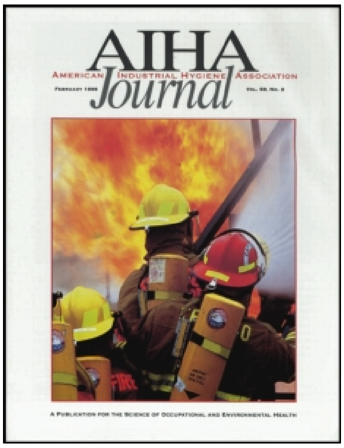

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Study and Models of Total Lead Exposures of Battery Workers

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In an attempt to establish a more realistic and reliable model for relating environmental exposure measurements to the biological indices of exposure, a study was undertaken to quantify the total sources of lead exposure among lead storage battery workers. In addition to the usual personal and area lead air sampling, quantitative and repeatable measurements of removable lead from work surfaces and the workers' hands and faces were obtained daily for ten consecutive work days in the pasting and battery assembly departments. Mathematical correlations of blood lead and zinc protoporphyrin (ZPP) levels as the dependent variable with the lead exposure sources were derived and demonstrated most strongly as log-log relationships. Statistical analyses by computer programming indicated that the airborne, hand, facial and work surface levels have a high degree of inter-correlation with a very significant positive individual correlation with blood lead levels and a somewhat lower correlation with ZPP. The results suggest that contaminated personal and work surfaces may play a more significant role in toxic occupational and environmental exposures, generally, than had heretofore been demonstrated or suspected.

Introduction

Lead exposures from the different processes in the manufacture of electric storage batteries have been shown to be variable and fluctuate considerably from hour to hour and from day to day.[1,2] Air lead concentrations have been reported in different departments of the battery plant with mean values as low as 9 $\mu g/m^3$ in the plastics department and as high as 218 $\mu g/m^3$ in the machine pasting department.[3] Several researchers have maintained, however, that industrial airborne concentrations are not always a reliable index of exposure due to: 1) high diurnal variations, 2) highly significant differences between workers doing the same job, 3) the intermittences of exposures, 4) individual peculiarities of work and personal habits; 5) added exposure from off-the-job activities and 6) dietary sources.[4,5] Work surface and personal contaminations have been acknowledged but not quantitatively studied as possible sources of accidental lead ingestion among lead workers.[6,7]

The routes of lead entry and uptake have been extensively studied with the conclusions that the amount of lead absorbed depends on the dose, particle size, chemical and physical forms of the lead, solubility, personal hygiene habits, and also specific host factors, such as age, nutritional and physiological status.[1,6,8] Based on a model developed by the Task Group on Lung Dynamics of the ICRP and the available data, the absorption of the inhaled lead into the blood for the average adult was estimated to be 40%.[9]

On the other hand, there is general agreement that only 8% to 10% of dietary lead ingested by adults is absorbed.[10,11] In a typical battery plant, the lead dust settled on work surface and the workers' bodies and clothing may lead to a relatively greater dose by ingestion than that by inhalation.[3]

There is a general agreement among most researchers that the blood lead level is a reliable integrated indicator of current lead exposure history of an individual, particularly for those with current industrial exposures.[7,8,12,13] Both clinical and epidemiological studies have attempted to correlate inhaled and ingested lead with the blood lead levels. Typically, the clinical studies have been conducted by having volunteers ingest lead incorporated in their food[10,14] or by inhaling lead particles[15,16] with results suggesting a positive relationship of both ingested and inhaled lead with blood lead levels.[7,17]

Epidemiological studies of adult blood lead levels and environmental sources of exposure have emphasized mainly the relationship of the air lead and blood lead levels.[7,17] Only in pediatric studies have other variables such as lead in soil, house dust, paint chips, and other forms of contamination been investigated as the sources of lead ingestion which may contribute to the blood lead levels.[18-20] The lesser attention to ingested lead among occupational adult population may be due to the relatively lower percentage of absorption of ingested lead,[8] the inadequacy of surface contamination measurement methods[21] with the consequent lack of monitoring data, and the traditional reliance on airborne threshold limit values as the criteria for evaluating occupational exposure.

However, poor personal hygiene habits of industrial workers have long been recognized by hygienists as a potential source of unintentional ingestion. This exposure source has not been acknolwedged by OSHA or incorporated into the blood lead-air relationship model despite the common consensus among industrial hygienists that food, smoking and body and clothing contaminations may be sources of lead exposure and absorption through ingestion.[22]

Routine wipe sampling of work surfaces has been used to identify potential sources for ingestion of toxic substances[23,24] with few or no measurements of contamination on

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workers' hands, lips or face, hair and clothing. Thus, the total sources of lead exposure and their interrelationship among lead workers have never been appreciably investigated either qualitatively or quantitatively.

In attempting to define the role of total lead exposure to the biochemical indices of absorption, it was particularly propitious to perform this study at a lead battery plant due to the availability of long term and current blood lead levels of the workers and extensive air sampling data. The first objective of this study was to supplement with current monitoring the airborne lead levels and, for the first time, to perform comprehensive monitoring of personal surface contamination, *i.e.*, on workers' hands and face and on work surfaces. Secondly, the mathematical relationships and inter-relationship of the biochemical indices and the airborne and surface measurements of lead would then be established employing simple and multiple regression analyses. In addition, correlations between the biochemical measures and independent variables of smoking habits, use of respirators, use of protective gloves, and tenure on the job were also studied.

Experimental

Process Description

Storage battery manufacture is comprised of several operations performed in separate departments in which the lead exposure levels vary accordingly.[25] Briefly, a lead grid is formed by casting molten metal or by an expanded metal process. The grid or plate is then pasted with a mixture composed generally of lead, lead oxide, sulfuric acid, water and expanders. The pasted plates are placed on racks, heat cured and stored in humidity controlled chambers. The plates are then "dressed up" by a brushing machine to get rid of excess paste and then manually stacked to form the battery elements, alternating negative and positive plates with an inert separator between each plate, welded to form groups, and finally charged. Based on established air sampling data, the pasting and assembly departments represent high and medium exposure levels, respectively, and were consequently selected for the areas of study.

Subjects

The criteria for selecting the plant workers were those used in a prior battery plant study;[3] no job change within the last year, employment at the plant for at least the prior six months, no recent or extended illness, holiday or absence, and no significant work schedule change, *e.g.*, overtime. Although it was proposed to involve all the 12 assembly workers and all 10 pasting department workers, one assembly worker could not participate because of OSHA's Medical Removal Program and five pasting department workers changed their minds and refused to participate. The subjects, their job classification, age and years of exposure are indicated in Table I. Consequently, 11 assembly department workers, 5 pasting department workers and 4 control subjects from the research and development laboratory and the medical department (plant nurse) were measured daily for facial and hand lead for 10 consecutive working days in a two week period. Current blood samples were obtained for each and analyzed for lead, hemoglobin and zinc protoporphyrin.

TABLE I
Employee Participants In Study

Subject	Job Classification	Age	Years of Exposure
C1	Research and Development	48	1.0
C2	Research and Development	43	1.0
C3	Research and Development	28	1.0
C4	Nurse	55	7.0
A1	Floorperson-Assembly	35	4.5
A2	Floorperson-Assembly	59	29.5
A3	Finisher-Steel & Wood Tray Batt.	51	13.0
A4	Group Builder-Industrial Truck	23	3.3
A5	Industrial Cell Finisher	52	33.8
A6	Terminal Cable Maker	54	34.1
A7	Plate Wrapper	48	18.3
A8	Group Builder-Large Power	33	8.1
A9	Group Builder-Large Power	31	11.4
A10	Group Builder-Large Power	62	10.8
P1	Plate Dresser	36	1.6
P2	Plate Dresser	33	4.5
P3	Trucker-Hand	53	1.3
P4	Plate Dresser	34	10.2
P5	Asst. Pasting Machine Operator	24	4.4

Contamination Monitoring

Personal airborne lead samples were taken daily in the breathing zones of each worker in the assembly and pasting departments, including the lunch period. Essentially, full shift area samples were concurrently taken in each of the control group and workplaces. Airborne samples were collected on a mixed cellulose ester filter, 37 mm diameter, 0.8 μm pore size using personal air samplers at sampling rates of 1.5 to 2.0 Lpm.

The personal and surface contamination methodology have been previously reported in detail[26] and the air sampling procedures and analytical methods for lead are standard procedures,[27] which were modified slightly. The personal contamination samples were taken by wiping the hand and face with a commercially available paper towel, 14 × 20 cm, premoistened with benzalkonium 1:750 and alcohol, 20%. Each participant was requested to open the paper towel packages, unfold the moistened towel and wipe his/her hands thoroughly including the palms, the back of the hand and each finger. Sampling was performed each afternoon and the hand wipes were placed in sealed plastic bags. With the exception of the controls, each participant also had his or her face wiped with the paper towel daily. The facial wipe began at the right corner of the participant's forehead and was moved to the left, down to the left cheek, the chin and then up to the right cheek, down the nose and finally around the mouth.

Five representative work surfaces were sampled each morning with the Whatman filter paper no. 42, cut to 10 × 10 cm and moistened with distilled water. The filter papers were placed over representative work surfaces and pressed evenly over the entire surface with a gloved hand. The work surfaces included work bench tops, stacks of production material, tools, unfinished and finished product surfaces. All samples were transferred to clean, labeled plastic sealing bags and analyzed by atomic absorption spectrophotometry.[27]

Exogenous and Other Factors

The following suspect exogenous lead sources or activities of the subjects were reported: cigarette smoking, alcohol use, canned food, medications, automotive repair work, painting, use of firearms. In addition, the presence of facial hair, use of dust respirators and personal protective equipment (gloves, head covers, aprons) and personal hygiene practices were noted. Approximately 30% of the subjects smoked at least one package of cigarettes a day, only 15% regularly used firearms and 75% admitted to drinking alcohol regularly or occasionally. The wearing of approved dust/mist respirators was required and practiced in the pasting department whereas only 20% of the assembly workers wore the respirators where the use was voluntary. All subjects reported washing their hands 3 to 4 times a day and 55% of the workers routinely wore cotton work gloves which are not impermeable to the lead dust.

Statistical Analysis

Eight independent variables including airborne lead levels, hands, facial and work surface wipe measurements, tenure (as months of service), smoking habits and the use of respirators and protective gloves were evaluated as possible predictors for the current blood lead and ZPP levels, as the dependent variables. The last three of the independent variables were expressed in quantal fashion with values of 0 (no) or 1 (yes).

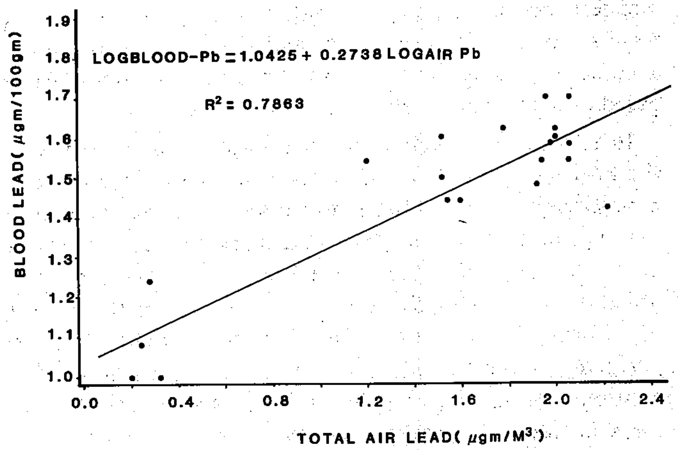

Figure 1 — Log blood vs log air.

Stepwise multiple regression analyses were used to calculate the coefficients for the variables in the tested models. An analysis of variance was used to test the null hypothesis of linearity between the transformed dependent and independent variables. All calculations were performed using a computerized program package (Statistical Analysis System - SAS).[28] The fitness of the data was tested as linear-linear, log-linear and log-log models. For successive model testing, only variables with coefficients of correlation of less than 0.7 were considered for inclusion so as to reduce excessive multicolinearity effects.

TABLE II
Lead Levels of Environmental and Biological Samples

Measurement	Group/Location	Results Range	Mean	S.D.
Air borne lead, mg/m³	Control	1.6 - 2.1	1.8	0.2
	Assembly Dept.	16.1 - 164.8	71.2	46.1
	Pasting Dept.	90.6 - 114.2	99.9	8.9
Hand lead, mg	Control	38.2 - 155.6	72.0	36.9
	Assembly Dept.	1523 - 14023	5227	4190
	Pasting Dept.	1956 - 8381	5510	2598
Facial lead, mg	Control	not measured		
	Assembly Dept.	2512 - 187.0	81.0	48.7
	Pasting Dept.	106 - 603	298	183
Work surface, mg/100 cm²	Control	2.2 - 11.9	7.1	4.3
	Assembly Dept.	353 - 2809	1230	837
	Pasting Dept.	218 - 7465	3885	2818
Blood lead, mg/100 mg	Control	<10 - 17.0	12.2	3.3
	Assembly Dept.	25 - 51	34.4	7.2
	Pasting Dept.	38 - 49	41.0	4.6
Blood ZPP, mg/100 mg	Control	11 - 35	19.2	11.0
	Assembly Dept.	39 - 382	122.4	96.6
	Pasting Dept.	69 - 121	85.0	21.9
Hemoglobin %	Control	13.1 - 16.1	14.6	1.2
	Assembly Dept.	12.7 - 15.2	13.7	0.7
	Pasting Dept.	14.1 - 15.2	14.7	0.4

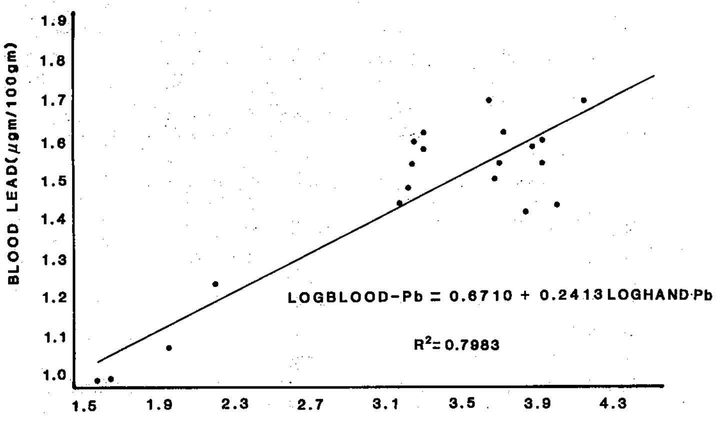

Figure 2 — Log blood vs log hands.

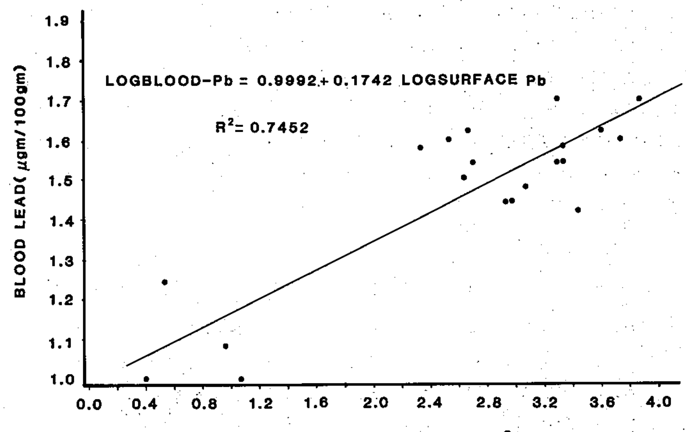

Figure 4 — Log blood vs log surface.

Results and Discussions

The mean, standard deviations and ranges of all measurements are shown in Table II.

Airborne Lead Exposures

The personal air sampling results (representing time-weighted averages) are expressed as the averages of N daily measurements with their standard deviations (SD) in Table II. The individual averages range from a low of 1.6 $\mu g/m^3$ for a control subject to a high of 164.8 $\mu g/m^3$ for an assembly worker. The latter level is well in excess of the OSHA permissible exposure limit of 50 $\mu g/m^3$ as an 8 hour average. As might be expected, there were highly significant differences ($P < 0.01$) between the manufacturing activities and the controls but no significant differences between the pasting and assembly operators.

Hand and Facial Leads

The means, ranges and standard deviations of the daily hand and facial wipes measurements for the groups and controls are presented in Table II. Since trace amounts of lead may be contacted from such non-occupational sources as ordinary newsprint, it would not be surprising to find low but measureable quantities of hand contaminated lead on any control subject. However, the low levels of atmospheric lead measured in the control subjects' work areas, which presumably originate in part from the production areas, contribute to the source of hand lead measured on the controls. In any case, the mean hand measurements of the plant workers were from 40 to 90 times greater than the controls. Facial wipes, performed only on plant workers, indicate a wide range of values with the not unexpected finding that in the appreciably dustier pasting department, as indicated by the personal air lead results, also shown in Table II, the workers incur a significantly higher contamination ($P < 0.005$) than the assembly workers.

Since hand and facial wipes represent the most likely and immediate source for accidental ingestion, the relative significance of these amounts of removable lead can be related to the potential dose resulting from exposure to the allowable occupational airborne lead level. If we assume that a worker inhales ten cubic meters of air during a work shift at the current OSHA permissible exposure level of 50 $\mu g/m^3$ and that 35% of the lead aerosol is retained in the lungs as cited, then a theoretical daily inhaled delivered dose can be as high as 175 μg. The highest mean values for facial and hand lead wipes were 603 and 14032.5 μg, respectively. It is obvious that lead from contamined hands and faces cannot be ignored in any evaluation of the total lead exposure.

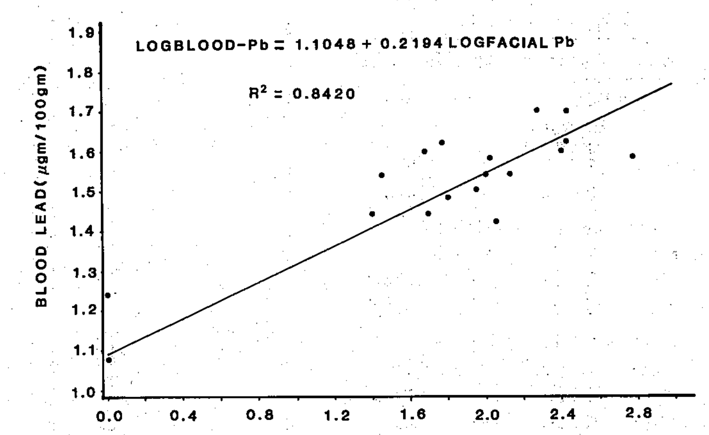

Figure 3 — Log blood vs log face.

TABLE III
Relationship Between Log and Blood Lead and Logs of Facial, Hand, Air, Surface Lead, and Tenure

Independent Variable	Intercept	Slope	R^2
Log Facial-Pb	1.1048	0.2194 ($P < 0.0001$)	0.8420
Log Hand-Pb	0.6710	0.2413 ($P < 0.0001$)	0.7983
Log Air-Pb	1.0424	0.2738 ($P < 0.0001$)	0.7862
Log Surface-Pb	0.9991	0.1742 ($P < 0.0001$)	0.7452
Log Tenure	1.16	0.16 ($P < 0.0845$)	0.1560

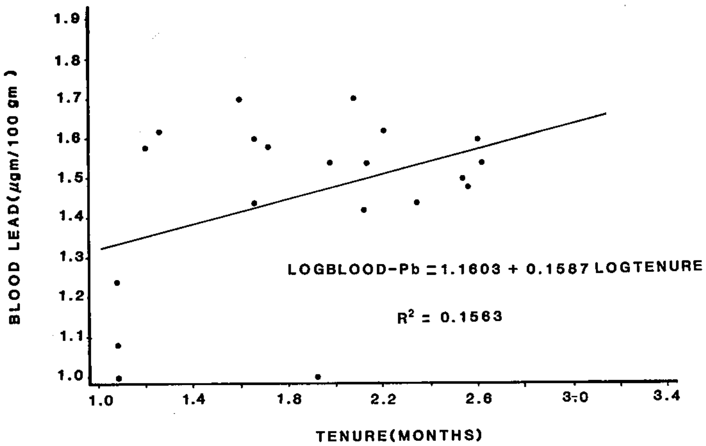

Figure 5 — Log blood vs log tenure.

Surface Lead

Five daily work surface wipes were obtained whenever possible so that the average values reported in Table II represent a maximum of fifty samples per worker station over the 10 day sampling period. The values ranged from a mean surface value of 2.6 $\mu g/100\ cm^2$ for a control subject to a high of 7465.3 $\mu g/100\ cm^2$ for a pasting worker. Once again, there were highly significant differences ($P < 0.005$) between the controls and manufacturing departments and significantly higher levels ($0.01 < P < 0.025$) at the pasting department compared to the assembly department. Over half of the plant work surfaces locations indicated mean values well in excess of 1000 μg per wipe and two pasting workers had maximum values in excess of 10 000 mg, so that even indirectly, work surfaces sources for possible ingestion in the workplace are indicative of significant potential exposure.

Blood Lead and Zinc Protoporphyrin

Blood lead, hemoglobin and zinc protoporphyrin (ZPP) levels are also shown in Table II. The analysis of variance method was used to test if the blood lead levels of the subjects in the assembly and pasting departments were

TABLE IV
Relationship Between Log of Blood-Lead and Logs of Hand-Lead and Gloves; and Facial Lead, Respirator and Gloves

Independent Variables	Intercept	Slope	Significance	R^2
Log (Hand-Pb)	0.6990	0.2175	$P < 0.0001$	0.84
Gloves		0.0923	$P < 0.05$	
Log (Facial-Pb)	1.0854	0.2316	$P < 0.0001$	
Gloves		0.0882	$P < 0.08$	0.88
Respirator		0.1183	$P < 0.05$	

affected by the external sources, personal habits and the wearing of protective equipment. Although smoking represents an indirect exposure by possible contamination with lead on the cigarette from the workers' hands or work surfaces, interestingly, there were no significant differences between smokers and non-smokers. No differences were found due to firearms, the wearing of respirators or gloves, and facial hair. With respect to the other external parameters, there was no unusual consumption of canned food or alcohol, unusual medication and no one "moon-lighted" appreciably in possible lead exposure activities such as automotive repair work or painting.

Relationship Between Lead Exposure and Biological Indices

Standard correlation analyses were first performed between each of the independent and dependent variables. Figures 1, 2, 3 and 4 graphically illustrate the lines of best fit for the log-log relationship of blood lead with the airborne, hand, facial and work surface results, respectively.

The data shown in Figures 1, 2 and 3 illustrate two extremes, *i.e.*, low, and high sets of data, which represent the "low exposure" (control) group and worker group of subjects, respectively. The slopes for these regression lines are found to be very significantly different ($P < 0.001$) from zero. In addition, the relationship between log (blood-Pb)

TABLE V
The Best One, Two, and Three Variable Models Found From Linear-Linear and Log-Linear Models

Linear-Linear Model			Log-Linear Model		
Dependent Variable: Blood-Pb			Dependent Variable: (Log (Blood-Pb)		
The Best One Variable	Estimate	R^2	The Best One Variable	Estimate	R^2
Intercept	21.5972	0.3973	Intercept	1.2722	0.4225
Air-Pb	0.1554	$(P < 0.0029)^A$	Air-Pb	0.0029	$(P < 0.0019)^A$
The Best Two Variables			The Best Two Variables		
Intercept	17.5000	0.4764	Intercept	1.1749	0.5599
Air-Pb	0.1677	$(P < 0.0014)^A$	Air-Pb	0.0032	$(P < 0.0004)^A$
Tenure	0.0244	$(P < 1279)$	Tenure	0.0005	$(P < 0.0341)^A$
The Best Three Variables			The Best Three Variables		
Intercept	16.1306	0.5719	Intercept	1.1529	0.6363
Air-Pb	0.1195	$(P < 0.0238)^A$	Air-Pb	0.0024	$(P < 0.0082)^A$
Facial-Pb	0.0309	$(P < 0769)$	Facial-Pb	0.0005	$(P < 0.0855)$
Tenure	0.0297	$(P < 0573)$	Tenure	0.0007	$(P < 0.0138)^A$

[A]Statistical Significance of Slope.

and log tenure was also evaluated and the slope was found to have a slightly significant difference ($0.05 < P < 0.09$) from zero as shown in Table III and Figure 5.

The evaluation of the models by the stepwise multiple regression methods has shown that only two of the four models, *i.e.*, hand Pb and facial Pb, would allow other independent variables, *i.e.*, gloves and respirator, to be added to the models as shown in Table IV. Most importantly from the industrial hygiene aspect, the wearing of cotton gloves or respiratory equipment does not appear to reduce the lead absorption from all sources.

ZPP Levels and Independent Variables

Significant correlation ($0.0001 < P < 0.0005$) between log ZPP and logs of air, hand, facial and work surface lead were also found as shown in Table V. The use of respirators or gloves and log ZPP were somewhat significantly correlated ($0.05 < P < 0.11$). Unlike the blood lead, there was significant correlation ($P < 0.02$) between smoking and log ZPP.

Interrelationship Between the Two Indices of Pb Absorption

There was a significant ($P < 0.0001$) correlation between log (blood-Pb) and log ZPP (Figure 6) with 65 percent of the variance in ZPP correlating with the blood lead (R^2 = 0.6514). No correlation was found between log (blood Pb) and log hemoglobin (Hb) (Figure 7). Log Hb and log ZPP were somewhat correlated with $P < 0.073$ (Figure 8).

Total Lead Exposure Model

The best models incorporating one, two and three variables were derived by stepwise multiple regression analysis from both the linear-linear and log-linear models and are shown in Table VI. Airborne lead alone, airborne lead and tenure, and airborne lead, facial lead and tenure were the independent variables producing the best one, two and three variable models, respectively. The t-tests on the coefficients of the proposed models show that only the coefficient of the airborne lead was significant ($P < 0.05$) in the linear-linear model. This was in fairly good agreement with the Benard Model derived by OSHA.[12] Only marginal significance can be attached to facial lead and tenure ($0.05 < P < 0.08$). The log-linear model proved better than the straight linear-linear model with slightly higher multiple coefficients of determination (R^2) for all three models. In the log-linear model, the coefficient of airborne lead and tenure was significant ($P < 0.02$) with marginal contribution from the facial lead ($P < 0.08$). The model can be expressed as: Log (Blood-Pb) = 1.1529 + 0.0024 (Air-Pb) + 0.0005 (Facial-Pb) + 0.0007 (Tenure).

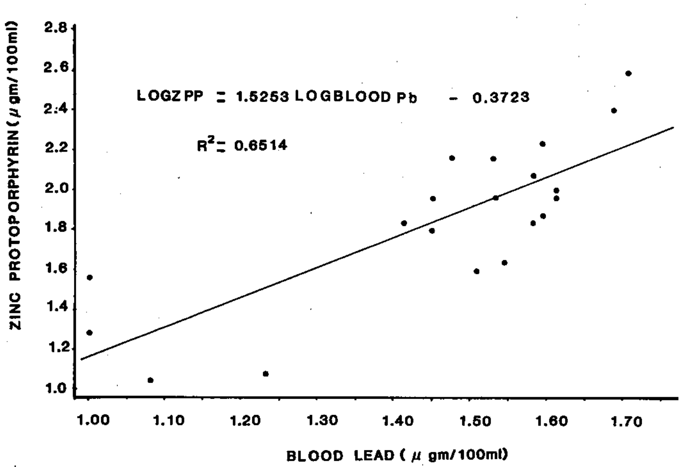

Figure 6 — Log ZPP vs log blood.

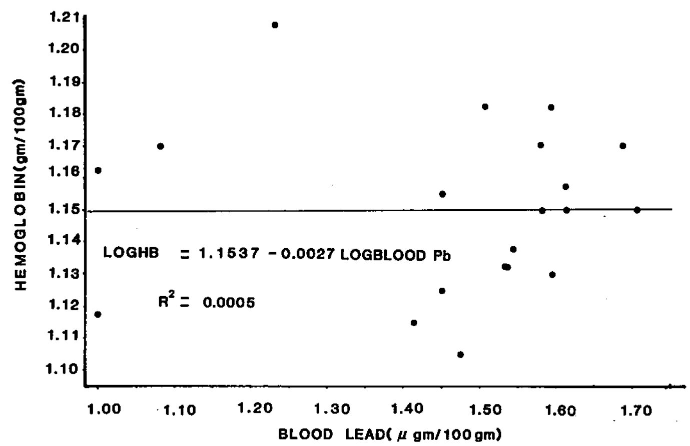

Figure 7 — Log HB vs log blood.

Summary and Conclusions

Since logarithmic relationships gave the best fit to the data in this study, all discussions and conclusions were made based on the logarithmic models. Significant intercorrelation among the multiple sources of exposure (airborne, hand, facial, surface lead) was observed, as expected. Overall, the facial lead level was the strongest independent variable in describing blood lead levels ($R^2 = 0.842$, $P < 0.0001$). Even so, the R^2 of the hand, airborne, work surface lead levels were 0.7983, 0.7863 and 0.7452, respectively. These four models clearly show the strong relationships between the blood lead levels and each source of exposure. On the other hand, job tenure (months of service) showed a rather weak correlation with the blood lead levels, which is consistent with the findings of others.[29] The absence of significant differences of blood lead levels between smokers and nonsmokers could be due to the small sample sizes.

ZPP levels were also found to correlate with the airborne, hand, face and work surface lead levels with a slightly lower

TABLE VI
Relationship Between Log ZPP and Logs of Facial, Surface, Air, and Lead Levels and Tenure

Independent Variable	Intercept	Slope	R^2
Log Facial-Pb	1.3008	0.3422 ($P < 0.0001$)	0.5733
Log Surface-Pb	1.0764	0.2942 ($P < 0.0001$)	0.5953
Log Air-Pb	1.2058	0.4255 ($P < 0.0005$)	0.5317
Log Hand-Pb	0.6814	0.3584 ($P < 0.0005$)	0.4942
Log Tenure	1.1060	0.3971 ($P < 0.0179$)	0.2739

R^2 and lower levels of significance than the blood lead levels. The stronger correlation of tenure with ZPP levels rather than with blood lead levels has been supported by other studies[29-32] and has been explained as follows: 1) For recently exposed workers the blood lead may be elevated, but the erythrocyte population is too young to reflect this in a corresponding elevation of ZPP. 2) Blood lead levels reflect recent or current lead absorption, whereas ZPP represents a biological effect of lead toxicity, slower in appearance but more persistent in duration.[29]

The type of predictive model developed is, of course, still in an untested stage and the use of these models requires further experimental validation. However, these contamination models may be found valuable for promoting more comprehensive monitoring of the workplace so as to identify heretofore neglected sources of personal and surface contamination and provide a more valid representation of the total exposure of the worker.

Acknowledgements

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