2-month follow-up test. These findings indicate the implemented exposure controls were not effective at maintaining worker BLLs < 25 μg/dl. The 95th percentile BLL exposure profile probability distribution for the painters and the laborers indicate unacceptable exposures that warrant changes in the site exposure controls (Fig. 1).

One contractor reported medically removing a worker (painter) for two weeks from lead exposure due to a BLL that exceeded OSHA's medical removal threshold.

Another measure that demonstrates poorly controlled exposures is the percentage of workers with a BLL > 25 μg/dl after two months of exposure. In total, 15% of the workers from all exposure groups (n = 43) had a BLL > 25 μg/dl after two months of exposure. The data from our study suggests that the prevalence of elevated BLLs among workers in the industrial painting industry is likely much higher than reported by NIOSH (90 cases in 2016 from 26 states) (Alarcon, 2016).

Lead exposures were adequately controlled among the work tasks abrasive blaster and abrasive blaster/painter after two months of exposure. As these two exposure groups are generally associated with

Table 9
Worker BLLs by Work Task (1st follow-up - 2 months after baseline).

Work Tasks (Exposure Group)	N	Mean BLL μg/dl (SD)	GM (SD) BLL μg/dl	MI BLL μg/dl	II BLL μg/dl 95th %centile (CI)	N (%) II BLL ≥10 μg/dl (%)	N (%) II BLL > 25 μg/dl
All work tasks	283	14.9 (11.9)	11.0 (2.2)	57	18.3 (15.4–22.1)	51 (100)	17 (100)
High Exposure Intensity							
Abrasive Blaster	41	11.4 (8.5)	9.0 (1.9)	17	5.4 (4.1–7.6)	2 (4.0)	0 (0.0)
Abrasive Blaster/Painter	103	13.7 (10.3)	10.2 (2.3)	48	12.9 (10.1–17.3)	14 (27.4)	2 (11.8)
Laborer	54	19.4 (14.5)	14.5 (2.2)	45	40.2 (26.6–66.9)	19 (37.2)	5 (29.4)
Painter	49	17.6 (13.8)	13.1 (2.2)	57	38.1 (24.1–66.9)	14 (27.4)	8 (47.2)
Medium Exposure Intensity							
Equipment Operator	6	15.2 (6.7)	14 (1.5)	2	2.1 (1.5–4.4)	0 (0.0)	0 (0.0)
Rigger	9	5.7 (3.4)	4.9 (1.8)	3	3.4 (2.3–6.7)	0 (0.0)	0 (0.0)
Low Exposure Intensity							
Competent Person	3	7.7 (5.1)	6 (2.6)	8	12.1 (3.9–118)	0 (0.0)	0 (0.0)
Foreman	3	19.7 (7.6)	18 (1.6)	9	13.3 (4.2–144)	0 (0.0)	0 (0.0)
Quality Control	11	10.1 (11.9)	7.2 (2.1)	35	8.4 (4.4–23.6)	1 (2.0)	1 (5.8)
Superintendent	4	23.5 (15.6)	20 (1.8)	27	33.8 (9.4–397)	1 (2.0)	1 (5.8)

BLL = Blood Lead Level; CI = Credible Interval; GM = Geometric Mean; II = Incremental Increase; MI = Maximum Increase.
SD = Standard Deviation; μg/dl = Microgram/Deciliter.

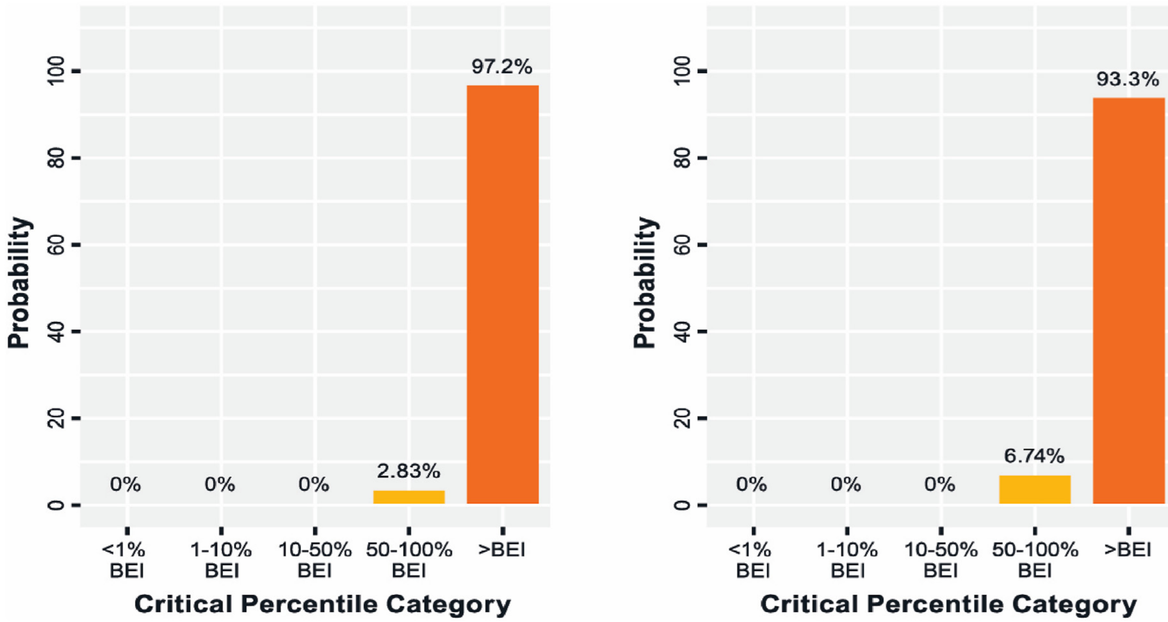

Fig. 1. 95th percentile BLL Exposure Profile Probability Distribution Laborers 2-month follow-up BLL (left) and Painters (right). BEI (Biological Exposure Index) Refer to Section 2.7 for rationale.

intense lead exposure on bridge painting projects, it suggests the contractors focused on controlling the exposures unique to these similarly exposed groups. The incremental increase in BLLs in the exposure groups superintendent and quality control are not unexpected as the contractors reported workers in these work tasks did not wear respiratory protection. Based on the elevated BLLs among the low exposure intensity work tasks, lead exposed workers should wear respiratory protection when performing these tasks. As the contractors reported airborne exposures below the lead permissible exposure limit (50 μg/m^3) during these work tasks, paint contractors should place a greater emphasis on ingestion exposure control strategies.

We also calculated the percentage of employees with a 10 μg/dl BLL incremental increase or greater between sampling periods to measure the adequacy of OSHA's biological monitoring testing frequency. Three out of the four high-intensity exposure groups had ≥10% of the workers with a BLL incremental increase of 10 μg/dl or greater. Our findings provide support for the argument put forth by Levin and Goldberg (2000) and Kosnett et al. (2007) that OSHA's current blood testing frequency is inadequate to protect worker's health. Our findings also support the conclusion that the OSHA frequency of blood testing in the construction industry is not reliable for the adequate management of blood lead exposures using the study decision logic.

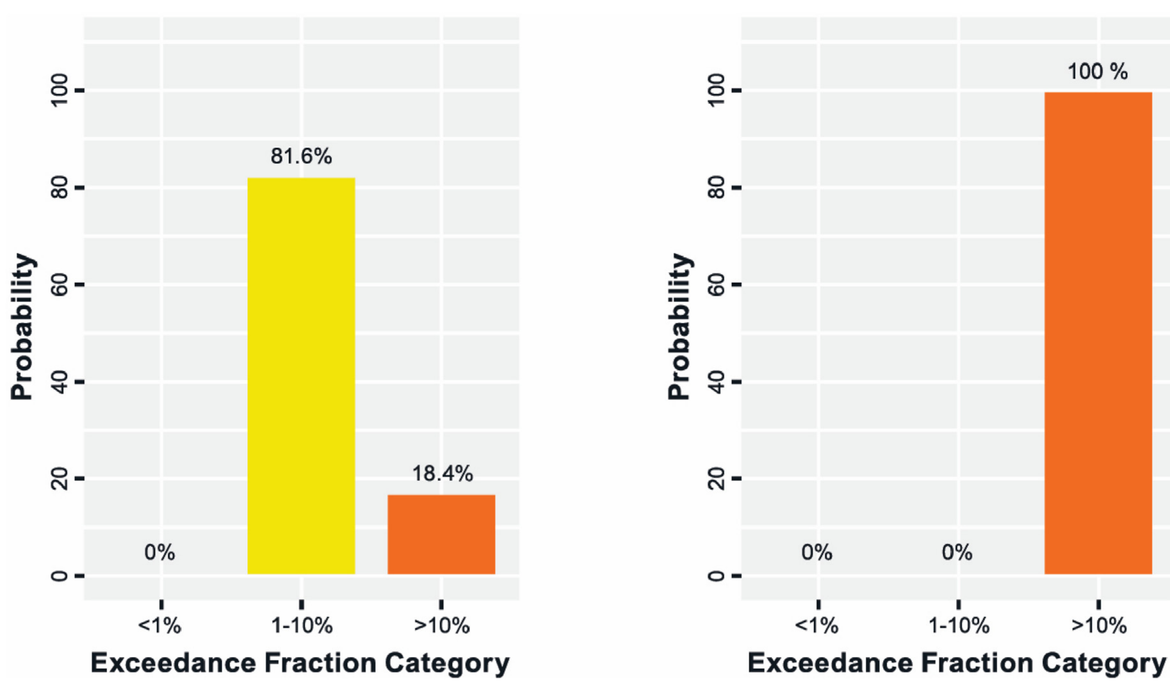

Fig. 2. BLL Exceedance Fraction Probability Distribution 2 months after exposure (Abrasive Blaster/Painter (Left) Painter and Laborer (Right) Refer to Section 2.7 for rationale.

Table 10
Worker BLLs by Work Task (2nd follow-up - 4 months after baseline).

Work Tasks (Exposure Groups)	N	Mean BLL μg/dl (SD)	GM (SD) BLL μg/dl	MI BLL μg/dl	II BLL μg/dl 95th %centile	N (%) II BLL ≥10 μg/dl	N (%) II BLL > 25 μg/dl
All work tasks	141	15.0 (10.3)	12.1 (2.0)	15	4.2 (3.7–4.9)	3 (100)	0 (100)
High Exposure Intensity							
Abrasive Blaster	18	11.2 (6.7)	9.6 (1.8)	9	5.7 (3.8–10.1)	0 (0.0)	0 (0.0)
Abrasive Blaster/Painter	44	11.0 (7.1)	9.2 (1.8)	15	4.0 (3.2–5.4)	2 (67.7)	0 (0.0)
Laborer	32	20.4 (11.1)	17.4 (1.8)	13	5.5 (4.1–8.3)	1 (33.3)	0 (0.0)
Painter	30	19.9 (11.3)	16.9 (1.8)	5	2.6 (2.1–3.3)	0 (0.0)	0 (0.0)
Medium Exposure Intensity							
Equipment Operator	1	8.0 (0)	8.0 (1.0)	0	3.5 (1.0–97.4)	0 (0.0)	0 (0.0)
Rigger	8	6.3 (1.7)	6.1 (1.3)	5	5.0 (3.1–11.8)	0 (0.0)	0 (0.0)
Low Exposure Intensity							
Competent Person	2	9.5 (0.7)	9.5 (1.1)	0	2.4 (1.2–19.3)	0 (0.0)	0 (0.0)
Quality Control	5	14.4 (12.5)	10 (2.9)	5	8.6 (4.3–36.5)	0 (0.0)	0 (0.0)
Superintendent	1	36.0 (0)	36.0 (1.0)	0	3.5 (1.0–97.4)	0 (0.0)	0 (0.0)

BLL = Blood lead level; MI = Maximum increase; II = incremental increase; SD = standard deviation.
μg/dl = Microgram/Deciliter.

3.2.3. BLL 4-month follow-up

After a review of the worker BLLs two months after initial lead exposure, the contractors that had projects that lasted longer than 2-months (n = 5) reported modifying the project engineering control. Specifically, the air velocity in the containment system was raised to greater than minimum designed 100 fpm to increase the number of air exchanges per hour to more rapidly remove the lead dust from the work area. The modified air velocities were not provided by the contractors. Three of the remaining five contractors also reported retraining their workers on working safely with lead. Training included the proper use and maintenance of PPE. Special emphasis was placed on the importance of proper handwashing at breaks and showering at the end of the workday.

All work tasks had a 95th percentile (point estimate) BLL exposure profile less than 25 μg/dl four months after initial exposure. With all exposure groups combined, 18% of the workers had a BLL incremental increase of 10 μg/dl or greater two months after baseline compared with only 2% measured at the 4-month follow-up period. Similarly, no worker had an incremental increase of 25 μg/dl or greater at the 4-month follow-up compared with 17 workers during the first two months of lead exposure. There was a modest reduction in BLLs from the 2-month follow-up to the 4-month follow-up testing period. As the exposure intensity was reported by the contractors as consistent during all exposure periods, the reduction in the 95th percentile (point estimate) BLL exposure profile for each exposure group at the 4-month follow-up testing period suggests the modified controls were effective at reducing the very high BLL incremental increases within each group. We believe the observed reduction is associated with modified controls and not by any differences between the cohorts.

3.2.4. Medical surveillance testing frequency

The key to reducing elevated BLLs among workers in the bridge painting industry is minimizing exposure. OSHA's current testing scheme for the management of worker BLLs has a significant gap in that improper controls are not commonly identified until after workers have elevated BLLs due to the potential for intense exposures to lead over a two-month time frame. A 10 μg/dl incremental BLL increase between testing periods indicates a trend that BLLs are rising likely due to ineffective exposure controls.

While OSHA has not revised the lead construction standard since it was enacted in 1993, MIOSHA recognized the need to update their lead medical surveillance requirements to reflect the present scientific understanding of lead health effects at lower blood concentrations than currently allowed under the federal standard. MIOSHA lowered the medical removal threshold from 50 μg/dl to 30 μg/dl. Another significant divergence from the federal lead standard is workers cannot return to work if they have been medically removed until their BLL is < 15 μg/dl compared to 40 μg/dl allowed under the federal standard (NSC, 2019).

The American College of Occupational and Environmental Medicine (ACEOM) recommends even more protective medical removal requirements than MIOSHA. ACEOM recommends medical removal of pregnant woman or those trying to become pregnant at > 10 μg/dl (Holland and Cawthon, 2016). Likewise, the California Department of Public Health's (CDPH) Occupational Lead Poisoning Prevention Program (OLPPP) also recommends more protective medical surveillance requirements than MIOSHA. CDPH-OLPPP provided recommendations to CAL-OSHA suggesting blood lead testing of workers every month for the first three months of a project (CDPH, 2014). CDPH also recommends BLL testing every four weeks when a BLL is ≥ 20 μg/dl. If the measured BLL is ≥ 20 μg/dl, the frequency of BLL testing is to continue until three BLLs (consecutive) taken four weeks apart are < 10 μg/dl (CDPH, 2014).

Given the fact that 18% of the exposure groups combined, and 20% of the high-intensity exposure groups, had a BLL incremental increase of 10 μg/dl or greater two months after the baseline testing, suggests more protective measures for preventing lead exposures are necessary. It also indicates OSHA's frequency of blood testing in the construction industry is not reliable for the adequate management of blood lead exposures. This raises an important question. Why did OSHA not modify the BLL testing frequency adopted from the general industry standard to address the exposure characteristics found in the construction industry?

It is unfortunate that OSHA failed to amend the follow-up medical surveillance testing frequency that is modeled after the general industry-considering the fact the construction industry was excluded from the lead worker protection provisions in the 1978 lead standard due to "infeasibility (technical and economic) of compliance with certain provisions" (OSHA, 1978). One of the specific issues OSHA considered infeasible was the effectiveness of medical surveillance in the construction industry. An excerpt from the General Industry standard will illustrate this point:

Because initial medical surveillance and periodic follow-up is predicated upon air monitoring results, the shortcomings of air monitoring for the construction industry, as discussed above, undermines the effectiveness of the medical surveillance program. The temporary worker may thus not get a medical exam or blood test result until after the lab results of air sampling return, and follow ups long after he leaves the job (OSHA, 1978).

OSHA attempted to address the cited medical surveillance shortcomings in the construction standard by requiring blood lead testing before workplace exposure if a worker was to perform a trigger task and also by requiring the blood testing of a worker if exposed to the Action Level (30 μg/m^3) for any one day (OSHA, 1993b). Yet, the follow-up blood testing frequency of every two months remained the same as the general industry-despite the fact OSHA acknowledges in the preamble of the lead in construction standard that many construction projects do not last longer than 4-months (OSHA, 1993b). The projects included in this study are a case in point – as 82% (n = 9) of them were 4 months or less. It appears that OSHA failed to address the "effectiveness" issue identified in the General Industry lead standard regarding the medical surveillance testing frequency in the construction industry.

The observed decrease in incremental increases in BLLs from the 2-month to 4-month follow-up testing-even with no changes in exposure intensity - highlights the need for more frequent blood testing than currently required by OSHA for the management of worker BLLs. Monthly blood testing could identify poorly controlled exposures earlier and could prevent elevated BLLs. Based on our research findings, a monthly BLL testing scheme as proposed by Levin & Goldberg (2000) and Kosnett et al. (2007) is more appropriate for the management of worker BLLs based on the type and duration of exposures experienced on construction projects.

One limitation of the study is there was not a practical way to verify the participating contractors properly implemented exposure controls. An attempt was made to resolve this weakness by creating specific inclusion criteria to minimize the impact of this issue. Also, exposure modifiers such as the paint lead concentration and duration of exposure for each work task from each project could not be obtained, which makes comparisons between the selected projects difficult.

Additional research on the efficacy of exposure controls and the adequacy of OSHA's follow-up blood lead level testing frequency is needed. The findings from this study regarding the effectiveness of exposure controls on bridge painting projects could allow for more focused interventions on future bridge painting projects, and could help address the remaining gaps in industrial hygiene lead exposure prevention knowledge. Also our findings may yield more effective risk management strategies to reduce lead exposure in the construction industry.

4. Conclusions

Through the analysis of worker blood lead levels, we generated data to assess the effectiveness of exposure controls on bridge painting projects. The BLL analyses filled some gaps in the literature regarding the adequacy of OSHA's medical surveillance testing frequency as a lead exposure prevention measure.

Some high-intensity exposures were not adequately controlled during the first few months of exposure, but with the use of the biomonitoring data, controls were modified, and lead exposures were adequately controlled 4 months after baseline testing. The results of our BLL data analysis support a monthly biological monitoring frequency consistent with the recommendations of Levin and Goldberg (2000) and Kosnett et al. (2007) to address a shortcoming in OSHA's current medical surveillance program to reduce elevated BLLs.

Some published literature suggests that the level of lead that results in adverse health effects in humans may be less than allowed under the lead construction standard (CDC, 2015; Kosnett et al., 2007; Shaffer & Gilbert, 2018). It would be prudent for industrial painting contractors to voluntarily adopt a more protective medical surveillance program than required by OSHA.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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