Journal of Occupational and Environmental Hygiene

ISSN: 1545-9624 (Print) 1545-9632 (Online) Journal homepage: www.tandfonline.com/journals/uoeh20

Residential washing machine efficacy in removing lead from clothing: A pilot study

Chandran Achutan, Krystin Carlson, Kerri LeVanseler & James Couch

To cite this article: Chandran Achutan, Krystin Carlson, Kerri LeVanseler & James Couch (2025) Residential washing machine efficacy in removing lead from clothing: A pilot study, Journal of Occupational and Environmental Hygiene, 22:10, 779-787, DOI: 10.1080/15459624.2025.2497871

To link to this article: https://doi.org/10.1080/15459624.2025.2497871

Published online: 12 May 2025.

JOURNAL OF OCCUPATIONAL AND ENVIRONMENTAL HYGIENE
2025, VOL. 22, NO. 10, 779–787
https://doi.org/10.1080/15459624.2025.2497871

Residential washing machine efficacy in removing lead from clothing: A pilot study

Chandran Achutan[a], Krystin Carlson[b], Kerri LeVanseler[c], and James Couch[d]

[a]Division of Science Integration, National Institute for Occupational Safety and Health, Cincinnati, Ohio; [b]Synergy America, Inc, Duluth, Georgia; [c]NSF International, Ann Arbor, Michigan; [d]Division of Field Studies and Engineering, National Institute for Occupational Safety and Health, Cincinnati, Ohio

ABSTRACT

Workers exposed to lead sometimes wear their work clothes home. It is possible that lead from contaminated work clothing can transfer to uncontaminated clothing, including children's items that may be in the same load, during laundering. This is concerning because lead is especially toxic for children. The purpose of this pilot study was to understand lead extraction from fabrics typically worn by workers, the amount of lead removed during normal laundering, and lead transfer to other fabrics during a laundry washing cycle. The study validated EPA analytical method 200.8 Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma—Mass Spectrometry to analyze lead in Dickies pant fabric (DPF), T-shirt material (TSM), and blue jeans material (BJM). Because this methodology of extracting lead from fabrics is novel, a priori definitions of accuracy and precision used were ± 40%. Researchers spiked two levels (9 µg and 9,000 µg) of lead nitrate and three levels (9 µg, 900 µg, and 9,000 µg) of lead carbonate on 9 cm^2 fabric swatches and extracted lead by microwave-assisted digestion. Across all spike levels, mean recoveries were within 60% and 140% recovery. All percent coefficient of variation values were less than 20% for lead nitrate, indicating that this method for lead nitrate was sufficiently accurate and precise. For lead carbonate, the method was neither accurate nor precise at the 9 and 900 µg levels but was sufficiently accurate and precise at the 9,000 µg level. Eighteen loads of fabric swatches were spiked with either lead form and laundered in a washing machine using a common laundry detergent. The mean amount of lead removed from laundered DPF and TSM was similar (97.4 and 95.9%) and significantly higher ($p < 0.05$) compared to laundered BJM (70.6%). The amount of lead carbonate removed (92.6%) was significantly higher ($p < 0.05$) than lead nitrate (83.4%). The levels of lead that transferred from spiked fabric to bedsheets included in the same washing load were less than 0.5 µg. It is important to follow public health recommendations, such as laundering work clothes separately.

KEYWORDS

Laundry; lead; occupational health; take-home exposures; worker clothing contamination

Introduction

Workers are exposed to lead at a variety of levels and across several industries, including construction, battery manufacturing, electronics recycling (e-waste), smelting, and at firing ranges (Ceballos et al. 2017; Koh et al. 2015; Laidlaw et al. 2017). Occupational lead exposures occur through multiple pathways of exposure, with the primary route being inhalation of dust that contains lead particles in air (Staudinger and Roth 1998) and can also be absorbed through the skin (Niemeier et al. 2022) or via ingestion (Fischbein 1992).

Studies have shown that airborne lead from production or job activity areas can contaminate non-production areas, such as breakrooms, offices, and conference rooms, while workers often assume these spaces to be free from lead contamination (NIOSH 2006, 2018). Lead has been found in the personal vehicles (Piacitelli et al. 1995) and inside the homes of workers who were exposed to lead at work (Kalweit et al. 2020; Piacitelli et al. 1997). Children living in households of workers exposed to lead are at risk of having high blood lead levels (Levin et al. 2008; Whelan et al. 1997), which are associated with increased likelihood of developmental delays and other negative health outcomes.

To minimize take-home lead exposures, some workplaces provide shower facilities, uniforms, and locker rooms to workers, allowing them to shower

CONTACT Chandran Achutan cma4@cdc.gov Division of Science Integration, National Institute for Occupational Safety and Health, Cincinnati, OH.
This article has been corrected with minor changes. These changes do not impact the academic content of the article.

after work and leave their contaminated clothing at work. Workers can change into street clothes at work, reducing the potential for take-home lead exposures. However, these practices do not eliminate take-home lead exposures (NIOSH 2014, 2018). Some workplaces do not offer uniforms or laundering services and therefore require workers to launder their clothes at home, which increases the risk of contaminating items in their personal space with lead (NIOSH 2017).

In 1991, following public and occupational health concerns surrounding take-home lead exposures, the U.S. Congress tasked the National Institute for Occupational Safety and Health (NIOSH) to study take-home contamination from workplace chemicals (29 USC 671a 1991). In 1995, NIOSH reported to Congress that preventing take-home exposures before they occur is critical to limiting lead exposures. When preventive methods are not used or are ineffective, then decontamination can be used as a last resort (NIOSH 1995). In addition, decontamination through normal house cleaning and laundering methods is inadequate for lead removal and has the potential for exposing those doing the cleaning and laundering (NIOSH 1995). When workers must launder clothes at home, NIOSH has recommended workers "launder work clothes separately" but has further indicated that "normal house cleaning and laundry usually do not succeed" at completely removing lead contamination (NIOSH 1995).

There is a paucity of quantitative data on the efficacy of residential washing to remove lead from contaminated clothing. Past studies have focused on the absence or presence of lead in laundering areas and residential washing machines rather than measuring the effectiveness of residential laundering in removing lead from work clothes. One study showed 28 surface wipe samples taken from inside washing machines in the homes of workers exposed to lead had a mean lead level of $72\,\mu g/m^2$ or $6.69\,\mu g/ft^2$ (Piacitelli et al. 1997). Another study determined that the average level of lead dust in a laundry room inside the homes of lead-exposed workers was $140.8\,\mu g/ft^2$ compared to $10.2\,\mu g/ft^2$ in a nonexposed group (Aguilar-Garduño et al. 2003).

Published scientific studies related to the effectiveness of laundering to remove lead from clothing contain notable gaps. No information was found on the impact of types of occupational take-home lead (forms and particle size), fabric types, washing machine variables (front or top loader; cycle length; impeller design), typical water characteristics, or temperature of the laundry wash cycle. The literature search also found few to no existing protocols and laundering guidelines outside of general recommendations. The search did not find literature that addressed the efficacy of residential washing machines to remove lead contamination from clothing. Therefore, more data is needed to determine if residential washing machines are effective in removing lead contamination and the degree to which the washing machines become contaminated, potentially leading to cross-contamination of other clothing during subsequent laundering cycles.

The purpose of this pilot study was to evaluate lead removal in the practice of routine residential washing, as well as the possibility of lead transfer to another fabric or contamination of the washing machine. The study evaluated lead removal by studying two forms of inorganic lead and three types of fabric typically worn by workers.

Materials and methods

The research data associated with this study is with the corresponding author and will be shared on request.

Study design

This experimental pilot study involved spiking fabrics with lead, laundering the fabrics in residential washing machines, and testing the lead levels of the laundered fabrics. The authors first evaluated the analytical methodology by computing the recovery of known amounts of lead spiked on fabric and determining the accuracy and precision of the method.

The authors then evaluated the levels of lead present on laundered swatches that had been spiked with two forms of lead. The swatches were of three fabric types commonly worn by workers. Along with the fabric, eight pounds of bedsheets and pillowcases were washed to simulate a typical household laundry load (Leverette 2022). The spiked $3\,cm \times 3\,cm$ swatches were attached to a pillowcase in the laundry load. Levels of carryover lead were also determined in uncontaminated bedsheets and pillowcases that were run in a laundry load with the spiked fabric. The authors cut a $3\,cm \times 3\,cm$ swatch from a random section of the bedsheet and analyzed it for carryover levels of lead. All bedsheets and pillowcases were purchased new and washed twice before use.

To document other variables that may have influenced lead removal and are pertinent to local laundry situations, both the pH and hardness of the wash water were measured. A common consumer detergent and a common washing machine were used for experiments where swatches were laundered. The washing machines were purchased new. Finally, to measure the levels of cross-contamination, the interiors of the washing machines were tested for residual lead.

Fabrics

This pilot study included three fabrics:

- Dickies Pant Fabric (DPF): Dickies 874 Flex Material 65% Polyester/35% Cotton.
- T-shirt material (TSM): Hanes 100% Cotton.
- Blue jeans/denim material (BJM): Falls Creek Relaxed Stretch Polyester/Cotton blend with other fibers.

Based on anecdotal observations made by the authors on field studies, these fabrics are examples of those often worn by workers in industries where lead exposure is a concern. All items were purchased commercially and washed twice before using them for testing.

Lead sources

Experiments were done with water-soluble lead nitrate [$Pb(NO_3)_2$] and water-insoluble lead carbonate [$Pb(CO_3)_2$]. Lead nitrate was obtained from JT Baker. Lead carbonate was obtained from NIST (National Institute of Standards and Technology, Gaithersburg, MD; Standard Reference Material #2589), which is a paint dust with ~9.99% lead. When lead carbonate is mentioned in this study, it refers to lead paint/SRM 2589 and not pure lead carbonate.

Known concentrations of lead nitrate were applied to the fabric swatches using aqueous solutions of lead nitrate or a slurry/paste of lead nitrate solid in deionized water. Lead carbonate was applied to the fabric swatches as a powder, to which deionized water was added. The swatches were folded once and pressed by hand to smear the lead carbonate slurry across the fabric.

pH and water hardness

A Mettler-Toledo Seven2Go portable pH meter was used once each day of washing machine operation to measure the pH of incoming water into the washing machine. The instrument was calibrated daily when the washing machines were run, using buffer standards at pH 4, pH 7, and pH 10. A sample of the water was analyzed once each day of washing machine operation for a hardness determination. Hardness was based on the sum of calcium and magnesium calculated as calcium carbonate hardness (U.S. EPA 1994).

Analytical method validation

Fabric swatches were cut into squares approximately 3 cm × 3 cm (9 cm^2) in size. A known quantity of lead (9 µg, 900 µg, or 9,000 µg) was spiked on each fabric swatch, dried, and weighed for a final level of 1 µg/cm^2, 100 µg/cm^2, and 1,000 µg/cm^2. These levels span the range of concentrations (in µg/m^3) seen in industrial settings (Koh et al. 2015). Lead nitrate was spiked at two levels: 1 µg/cm^2 and 1,000 µg/cm^2. Lead carbonate was spiked at three levels: 1 µg/cm^2, 100 µg/cm^2, and 1,000 µg/cm^2. The swatches were then subjected to microwave-assisted digestion using nitric acid and peroxide and closed digestion vessels. The solution was diluted to 20 mL volume with deionized water and analyzed by Inductively Coupled Plasma Mass Spectroscopy using EPA method 200.8 Determination of Trace Elements in Waters and Wastes by Inductively Coupled Plasma—Mass Spectrometry (U.S. EPA 1994).

Recovery and precision

Recovery experiments were performed on the spiked fabric matrix with lead nitrate ($n = 40$) and lead carbonate ($n = 32$). Of the 72 samples, 25 each were spiked at the 1 µg/cm^2 and 1,000 µg/cm^2 levels, and 22 were spiked at the 100 µg/cm^2 level. Percent recoveries of lead at each spike level were calculated by dividing the final mass by the initial mass and multiplying by 100. The percent coefficient of variation (%CV) was reported as a measure of precision. A method with a %CV less than or equal to 20 was deemed precise (Reed et al. 2002).

Detection limit

The lower reporting limit was determined by taking the lowest concentration in the calibration curve divided by the weight of the sample fabric digested and prepared. The volume upon digestion was 20 mL. The lowest concentration of the calibration curve was 0.5 µg/L.

Lead extraction from laundered fabrics

A known amount of lead (9 µg; 900 µg; or 9,000 µg) was spiked on 3 cm × 3 cm (9 cm^2) swatches of DPF, TSM, or BJM, for a spike level of 1 µg/cm^2, 100 µg/

Table 1. Experimental characteristics of 18 laundry loads.

Load	Fabric	Lead form
1	DPF	Nitrate
2	DPF	Nitrate
3	TSM	Nitrate
4	TSM	Nitrate
5	BJM	Nitrate
6	BJM	Nitrate
7	DPF	Carbonate
8	DPF	Carbonate
9	TSM	Carbonate
10	TSM	Carbonate
11	BJM	Carbonate
12	BJM	Carbonate
13	DPF	Nitrate
14	TSM	Nitrate
15	BJM	Nitrate
16	DPF	Carbonate
17	TSM	Carbonate
18	BJM	Carbonate

DPF = Dickies Pant Fabric; TSM = T-shirt Material; BJM = Blue Jean Material.

cm^2, and 1,000 µg/cm^2. Two forms of lead were used: lead nitrate and lead carbonate. The fabric swatches, along with eight pounds of bedsheets and pillowcases, were washed using top- and front-loading washing machines. Two sets of sheets and pillowcases that represented a load of laundry were alternated between them for use in the wash load. These sheets were a combination of king, queen, and twin sizes and included flat and fitted sheets.

Each washing load had six swatches of the same type (two swatches each of 1 µg/cm^2 and 100 µg/cm^2; one swatch of 1,000 µg/cm^2; and one blank). All six fabric swatches were attached to pillowcases using a plastic tag applicator. The swatches were then analyzed to determine the amount of lead still present on the spiked swatch following one laundering cycle. The percentage of lead that was removed from each swatch was reported. Table 1 lists the combination of variables used in each of the 18 laundry loads.

In each load, the initial mass of lead was 10,818 µg $[(2 \times 9) + (2 \times 900) + (1 \times 9{,}000)]$. The lead in these spikes could redeposit on each other, on the blank swatch, or the 8 pounds of bedsheets and pillowcases. The percentage of lead removed during the laundry process was determined by computing the mass of lead based on the analytical lead result after each wash. The difference between the initial and final mass was divided by the initial mass and multiplied by 100. This was the percentage of lead removed.

Quality control samples

Positive and negative controls were included in the analysis as a quality control step. The positive control was a 100 µg/cm^2 spiked fabric swatch using the same form of lead and the same fabric type as the other fabric swatches in the analytical run, which did not undergo washing. A recovery between 60% and 140% was deemed acceptable. This range accounted for the physical loss of lead and the redeposition of lead from one fabric swatch to another. Negative controls were unspiked fabric swatches. Positive and negative controls were not included in the washing machine loads. There were 18 samples each of positive and negative controls.

Lead cross-contamination

Residual lead

After laundry loads #1 and #7 were removed from the washing machine, two clean fabric swatches from a bedsheet were used to wipe surfaces inside the washing machine tub to evaluate whether lead removed from the fabric was deposited on the washing machine surfaces.

Carryover

To assess whether lead was building up on the bedsheets being laundered, after laundry loads #1 and #7, two 3 cm × 3 cm swatches (one for each load) were cut from the washed sheets and analyzed for lead.

Statistical analysis

SAS v. 9.4 (Cary, NC) was used for all analyses. Significance was set at $\alpha = 0.05$.

Method validation

For the three spike levels, the %CV was computed as the standard deviation divided by the average.

Lead extraction from fabrics

Descriptive statistics (mean, range, coefficient of variation) of the percent of lead removed were computed for the following two explanatory variables: fabric and lead type. The Generalized Linear Model (GLM) was used to analyze all the variables in one model, with the response variable being the percent of lead removed, and the explanatory variables being fabric and lead. Interaction between these two variables was also checked.

Results

Method validation

The overall mean recovery from 72 spikes was 109.1%. The recoveries ranged from 12% to 612% and

Table 2. Method validation: Spiked samples outside the acceptable recovery criterion of 60%–140%.

Spike level (μg/cm^2)	Fabric	Lead type	Recovery (%)
1	DPF	Carbonate	256
1	DPF	Carbonate	612
1	TSM	Carbonate	441
100	DPF	Carbonate	16
100	DPF	Carbonate	18
100	DPF	Carbonate	12
100	DPF	Carbonate	19
100	DPF	Carbonate	146
100	TSM	Carbonate	146

had a %CV of 72.2%. Nine samples were below or above the accepted percent recovery criterion of 60% to 140%. Four samples showed less than 20% recovery, and five samples had recoveries between 146% and 612%. Table 2 shows the nine samples that were not within the acceptable recovery criterion. All nine were spiked with lead carbonate.

Table 3 summarizes the mean percent recovery with range and %CV for the three spikes, three fabrics, and two lead sources. The highest amount of lead recovered was when lead carbonate was spiked on a DPF fabric at the 1 μg/cm^2 level. The lowest amount of lead recovered was when lead carbonate was spiked on a DPF fabric at the 100 μg/cm^2 level. The authors concluded that the method was accurate and precise for lead nitrate across all three spike levels because all mean recoveries were between 60% and 140% of the expected 100% recovery, and all %CVs were less than 20%. However, the method for lead carbonate was neither accurate nor precise at the 1 μg/cm^2 level.

Lower report limit

The lowest calibration standard was 0.5 μg/L, and the volume upon digestion was 0.02 L. Therefore, the minimum mass of lead was 0.01 μg. The heaviest fabric swatch was 482 mg. Therefore, assuming fabric swatches could weigh up to 500 mg, the detection limit equates to 0.02 mg/kg. The specific detection limit for TSM was 0.07 mg/kg (135 mg), for BJM was 0.03 mg/kg (350 mg), and for DPF was 0.04 mg/kg (250 mg).

Lead extraction from laundered fabrics

The mean percent lead removed was 88.0%, and the median was 96.6% (range: 48.7 to 99.9). The %CV was 18.4%.

Among the three fabrics tested, BJM appeared to have the least amount of lead removed by laundering (70.6%). The amounts of lead removed from DPF and TSM were similar (97.4% versus 95.9%). The variability was higher for BJM ($n = 6$, %CV = 25.3) than DPF ($n = 6$, %CV = 2.7) or TSM ($n = 6$, %CV = 4.5).

More lead was removed in the carbonate form (92.6%) than in the nitrate form (83.4%) by laundering. GLM was used to explore the relationships between the percentage of lead removed and the fabric and lead. Statistically significant differences were found among the fabric and lead explanatory variables ($p < 0.05$). Significant interaction was also found between fabric and lead ($p < 0.05$). Table 4 summarizes these findings. The R-squared value was 0.86, which means that 86% of the variability in the percent lead removed can be explained by the model.

Based on an examination of the residual plots, the four assumptions of linear regression (linearity, independence, normality of error terms, and equal variance of error terms) were met.

Quality control samples

The recoveries from the 100 μg/cm^2 positive controls ranged from 84.5% to 188.2%. Four out of 18 positive controls gave recoveries higher than 140% (quality control for loads 3, 4, 10, 12). Only one positive control gave a recovery below 90% (84.5% in Load 17). Therefore, losses of lead were not typical for the positive controls. None of the negative controls were above the limit of detection.

pH and water hardness

The average ± standard deviation of the pH and hardness of the water were 9.1 ± 0.1 units and 40.4 ± 4.0 mg/L, respectively.

Lead cross-contamination

To ensure that the results from each load washed in the machine were not influenced by the prior loads washed, experiments were performed to assess potential carryover between loads. The "sheet control, not washed" represented a bedsheet sample that was not included in the load in the machine. Since each load of laundry had five spiked swatches for a total of 10,818 μg of lead, residues and carryover checks showing <1 μg of lead were considered as evidence of no significant lead levels remaining on the fabric (sheets) or in the washing machine (Table 5).

Discussion

Method validation

No analytical method existed for the extraction and analysis of lead from the three fabrics in this pilot study (DPF, TSM, and BJM) at 1 μg/cm^2, 100 μg/cm^2,

Table 3. Method validation: Mean lead recovered (%).

Spike level (μg/cm^2)	Fabric	Source	Sample size	Mean recovery (%)	Minimum (%)	Maximum (%)	%CV
1	BJM	Carbonate	1	97	97	97	No data
		Nitrate	4	100.18	96.6	102.5	2.76
	DPF	Carbonate	3	332.67	130	612	75.1
		Nitrate	12	99.0	91.8	108.70	4.9
	TSM	Carbonate	1	440	440	440	No data
		Nitrate	4	96.5	92.1	104.8	5.9
100	BJM	Carbonate	2	104	94	114	13.6
		Nitrate	0	No data	No data	No data	No data
	DPF	Carbonate	18	88.5	12.0	146.0	47.8
		Nitrate	0	No data	No data	No data	No data
	TSM	Carbonate	2	131	116	146	16.2
		Nitrate	0	No data	No data	No data	No data
1,000	BJM	Carbonate	1	106	106	106	No data
		Nitrate	4	91.8	82.2	99.4	7.8
	DPF	Carbonate	3	105	88	117	14.4
		Nitrate	12	85.5	61.8	110.2	19.2
	TSM	Carbonate	1	107	107	107	No data
		Nitrate	4	89.6	78.5	95.7	8.9

DPF = Dickies Pant Fabric; TSM = T-shirt Material; BJM = Blue Jean Material.

Table 4. Mean lead removed (%) from loads 1–18.

Explanatory variable	Type	Sample size	Mean % lead removed	%CV	*p*-value
Fabric					<0.0001
	BJM	6	70.6	25.3	
	DPF	6	97.4	2.7	
	TSM	6	95.9	4.5	
Lead					0.0201
	Nitrate	9	83.4	24.1	
	Carbonate	9	92.6	11.1	
Fabric*Lead					0.0116

Table 5. Lead residue and carryover in micrograms (μg) and (sample size).

	Background lead (μg)	Lead residue (μg)[a]	Lead carryover (μg)[b]
Sheet control, not washed	0.02–0.04 ($n = 2$)		
Load 1		0.02–0.06 ($n = 2$)	0.02
Sheet control, not washed	0.02 ($n = 1$)		
Load 7		0.05–0.13 ($n = 2$)	0.04

[a]Wipe sample taken inside the washing machine.
[b]Lead level in 3 cm × 3 cm swatches taken from bedsheet.

and 1,000 μg/cm^2. Therefore, the authors adapted and validated an analytical method where fabric samples containing lead were prepared and analyzed by microwave digestion using nitric acid and hydrogen peroxide, and subsequent analysis by ICP-MS (National Institute of Standards and Technology 2021).

The range of lead levels selected is relevant to occupational health as it covers a range of measures typically seen in workplace wipe and air lead samples. A NIOSH health hazard evaluation found between 23 and 940 μg of lead in hand wipe samples (NIOSH 2014). Although airborne lead samples as low as 4 μg/m^3 and as high as 4,100 μg/m^3 have been reported (NIOSH 2014), most airborne samples in occupational settings with lead exposures are between 60 and 800 μg/m^3 (Koh et al. 2015). This translates to 58–768 μg, assuming an 8-hr sample at a nominal flow rate of 2 liters/min. This study intended to mimic the amount of lead that may accumulate on clothing during an employee's workday in an occupation where lead exposure was possible. Therefore, the spikes of 9 μg, 900 μg, and 9,000 μg spanned the ranges reported in the literature.

Of the 72 samples analyzed for the validation study, the mean percent of lead recovered was 109%. However, since the samples were prepared in the laboratory, there were practical limits impacting accuracy and precision, especially at the low 9 μg level with the lead carbonate from the paint dust. Challenges with the application of trace levels of paint dust caused more variability in the recovery. SRM 2589 is a powdered paint with a certified amount of lead. The presence of other compounds in the paint may have affected the efficiency of the digestion and the lead recovery. Moreover, according to the Certificate of Analysis for SRM 2589, 100 mg is the minimum sample size to use. For the lowest level, this study used less than 1 mg of bulk, which may have affected the homogeneity of the sample, which would have led to lower and more variable recoveries. Therefore, the authors determined an acceptable recovery range between 60% and 140% instead of the more restricted 80% to 120% range (U.S. EPA 1994). The range was determined by spiking the fabric swatches and preparing them for analysis without any laundering.

The validation study initially used two spike levels, each of 1 $\mu g/cm^2$ and 1,000 $\mu g/cm^2$. Spiking the fabric with a known volume of a lead nitrate solution was more controlled compared to working with lead carbonate, which was in the form of a solid powdered paint to achieve the spike level. Because of the challenges with working with the powdered paint for lead carbonate, the additional 100 $\mu g/cm^2$ level was included.

The validation results showed that the quantitative accuracy was not reliable when 9 µg of lead from the lead carbonate form was spiked on a 500 mg swatch. Whereas spiking levels of 100 µg lead as lead carbonate on a 500 mg swatch (or approximately 200 mg/kg) showed acceptable quantitative accuracy. From the results of the two spiking levels, a practical quantitation limit of approximately 100 mg/kg can be inferred from the results for the lead carbonate form. This would equate to about 50 µg lead on a 500 mg swatch. The validation study showed that when using lead nitrate, the method demonstrated improved performance at the low spiking level with an average recovery of 99.0% of lead when 9 µg of lead was spiked on a 500 mg swatch (or approximately 18 mg/kg).

During day 3 of the validation study using lead carbonate for spiking, four samples at the 100 $\mu g/cm^2$ level returned extremely poor recovery results (under 20%). Review of the instrumental results did not reveal any dilution or calculation errors. There were no differences in how the samples were processed as compared to any other analysis days. A subsequent data set, including six samples at the 100 $\mu g/cm^{2,}$ showed an average recovery of 115%. One sample using DPF and one sample using TSM gave high recoveries for the 100 $\mu g/cm^2$ spiking level, at 146%. No difference in preparation or processing occurred for these fabric swatches, and no laboratory justification exists for the elimination of the data points.

Lead removal from laundered fabrics

On average, 88% of lead was removed from the fabrics; however, no single washing machine cycle completely removed spiked lead from the fabrics. Any lead remaining on the fabrics after washing could be considered a health hazard because when the fabrics are dried, particles of lead on the fabric could become airborne.

The removal mechanism appears to be based more on agitation and physical "soil" removal as compared to dissolution of the lead. This statement draws from the effectiveness of removing lead carbonate, which is insoluble compared to lead nitrate, which is a soluble form of lead. The authors chose to combine three concentration levels (for a total of 10,818 µg) to reduce the length of experimental time and to reduce costs.

Three fabrics were chosen based on observations of the type of clothing often worn by workers. Of the fabrics selected for this study, the BJM represented the most challenging fabric from which to remove lead compared to the DPF and the TSM. This could be due to the denser nature of the denim and the coarse weave of the fabric. The fabric resisted efficient removal during the residential laundry washing. More studies need to be done on lead retention on denim because the weaves of denim can vary. Non-denim fabrics, such as DPF, may be a better choice for avoiding lead build-up within the fabric after washing.

Results indicated that residential washing machines used to launder lead-contaminated fabrics after occupational exposure can remove some, but not all, of the lead contamination.

Lead cross-contamination

This study found some level of lead residues in the washing machine between loads. The study also found that small amounts of lead were transferred from the spiked swatches to clean bedsheets. However, the values were less than 0.5 µg. It did not appear that lead built up in the washer after lead-contaminated clothes were washed. However, due to the small number of samples, additional data are needed. Given the limited scope of this study, it is important to continue to follow public health recommendations for preventing lead exposure, such as laundering work clothes separately from other household clothes.

Public health relevance

The 1995 NIOSH report to Congress (NIOSH 1995) identified five effective workplace measures to prevent take-home lead exposures: (1) reducing exposures in the workplace, (2) offering employees the opportunity of changing clothes before going home and leaving soiled clothing at work for laundering, (3) storing street clothes in areas separate from work clothes, (4) offering employees the opportunity to shower before leaving work, and (5) prohibiting the removal of toxic substances or contaminated items from the workplace.

However, not all workplaces offer showering and laundry facilities, and many workers may have no choice but to launder their work clothes at home (NIOSH 1995). The impetus behind this study was to develop a better understanding, from a quantitative perspective, of the effectiveness of and challenges to residential laundering to minimize lead exposure to household members. The public health recommendation to "launder lead-contaminated clothing separately" is based on prudent best practices. This study has provided some information to better quantify the effectiveness of residential laundering in removing lead, lead removal from fabrics commonly worn by workers, and the effectiveness of household detergent on lead removal.

Future studies can build on the data presented here. More research is needed, especially in the determination of background levels of lead and other heavy metals in work clothes, the amount of lead and heavy metals removed in a variety of fabrics, the number of washes needed to remove most of the lead and heavy metals, the amount of residue on washing machines, and the varieties of detergent formulations that can remove the greatest amount of lead. In future experiments, it would be helpful to follow a randomized design to mitigate random experimental errors.

Additionally, the pilot study findings suggest that lead may not be fully removed from clothing during residential laundering. Over time, lead may accumulate on clothing (especially on clothing that is used repeatedly in a lead environment) and could potentially contribute to overall occupational exposures. These exposures could occur via skin absorption through direct dermal contact with lead-contaminated clothing or indirectly through contact with a contaminated surface in the home. This potential exposure pathway has not been characterized in the occupational health literature, but understanding this pathway could play an important role in reducing lead exposure in both workers and their households.

Limitations

This pilot study has several limitations. First, although overall %CVs were computed by spike level, comprehensive computations of %CVs by type of lead and fabric were not made. For example, in the validation studies, the authors did not spike lead nitrate at the 100 μg/cm^2 level for any fabric; also, several spikes with lead carbonate only had one data point, so it was not possible to determine method variability. Therefore, the understanding of the precision of this method by fabric type and lead form may not be complete. The authors were not able to analyze the results by washing machine orientation because neither the top- nor the front-loading washing machines had an agitator. Finally, the experiments in this study are limited in number, and the investigation of different variables was not randomized. Therefore, the results could be affected by random errors such as operator error and the lab environment.

Conclusion

This pilot study developed and performed an initial validation on an analytical method suitable for the determination of lead levels, between 1 μg/cm^2 and 1,000 μg/cm^2, present in three varieties of fabric: DPF, TSM, and BJM. While residential washing removed most of the lead, it did not completely remove lead from any of the three types of fabrics tested. Of the three fabrics included in this study, BJM retained the most lead. The levels of lead that transferred from spiked fabric to bedsheets included in the same washing load were less than 0.5 μg. However, given the study limitations, it is important to continue to follow public health recommendations for preventing lead exposure, such as laundering work clothes separately.

Acknowledgments

We want to thank Dr. Ronnee Andrews, Research Chemist with the Chemical and Biological Monitoring Branch at the National Institute for Occupational Safety and Health, and Dr. Christopher Wichman, Assistant Professor of Biostatistics at the University of Nebraska Medical Center College of Public Health, for reviewing this manuscript. We also want to thank Ms. Mary Beth Bohman for editing this manuscript. The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC). Mention of any company or product does not constitute endorsement by NIOSH, CDC.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

29 USC 671a. 1991. Workers' Family Protection Act, S.353, 102nd Cong., 1st Sess. [accessed 2022 Aug 5]. 29 USC 671—Workers' family protection (govregs.com).

Aguilar-Garduño C, Lacasaña M, Tellez-Rojo MM, Aguilar-Madrid G, Sanin-Aguirre LH, Romieu I, Hernandez-Avila M. 2003. Indirect lead exposure among children of radiator repair workers. Am J Ind Med. 43(6):662–667. doi: 10.1002/ajim.10204.

Ceballos D, Beaucham C, Page E. 2017. Metal exposures at three U.S. electronic scrap recycling facilities. J Occup Environ Hyg. 14(6):401–408. doi: 10.1080/15459624.2016.1269179.

Fischbein A. 1992. Occupational and environmental lead exposure. In: Rom WN, editor. Environmental and occupational medicine. 2nd ed. Boston (MA): Little, Brown. p. 735–758.

Kalweit A, Herrick RF, Flynn MA, Spengler JD, Kofi Berko J, Jr, Levy JI, Ceballos DM. 2020. Eliminating take-home exposures: recognizing the role of occupational health and safety in broader community health. Ann Work Expo Health. 64(3):236–249. doi: 10.1093/annweh/wxaa006.

Koh DH, Locke SJ, Chen YC, Purdue MP, Friesen MC. 2015. Lead exposure in US worksites: a literature review and development of an occupational lead exposure database from the published literature. Am J Ind Med. 58(6):605–616. doi: 10.1002/ajim.22448.

Laidlaw MAS, Filippelli G, Mielke H, Gulson B, Ball AS. 2017. Lead exposure at firing ranges—a review. Environ Health. 16(1):34. doi: 10.1186/s12940-017-0246-0.

Leverette MM. 2022. Washing machine load size: an easy reference chart. The Spruce; [accessed 2023 Oct 31]. https://www.thespruce.com/formula-to-calculate-washer-tub-capacity-2145871#How%20Much%20Does%20Laundry%20weigh?.

Levin R, Brown MJ, Kashtock ME, Jacobs DE, Whelan EA, Rodman J, Schock MR, Padilla A, Sinks T. 2008. Lead exposures in U.S. children, 2008: implications for prevention. Environ Health Perspect. 116(10):1285–1293. doi: 10.1289/ehp.11241.

National Institute of Standards and Technology. 2021. Standard Reference Material #2589—powdered paint. [accessed 2022 Aug 16]. NIST—SRM Order Request System SRM 2589—Powdered Paint (Nominal Mass Fraction of 10 % Lead).

Niemeier RT, Maier A, Reichard JF. 2022. Rapid review of dermal penetration and absorption of inorganic lead compounds for occupational risk assessment. Ann Work Expo Health. 66(3):291–311. doi: 10.1093/annweh/wxab097.

NIOSH. 1995. Report to Congress on workers' home contamination study conducted under the Workers' Family Protection Act (29 U.S.C. 671a). DHHS Publication Number 95-123. https://www.cdc.gov/niosh/docs/95-123/default.html.

NIOSH. 2006. Health hazard evaluation report: Broward County Parks and Recreation Division, Markham Park, Sunrise, Florida. By Eisenberg J, King B. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. NIOSH HETA No. 2005-0153-2997.

NIOSH. 2014. Evaluation of employees' exposures to lead, noise, and heat at an automotive lead-acid battery recycling company. By King B, Musolin K, Ceballos D, Brueck S, Beaucham C. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. NIOSH HETA No. 2012–0071–3224. https://www.cdc.gov/niosh/hhe/reports/pdfs/2012-0071-3224.pdf.

NIOSH. 2017. Evaluation of lead exposure at an indoor law enforcement firing range. By Grant MP, Eisenberg J, Methner M. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. Health Hazard Evaluation Report 2016-0232-3285. http://www.cdc.gov/niosh/hhe/reports/pdfs/2016-0232-3285.pdf.

NIOSH. 2018. Evaluation of nonproduction area air and surface lead levels, employee blood lead levels, and psychosocial factors at a battery manufacturing plant. By Harney JM, Musolin K, Wiegand D, Mueller C, Henn S. Cincinnati (OH): U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. NIOSH HETA No. 2013-0226-3314. https://www.cdc.gov/niosh/hhe/reports/pdfs/2013-0226-3314.pdf.

Piacitelli GM, Whelan EA, Ewers LM, Sieber WK. 1995. Lead contamination in automobiles of lead-exposed bridgeworkers. Appl Occup Environ Hyg. 10(10):849–855. doi: 10.1080/1047322X.1995.10387700.

Piacitelli GM, Whelan EA, Sieber WK, Gerwel B. 1997. Elevated lead contamination in homes of construction workers. Am Ind Hyg Assoc J. 58(6):447–454. doi: 10.1080/15428119791012694.

Reed GF, Lynn F, Meade BD. 2002. Use of coefficient of variation in assessing variability of quantitative assays. Clin Diagn Lab Immunol. 9(6):1235–1239. doi: 10.1128/cdli.9.6.1235-1239.2002.

Staudinger KC, Roth VS. 1998. Occupational lead poisoning. Am Fam Physician. 57(4):719–726.

U.S. EPA. 1994. Method 200.8: determination of trace elements in waters and wastes by inductively coupled plasma-mass spectrometry, Revision 5.4. Cincinnati (OH). https://www.epa.gov/esam/epa-method-2008-determination-trace-elements-waters-and-wastes-inductively-coupled-plasma-mass.

Whelan EA, Piacitelli GM, Gerwel B, Schnorr TM, Mueller CA, Gittleman J, Matte TD. 1997. Elevated blood lead levels in children of construction workers. Am J Public Health. 87(8):1352–1355. doi: 10.2105/ajph.87.8.1352.