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Relationship Between Lead Levels on Painted Surfaces and Percent Lead in the Particles Aerosolized During Lead Abatement

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Quantifying airborne lead on lead abatement work sites is critical in assessing worker lead exposures. Airborne lead levels depend on both the concentration of aerosolized particles and the percent lead in those particles. The lead level on the painted surface being abated may affect the percent lead in aerosolized particles. Experiments were performed in the University of Cincinnati Environmental Test Chamber (volume $\approx$ 24.3 m^3) using wood doors painted with lead-based paint. Three methods were used for paint removal: dry scraping, wet scraping, and dry machine sanding. Particles aerosolized during lead abatement activities were collected on filters using the Button Personal Inhalable Aerosol Samplers (SKC Inc., Eighty Four, PA) mounted in the workers' breathing zone. The filters were subsequently analyzed for percent lead in the particles. A portable X-ray fluorescence (XRF) instrument (NITON-700, NITON Inc., Bedford, MA) was used to measure surface lead levels of the doors. The accuracy of the XRF instrument was verified by testing standard reference materials prepared by the National Institute of Standards and Technology (NIST) and by Princeton Gamma Tech Inc. It was also verified by relating XRF results from painted door surfaces to laboratory lead analysis data obtained from paint chip samples taken from the same painted surfaces ($r^2 = 0.81$, $p < 0.001$). A highly significant relationship ($r^2 = 0.83$, $p < 0.001$) was found between the XRF readings and the percent lead in the particles aerosolized during dry scraping. No significant relationship was found for wet scraping ($r^2 = 0.09$, $p = 0.56$) or dry machine sanding ($r^2 = 0.002$, $p = 0.92$). The relationship between surface lead levels and percent lead in particles was found to be dependent on the paint removal method. This variation was attributed to the difference in water absorption property of the paint layers and the different particle aerosolization mechanisms inherent in each paint removal method.

Keywords Lead Abatement, Lead-Based Paint, Airborne Particles, XRF, Percent Lead

Significant levels of leaded particles are aerosolized during lead abatement.(1) These lead-contaminated particles are a potential health hazard to the workers performing lead hazard control work, which necessitates the use of engineering control and personal protective equipment (PPE) on lead abatement sites.(2) Selection of appropriate PPE is critical for adequate worker protection. This selection is based on the time-weighted average (TWA) of the airborne lead concentration sampled in a worker's breathing zone at an abatement site.(3)

Conventionally, the airborne lead concentration is determined by air sampling with a 37-mm filter cassette and laboratory lead analysis of the filters.(4) Instant assessment for the worker exposure cannot be determined by this conventional method because there is a considerable time lapse (days or weeks) between collecting the air sample and receiving the laboratory result.(3) On-site determination of the airborne lead concentration is desirable, as it would allow real-time exposure assessment to be used for selecting adequate worker protection.

A study was performed to determine the airborne lead concentration in a worker's breathing zone at a lead abatement site.(5) In the study, leaded particles aerosolized at bridge blasting projects were sampled using 37-mm cassettes. The lead loading on the filters was initially estimated by using a portable XRF instrument (NITON-700, NITON Inc., Bedford, MA). The filters were also analyzed for lead by graphite furnace atomic absorption spectrometry. No significant difference was reported between the lead concentration values obtained by the above two analytical methods. As a result of that study, the National Institute for Occupational Safety and Health (NIOSH) developed NIOSH Method 7702 for the portable and efficient XRF analysis of samples in the field.(4)

Alternatively, the airborne lead concentration can be estimated by combining the data on airborne particle concentration with the percent lead in the airborne particles. Indeed, the real-time concentration of airborne particles can be measured, for example, by utilizing inexpensive direct-reading aerosol instruments.(6) Since the percent lead in different particle sizes was shown to be the same,(7) it is sufficient to determine this percent for the entire filter sample using conventional analytical methods. If there is a correlation between percent lead in particles and surface lead concentration, the relationship can be used to estimate the airborne lead concentration resulting from abatement activities.

There have been several studies that attempted to identify a correlation between surface lead levels and the airborne lead concentration resulting from lead abatement activities. The Occupational Safety and Health Administration (OSHA) did not find a strong correlation between paint lead levels and airborne lead concentrations and concluded that "the results were so variable as to be impossible to apply."(3) A NIOSH (1992) study(1) also showed no significant relationship between the surface lead level (mg/cm^2) and the airborne lead concentration (μg/m^3) ($r = 0.22$). This NIOSH study, however, was conducted with the data provided by U.S. Department of Housing and Urban Development (HUD) contractors, and no attempt was made "to verify the accuracy or repesentativeness of the environmental samples [provided] by HUD contractors." The airborne lead concentration data in this study were presented in one plot for six abatement methods (abrasive removal, chemical removal, heat gun removal, encapsulation, enclosure, and replacement) and four other activities (initial set-up of the abatement job, pre-cleaning, daily cleaning, and final cleaning) in different combinations. While analyzing this integrated database, no attempt was made to establish a direct relationship for a specific lead abatement method. In contrast to the OSHA conclusion(3) and the NIOSH study result,(1) a more recent study showed a good correlation between paint lead levels in paint samples (percent) and worker exposures (μg/m^3) for 10 work surfaces ($r^2 = 0.794$) and 15 houses ($r^2 = 0.766$).(8)

A portable XRF instrument is a convenient tool for screening lead-based paint layers.(9) It provides real-time data and is non-destructive; therefore, it is widely used for risk assessments. Among commercially available portable XRF instruments, each one has its own performance characteristics including radiation source, sensitivity, detection limit, and so on.(10)

Several studies have been performed to examine field applicability of portable XRF instruments. Ashley et al. (1998) used a TN Spectrace 2000 instrument (TN Technologies, Round Rock, TX) and found a positive correlation (slope = 1.93) between XRF readings on leaded surfaces prepared for abatement and the results of laboratory lead analysis of the paint samples that were collected from the same locations where the XRF tests were performed.(9) All the XRF readings, however, were less than 7 mg/cm^2. Another study(5) successfully measured the lead loading on air filters by using a portable XRF instrument (NITON-700). The study showed a good correlation ($r^2 = 0.985$) between two data sets on the amount of lead collected with 37-mm filters: one determined by using the XRF instrument, and the other measured by the filter laboratory analysis.

The objective of this study was to determine whether the surface lead level measured with a portable XRF instrument could be used to predict the percent lead in the particles aerosolized during lead abatement. This determination was to be made following two stages of experimentation. The first was to verify the accuracy of the XRF instrument in quantitatively measuring the surface lead level. Once the instrument was proven to perform adequately, the following step was undertaken to determine the relationship between XRF data from surface lead measurements and the percent lead in the particles aerosolized during lead abatement activities.

MATERIALS AND METHODS

All the experiments were performed in the Environmental Test Chamber in the Department of Environmental Health at the University of Cincinnati.(7) The chamber represents a typical residential room with the volume of about 860 ft^3 $\approx$ 24.3 m^3 ($L \times W \times H = 12.4' \times 8.0' \times 8.7' \approx 3.78$ m $\times$ 2.44 m $\times$ 2.64 m). An attached air lock room prevents contamination inside the chamber from escaping into the adjacent laboratory space. The air lock room was also used to prepare the equipment required for the experiments that included paint removal and cleaning. The chamber's air purifying and ventilation system allowed us to decontaminate the chamber before and after each experiment. The system was not operated during paint removal or cleaning. The temperature and humidity in the chamber were recorded before and after each experiment. The floor of the chamber was covered with 6-mil plastic sheeting before each experiment and the sheeting was removed during the cleaning procedure.

Wood doors painted with lead-based paint were obtained at lead abatement sites in Cincinnati, Ohio. Only doors with surface XRF readings higher than 1 mg/cm^2 were selected for these experiments. The portable NITON-700 XRF instrument was chosen for this study because this device can detect surface lead levels as high as 40 mg/cm^2, which was the highest surface lead level detected on lead-based painted doors used in our previous study.(7) The XRF measurements were executed in accordance with the U.S. Environmental Protection Agency (EPA)/HUD Performance Characteristic Sheet.(11) Overall, 19 doors were used for particle aerosolization experiments and paint analysis. The surface areas consumed for each experiment varied (from 0.45 to 2 m^2) depending on the door condition and paint removal method.

Although testing by a portable XRF instrument is regarded as "a viable way to test for lead-based paint,"(10) the instrument is still considered only a screening tool for lead-based paint.(9) The accuracy of the portable XRF data for surface lead levels greater than 5 mg/cm^2 has not been sufficiently documented. This study intended to verify the reliability of the XRF data by the following two steps. The first step was to verify the reliability of the instrument by using standard reference materials (SRMs).

The SRMs made by either the National Institute of Standards and Technology (NIST) or Princeton Gamma Tech Inc. (PGT, Princeton, NJ) were used. Since the highest lead level in the NIST SRMs was relatively low (3.53 mg/cm^2), the two SRMs were stacked together on top of each other to form a higher level of 7.06 mg/cm^2. This lead level exceeded the highest XRF readings measured by Ashley et al. (1998),(9) about 7 mg/cm^2, and by NIOSH (1992),(1) about 5 mg/cm^2. The calibration standard made available by PGT contained 71.0 mg/cm^2 of lead. Although there was a considerable gap for the lead level in the SRMs provided by the NIST and the PGT Inc., the latter was tested as a reference material that contained the highest lead level available. This allowed us to examine the ability of the portable NITON XRF instrument to measure very high lead levels.

The second step was to examine the reliability of XRF methodology when used for in situ lead measurement. The XRF readings were recorded prior to the paint removal at the 15 specific locations on 12 painted door surfaces. Paint samples were taken from the same 15 locations. The sampling and analysis procedures followed the American Society for Testing Materials (ASTM)(12) and HUD(13) guidelines. The samples were analyzed for lead by flame atomic absorption spectrometry (FAAS). The XRF measurements were also conducted on the same sites after the paint samples were removed down to bare wood in order to determine the lead in the paint samples by subtracting the lead content associated with wood substrate. The post–paint-sampling XRF readings were subtracted from the corresponding pre–paint-sampling XRF readings (referred to as XRF readings) to determine the corrected XRF readings. Both non-corrected and corrected XRF readings were separately matched with the data obtained through the laboratory FAAS lead analysis of paint samples. The two data combinations were regressed: FAAS results versus non-corrected XRF readings and FAAS results versus corrected XRF readings.

Three different paint removal methods—dry scraping, wet scraping, and dry machine sanding—were used for aerosolizing leaded particles. Although dry scraping is not a HUD-recommended method except for limited surface areas,(13) previous studies demonstrated that lead-based paint removal from these relatively small areas could aerosolize a very high mass of leaded particles.(7) HUD requires that dry machine sanding be performed only in conjunction with a high-efficiency particulate air (HEPA)-filtered local exhaust ventilation system. However, we disabled the sander's local exhaust ventilation system in order to simulate the "worst-case scenario" resulting from a failure that may be caused by a clogged vacuum hose or overloaded filter. No water was applied to the door surfaces when either dry scraping or dry machine sanding was used. Wet scraping was utilized as it is a HUD-recommended lead abatement method. Overall, 30 experiments, 10 for each of the three paint removal methods, were performed by two workers in the Environmental Test Chamber.

Scrapers (Red Devil Inc., Union, NJ) with two different sizes of scraping blades of $2^1/_2$-inch and 3-inch were used for dry and wet scraping. Two machine sanders (Model 7447, Black & Decker Inc., Towson, MD) with belts of $3'' \times 21''$ (Medium, Grit 80, Norton Canada Inc., Hamilton, Ontario, Canada) were used for dry machine sanding.

After the active lead abatement task was completed, the workers left the chamber for one hour (the first waiting period) to allow the aerosolized dust to settle. Following this waiting period, the final cleaning began. The final cleaning procedures for experimental research were developed by our previous study.(14) The procedures included debris sweeping and 6-mil plastic sheeting removal, the first HEPA vacuuming, floor wet mopping and drying, and the second HEPA vacuuming.

The airborne particles were collected on 25-mm filters during lead abatement using the Button Personal Inhalable Aerosol Samplers (SKC Inc., Eighty Four, PA) and battery-operated personal pumps. Conventionally, worker lead exposure at a lead abatement site is assessed by personal air monitoring using a 37-mm filter cassette. This sampler, however, undersamples significantly compared to the American Conference of Governmental Industrial Hygienists (ACGIH®) inhalation curve,(15) especially for particles larger than 30 μm as was recently observed in the experiments with monodisperse particles of different sizes.(16) This leads to considerable underestimation of true worker exposure considering that the mass contribution of a single particle to the total particle mass increases dramatically as the particle size increases. In contrast, the Button personal inhalable aerosol samplers more closely approximates the ACGIH inhalation curve for various particle sizes including those greater than 30 μm in both laboratory and field studies.(16–17) Two Button personal samplers operated in a worker's breathing zone were used in each experiment: one during the paint removal procedure, another during the cleaning procedure. The flow rates of 4 L/min were calibrated before and after each test. The sampling time varied depending on the paint condition and the duration of the cleaning procedure: It ranged from 5 to 20 min for active abatement, and 57 to 78 min for cleaning.

Paint samples were collected from the same areas where XRF measurements were taken. An area of 5 cm × 5 cm on the door was outlined with a metal frame, then the paint was removed with a $1^1/_4$-inch scraper. In all cases, a heat gun was used to soften the paint. Each sample was stored in a 50-ml sample cup for lead analysis.

The 25-mm filters of the Button samplers were desiccated in a desiccator at room temperature for at least one day and weighed with a six decimal place balance. After sampling, the filters were desiccated and weighed again to measure the weight of the particles collected on the filters. The filters were then digested in concentrated HNO_3 on a hot plate. The digested solution was analyzed by FAAS using Perkin-Elmer 5000 spectrometer (Perkin-Elmer Inc., Norwalk, CT) following NIOSH Analytical Method 7082.(4) The bulk paint samples were desiccated in a desiccating oven at about 100°C for 1 hour before measuring the weight of the samples. After measuring the weight with a four decimal place balance, each paint sample was powdered until all particles were less than 1 mm in diameter. One gram of the sample was taken and digested with concentrated HNO_3 and 30% H_2O_2 on a hot plate.(18) The digested solution was analyzed for lead in the same manner as the filter samples.

During lead abatement, two workers were equipped with personal protective equipment including respirators with HEPA filters (North Inc., Cranston, RI), protective coveralls with hoods and boots (DuPont Inc., Wilmington, DE), goggles, ear plugs, and rubber protective gloves. The study was approved by the Institutional Review Board at the University of Cincinnati.

RESULTS AND DISCUSSION

Reliability of XRF Data for SRMs and Painted Surfaces

Table I compares the lead levels referenced in specific SRM with that measured by the NITON XRF. Three replicates of XRF measurements conducted on each specific SRM were averaged to obtain the mean and the standard deviation. As shown in Table I, the XRF accurately measured the amount of lead contained in the NIST SRMs at least up to the highest NIST SRM level of 3.53 mg/cm^2 (NIST SRM #4). A slight underestimation of the designated lead content (NIST SRM #5) may be caused by the interference of non-leaded material existing between the two SRMs stacked together. Although the XRF underestimated the highest available SRM of 71 mg/cm^2 (PGT, SRM #6) by < 20 percent, this measurement point agrees well with the trend of the XRF data.

TABLE I

Comparison between the designated lead content in SRMs and the measurement data with the portable NITON XRF

SRM[A]	Designated lead content (mg/cm^2)	Lead content from XRF reading[D] (mg/cm^2)
1	0.29	0.3 ± 0.03
2	1.02	1.1 ± 0.1
3	1.63	1.7 ± 0.1
4	3.53	3.4 ± 0.2
5[B]	7.06	6.8 ± 0.2
6[C]	71.0	59.3 ± 1.2

[A] SRM = standard reference material, unless otherwise noted, provided by NIST.

[B] Two #4 SRMs were stacked together on top of each other to yield this amount.

[C] The SRM was provided by Princeton Gamma Tech Inc.

[D] The XRF measurement data are shown as mean ± standard deviation.

Figure 1 compares the XRF readings on the painted surfaces (ranging up to 28.3 mg/cm^2) with the data from the laboratory FAAS lead analysis of paint samples taken from the same locations. Figure 1a presents the XRF readings obtained prior to paint sampling, while Figure 1b presents the corrected XRF readings. The solid lines in Figures 1a and 1b show the result

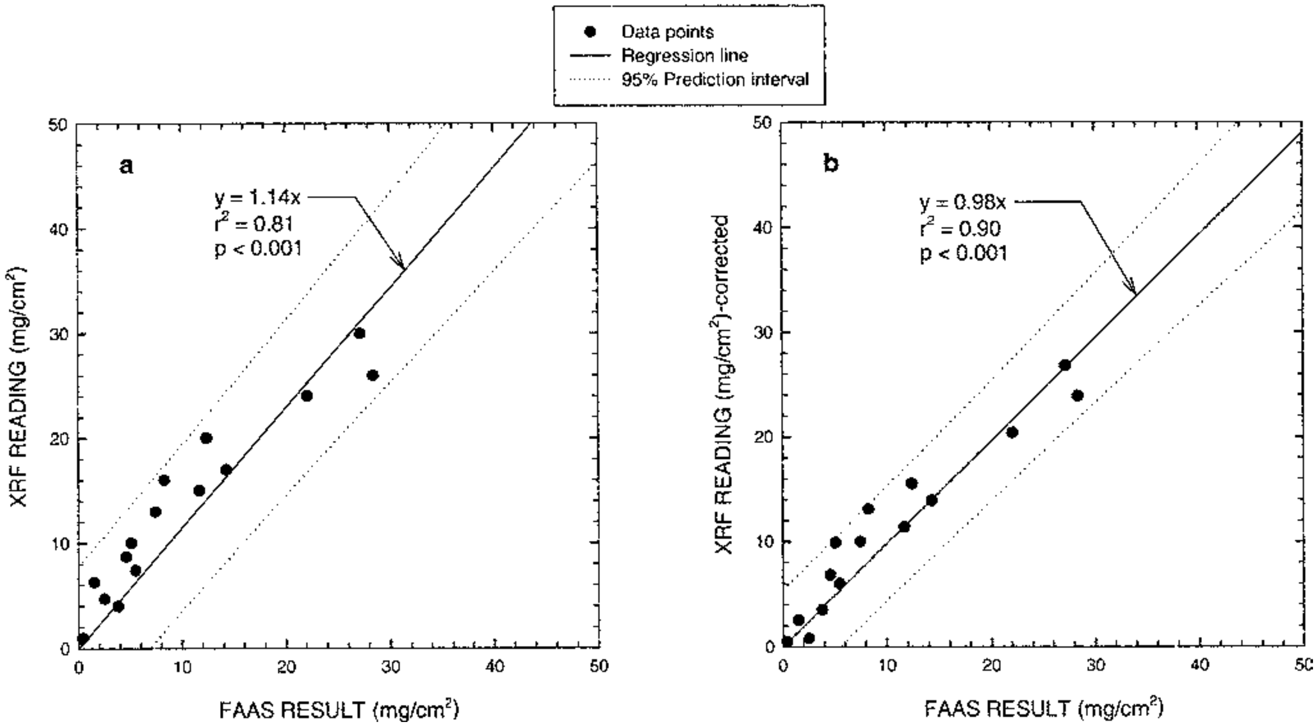

FIGURE 1

Correlation between lead analysis results of paint samples and (a) the XRF readings and (b) the corrected XRF readings on the surfaces from which the paint samples were taken.

of regression analysis and the dotted lines show the 95 percent prediction intervals.(19) A significant relationship ($r^2 = 0.81$, $p < 0.001$) is seen in Figure 1a. The slope of the linear regression line was 1.14. When the corrected XRF readings were regressed, the relationship became stronger ($r^2 = 0.90$, $p < 0.001$) and the slope (0.98) of the linear regression line was closer to unity (Figure 1b).

The data presented in Figure 1a were split into three groups based on XRF readings (up to 10 mg/cm^2, up to 20 mg/cm^2, and the entire range up to 28.3 mg/cm^2) and the same regression analysis was performed for each of the three groups. The analysis of the first group (XRF readings < 10 mg/cm^2) showed a weaker correlation ($r^2 = 0.52$, $p = 0.05$) and greater slope (about 1.68) than that of the data set for the entire XRF range ($r^2 = 0.81$, $p < 0.001$, slope = 1.14). The regression analysis conducted for the second group (XRF readings < 20 mg/cm^2) showed the same significant correlation ($r^2 = 0.81$, $p < 0.001$) but the slope of the regression line was 1.48. The difference in lead levels between XRF readings on surfaces and the FAAS data obtained from the paint samples is greater when the surface lead levels are lower. This result seems to be in a good agreement with the findings of Ashley et al. (1998),(9) who reported a significant correlation ($r^2 = 0.73$, slope = 1.93) between laboratory lead analysis data obtained by atomic absorption spectrometry and XRF readings for wood substrates with XRF readings <7 mg/cm^2.

The data measured by the portable XRF instrument used for this study showed a good agreement with the lead levels indicated in SRMs. The lead levels on the wood surfaces measured with this instrument also showed good agreement with laboratory data obtained with FAAS. Overall, the XRF method seems to be reliable for measuring surface lead levels in situ, at least up to about 30 mg/cm^2. This finding allows us to expand the XRF upper limit to considerably higher levels than those indicated in other studies.(1,9)

Relationship Between Surface Lead Levels and the Percent Lead in Airborne Particles

The surface lead levels as measured directly by XRF on the paint surface were regressed on the percent lead in the particles aerosolized during lead abatement to determine if there is a significant relationship between the two. The regression analysis showed a poor relationship ($r^2 = 0.01$, $p = 0.66$) when all the data from three paint removal methods were plotted together. When the same analyses were performed separately for each individual paint removal method, each case proved unique. The relationship between surface XRF readings and the percent lead in airborne particles aerosolized during dry scraping was found to be significant ($r^2 = 0.83$, $p < 0.001$, slope = 2.01) as shown in Figure 2a. At the same time, no significant relationship was found for wet scraping ($r^2 = 0.09$, $p = 0.56$) or for dry machine sanding ($r^2 = 0.002$, $p = 0.92$) as shown in Figures 2b and 2c, respectively. The figures for dry scraping (Figure 2a) and wet scraping (Figure 2b) show 10 data points each. Figure 2c shows 9 data points, since 1 point was found to be an outlier and thus was eliminated.

The doors used for this study were coated with multiple layers of paint that might be lead-based and non-leaded. The number of layers in the paint film on the tested doors ranged from three up to nine. At least one layer in the paint film was lead-based, as the doors selected for this study contained lead in the paint

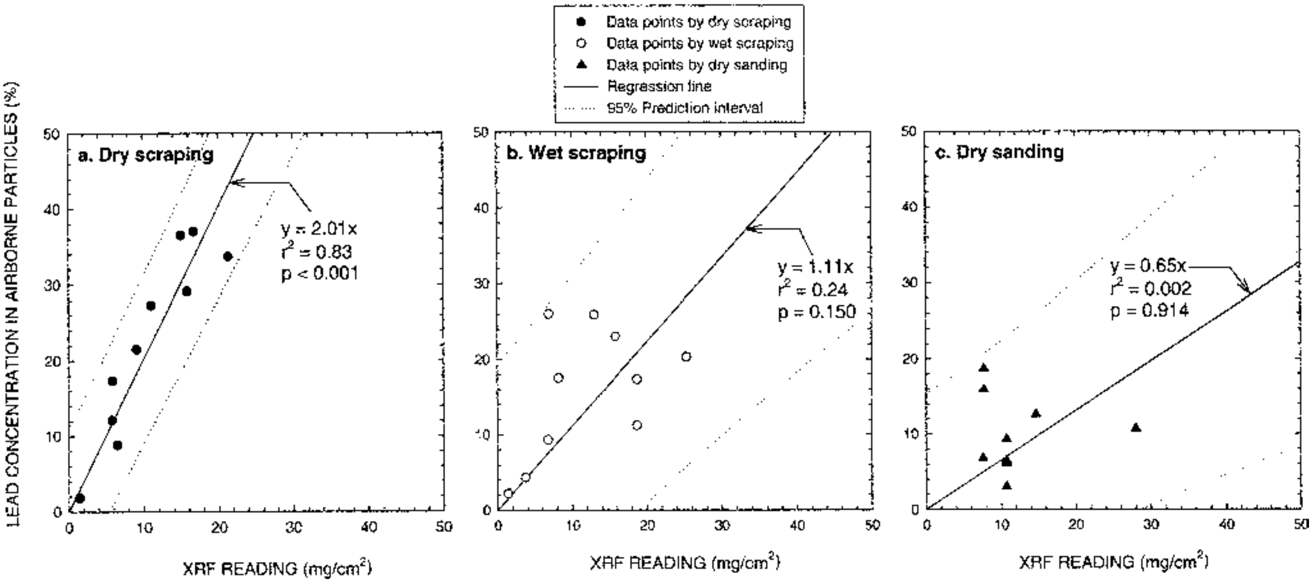

FIGURE 2

Correlation between XRF readings on lead-based painted surfaces and percent lead in the particles aerosolized during (a) dry scraping, (b) wet scraping, and (c) dry machine sanding.

as measured by XRF instrument and FAAS. No painting record was available since lead-based paint was applied to the doors apparently before 1978.(20) Many of the doors appeared to have been repainted after 1978. Therefore, it is likely that the paint layers closer to the substrate contain lead-based paint, while the outermost layers do not contain lead but may have latex paint. We observed that these outermost paint layers were difficult to remove irrespective of paint removal methods. Fewer particles aerosolized from these layers, and the paint was removed primarily in large chips. In contrast, it was observed that the paint removed from old (leaded) paint layers resulted in much higher aerosolization, especially when the paint removal activities were performed on the dry door surfaces (during dry scraping and dry machine sanding).

Thus, dry scraping that aerosolizes particles primarily from old (leaded) layers is characterized by a significant relationship between the surface lead level and percent lead in the particles. The dilution by the non-leaded particles aerosolized from the non-leaded paint layers is not significant, as release occurs primarily in chips, which settle quickly. When applying wet scraping, although approximately the same amount of water was used in each experiment, we observed that the paint on some doors absorbed water more readily than other doors. If the non-leaded paint layers readily absorb water but the leaded layers do not, the particles are aerosolized mainly from leaded layers. In this case, the percent lead in the particles is higher than the percent lead in the particles during dry scraping of the same door. In the reverse case, when the leaded paint layers readily absorb water but the non-leaded layers do not, the percent lead in the particles aerosolized during wet scraping will be lower than that during dry scraping of the same door. The poor correlation between the surface lead level and the percent lead in the airborne particles during wet scraping can perhaps be explained by this large variation in the wetting of the leaded and non-leaded paint layers.

When dry machine sanding is applied, we observed that the sanding belt penetrates into the wood deeper than the scraping blade during scraping and the particles are aerosolized not only from paint layers, but also from the door substrate. The large variation of the percent lead in the airborne particles aerosolized during dry machine sanding may be from the dilution caused by those wood particles that can be more pronounced than the dilution with non-leaded particles aerosolized from the non-leaded paint layers.

The variation of the percent lead in particles aerosolized during lead abatement might be partly from the different water absorption property of the paint layers (difference between dry and wet scraping) and partly from particle aerosolization mechanisms inherent in each paint removal method (scraping and machine sanding).

This study has some limitations. First, the tests were limited to one substrate material: only wood surfaces were used. Second, this laboratory study with a limited sampling size may need to be followed by a field study that would address various lead abatement methods, work practices, and environmental conditions. Third, while the dry scraping, the only one among the three methods tested, showed indeed a significant relationship between the surface lead level and percent lead in the airborne particles, it is not a preferred method in the field.

CONCLUSIONS

The goal of this research was to examine whether the percent lead in the particles aerosolized during lead abatement can be estimated by measuring the surface lead level with a portable XRF instrument.

The accuracy of the XRF data was verified first by the SRMs and second by relating the XRF readings obtained from the painted surfaces to the laboratory lead analysis of the paint samples taken from the same locations. The designated amount of lead in the NIST SRMs was within the range of the XRF measurement data. A significant relationship ($r^2 = 0.81$, $p < 0.001$) was found between the XRF readings on the lead-based paint (pre–paint-sampling XRF readings) and the laboratory lead analysis of the paint samples. An even stronger linear relationship ($r^2 = 0.90$, $p < 0.001$) was found between the above two data sets when post–paint-sampling XRF readings were subtracted from the pre–paint-sampling XRF readings.

A significant relationship ($r^2 = 0.83$, $p < 0.001$) was found between surface lead levels (mg/cm^2) measured with XRF and percent lead in the airborne particles aerosolized during dry scraping of wood doors. In contrast, there was no significant relationship between the XRF readings and the lead concentration of the particles aerosolized during wet scraping ($r^2 = 0.09$, $p = 0.56$) or dry machine sanding ($r^2 = 0.002$, $p = 0.92$). The different level of significance of the relationship between the above two data sets were from the variation of the percent lead in the particles generated by the three paint removal methods. The variation of the percent lead in particles was attributed to the difference in water absorption property of the paint layers and different particle aerosolization mechanisms inherent in each paint removal method. A field study should follow up to relate the XRF data and percent lead in airborne particles for various lead abatement methods, work practices, and environmental conditions.

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