

Evaluation of Postural Stability in Workers Exposed to Lead at a Secondary Lead Smelter

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U.S. Department of Health and Human Services, Public Health Service/Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, ¹Division of Biomedical and Behavioral Sciences, ²Division of Surveillance, Hazard Evaluations and Field Studies, ³Department of Mathematical Science, College of Arts and Sciences, University of Cincinnati

Abstract: Evaluation of Postural Stability in Workers Exposed to Lead at a Secondary Lead Smelter. ROBERT B. DICK, LYNNE E. PINKERTON, EDWARD F. KRIEG, JR., RAYMOND E. BIAGINI, JAMES A. DEDDENS, W. STEPHEN BRIGHTWELL, PAULA L. GRUBB, BOBBY T. TAYLOR AND JOHN M. RUSSO. *Neurotoxicology* 20(4): 595-608, 1999. Postural sway testing was carried out on a group of 145 workers exposed to lead in a secondary lead smelter and 84 workers not exposed to lead in a hinge manufacturing plant. All workers were measured for blood lead levels (BLL) and erythrocyte zinc protoporphyrin (ZPP) concentrations at the time of testing and both a total cumulative and a time-weighted average BLL value was constructed for the lead exposed workers. The lead exposed workers mean BLL at the time of testing was 38.9µg/dl and the non-exposed workers mean was 2.3µg/dl. ZPP levels averaged 55.2µg/dl for exposed workers and 18.9µg/dl for non-exposed workers. Total cumulative BLL averaged 83476 µg/dl days for the exposed workers, with a mean time-weighted average BLL of 35.1µg/dl.

Six tests of postural stability, four two leg conditions and two single leg conditions were administered to all subjects using a force platform to produce measurements of sway for comparison purposes. The two leg conditions also manipulated the visual and proprioceptive systems. A statistically significant association was observed for sway measurements and the current BLL for all workers, but not with the current BLL of only the lead exposed workers. No statistically significant associations were present with the cumulative measures of long-term exposure. Of the six tests of sway, only the single leg conditions showed significant exposure effects. The results suggest effects of lead exposure among those with average BLL near 40.0µg/dl, but only in the most challenging one leg conditions. ©1999 Intox Press, Inc.

Key Words: Neurotoxicity, Postural Sway, Lead Exposure, Blood Lead, Zinc Protoporphyrin

INTRODUCTION

Human exposures to lead continue to remain serious public health problems because: (1) Lead is present throughout the environment; (2) lead is toxic to most living organisms at high doses; and (3) lead has damaging effects on the nervous, hematopoietic, endocrine, renal and reproductive systems (Goyer, 1996; USDHHS, 1997). Although dramatic declines in U.S. population blood levels have been evident since the 1970s (USDHHS, 1997), major concerns still exist as to the minimal dose levels that are toxic to the various systems subject to lead effects. This paper will be primarily

concerned with the influence of past and present lead exposures on one indicator of nervous system effects, postural stability.

Effects on the nervous system of children have been reported at blood lead levels (BLL) as low as 10µg/dl (USDHHS, 1991), whereas for adults the lowest observed effect levels have historically been reported at 30-40µg/dl (Goyer, 1996; USDHHS, 1993). The risk of exposure in children is through ingestion from environmental sources (i.e., residence, neighborhood) while in occupational settings the primary route of exposure is inhalation from the workplace atmosphere (USDHHS, 1993). Presently, the Occupational Safety and Health Administration

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(OSHA) permissible exposure limit for lead in the workplace air is 50 $\mu\text{g}/\text{m}^3$ as an 8-hr time-weighted average. Blood lead levels, which are an indicator of internal dose, are used to report the health effects of lead rather than external exposure levels (USDHHS, 1993). Generally, workers with measured BLL that average 50 $\mu\text{g}/\text{dl}$ are required to be removed from the workplace and cannot return to jobs with lead exposure until their blood lead levels are below 40 $\mu\text{g}/\text{dl}$ (OSHA, 1978). BLL are primarily an indicator of acute exposures (< 14 days) and can be supplemented by additional biological and non-biological markers for indicators of intermediate and chronic exposures. Erythrocyte zinc protoporphyrin (ZPP) reflects average lead levels over the previous 4 months and can serve as an indicator of intermediate exposures. Chronic exposure indicators (> 365 days) include bone lead measurements using X-ray fluorescence, which estimates cumulative lead absorption over time, and calculations of cumulative blood lead levels using either airborne or blood lead measurements collected from workers during their work histories (Sommerville, *et al.*, 1988; USDHHS, 1993).

Lead has toxic effects on both the central and peripheral nervous systems and clinically overt symptoms may occur in children at BLLs of 80 $\mu\text{g}/\text{dl}$ or higher and with adults at 100 $\mu\text{g}/\text{dl}$ or higher (Goyer, 1996). Postural stability measures on lead exposed children and adults have shown some success as subclinical indicators of lead effects. Investigators (Bhattacharya *et al.*, 1988, 1995; Chia *et al.*, 1994, 1996; Yokoyama *et al.*, 1997) have reported subtle effects of lead at lower concentrations than the concentrations producing clinical symptoms. Bhattacharya *et al.*, (1995) reported results from the study of 202 children in the Cincinnati lead program project who were tested for postural stability. In a sub-group of 64 children whose blood levels never exceeded 20 $\mu\text{g}/\text{dl}$ significant increases in sway measures were associated with lead concentrations. Chia *et al.*, (1994) reported significant increases in one test of postural sway in a group of lead exposed workers whose BLL averaged 36.0 $\mu\text{g}/\text{dl}$ when compared to control workers whose BLL averaged 6.3 $\mu\text{g}/\text{dl}$. A subsequent report (Chia *et al.*, 1996), on the same group of workers using cumulative blood lead measurements indicated a significant correlation between postural sway measurements and cumulative BLL over the previous two years, but not for prior years. The authors speculated that the effects of lead may be more related to recent body burden increases rather than the total cumulative body burden. Yokoyama *et al.*, (1997) has recently reported lead effects from both current and past lead exposures using measures of postural sway analyzed by frequency differences to separate the cerebellar, vestibular, and spinocerebellar-afferent systems. In the Yokoyama *et al.*, (1997) study, the lead exposed workers BLL averaged 18 $\mu\text{g}/\text{dl}$ (reported as 18

$\mu\text{g}/100\text{ g}$); BLL was not measured in the control workers, who had never been occupationally exposed to lead.

In 1994, NIOSH, with support from the National Institute for Environmental Health Sciences conducted a large field study to investigate several immunologic parameters and postural sway in lead exposed workers. Both acute (blood lead) and intermediate (erythrocyte zinc protoporphyrin) body burden measures of exposure were collected from each participant. To estimate chronic exposures, cumulative indicators of exposure were calculated using historical blood monitoring results. The immunologic findings are published in a separate article (Pinkerton *et al.*, 1998). The purpose of this paper is to report the postural sway results and discuss the findings of this study in contrast to the other studies of lead exposure on postural sway.

EXPERIMENTAL PROCEDURES

Study Design

Postural stability assessments were carried out during a NIOSH cross sectional study of 84 non-lead exposed workers employed at a hinge manufacturing company and 145 lead exposed workers who were employed at a secondary lead smelter. This final study group represented 63% of the lead exposed population participants and 59% of the non-lead exposed population participants (Pinkerton *et al.*, 1998). Testing took place over a two-week period in May of 1994. Because few women worked in the lead exposed areas of the smelter, the study groups were limited to male workers on the first and second shifts who had been hired at least six months prior to study. The study protocol was approved by the NIOSH Human Subjects Review Board and informed consent was obtained from all workers who participated in the study.

Exposure Characterization and Sample Collection

Detailed exposure characterization and sample collection methods are described in another publication (Pinkerton *et al.*, 1998); only a brief description of these methods will be provided in this manuscript. Company monitoring data indicated that the primary exposure at the secondary lead smelter was lead. Air concentrations of other elements, like arsenic were negligible. After walk-around surveys at the hardware manufacturing plant, workers selected for the comparison group were employed in areas where exposures to compounds (e.g., solvents) that might affect the immune system or postural stability were minimal. Air sampling for metals and oil mist was conducted at the comparison facility, and concentrations were negligible. Electromagnetic field magnitudes were also measured at both plants and the

geometric means were similar.

Blood samples were drawn each day between 1:00 pm and 4:30 pm at both workplaces either prior to a worker's work shift or at the completion of a shift. If the blood draw was before testing, participants waited at least 30 minutes after blood samples were drawn before the sway testing. For most workers the postural sway testing occurred the same day of the blood sample collection. Thirty-seven workers at the secondary smelter had their postural sway tests the day before the blood draw. Because the half-life of lead in human blood is 28-36 days (USDHHS, 1993), this time difference is not considered critical for a current blood lead measurement. A separate statistical analysis confirmed that the time of the blood sample collection had no effect on sway measurements. Blood was withdrawn by antecubital venipuncture using special trace element tubes for blood lead analysis. The serum was separated on site by centrifugation at 1000 x g for 10 minutes. All blood was shipped from the study sites via overnight express to a commercial laboratory (Smith-Kline-Beecham, St. Louis, MO, OSHA Certified) for blood lead and ZPP analyses. On-site duplicates, representing 10% of samples, were prepared and assigned randomly. The coefficients of variations expressed in per cents were 5.6% for BLL and 41.5% for ZPP. The poor agreement for ZPP was due to two out of 22 duplicates that were widely divergent.

Two historical, cumulative measures of lead exposure were also developed. Cumulative blood lead exposure (CBL) in $\mu\text{g}/\text{dl}$ days was estimated for the lead exposed participants from company records of historical blood monitoring data using a method presented by Somerville *et al.*, 1988. The method uses a time integrated blood lead index using the trapezoidal rule to account for the non-uniform time intervals of the blood lead data. The formula for the index is:

$$T \int_0^T B(t)dt = \sum^{1/2} (B_i + B_{i+1}) \Delta t$$

$B_i + B_{i+1}$ represent the i^{th} and $(i + 1)^{\text{th}}$ blood lead measurements in $\mu\text{g}/\text{dl}$ respectively, and Δt denotes the time interval (in days) between measurements. This method has been compared to tibia lead in bone using x-ray fluorescence techniques and was found to have strong correlations ($r > 0.80$) [Somerville *et al.*, 1988]. A second measure of cumulative exposure, time-weighted average blood lead (TWBL), was calculated by dividing the total cumulative blood lead level by the duration (e.g., days) of exposure.

TEST PROCEDURES

The study plants were geographically separated by 50+ miles, so to perform testing within the same time frame, two identical postural sway test systems and five test administrators were used to test all the workers. Because the study could not feasibly be conducted single blind, both test systems and test administrators were alternated between test sites over the two week test period.

Postural stability testing was performed using a microcomputer controlled force platform using protocols established by NIOSH (Dick *et al.*, 1990; USDHHS, 1995) and the University of Cincinnati (Bhattacharya *et al.*, 1987; 1995). The protocol defined six test conditions, four standing on two legs and two standing on one leg. These test conditions are designed to test the three main afferents (e.g., vision, proprioception and vestibular) that are responsible for maintaining postural stability and are defined below. Starting with the two leg eyes open on the hard surface test condition, each test condition increases the difficulty of maintaining postural stability and requires reliance on higher cortical centers (i.e., cerebellum) to maintain balance (Bhattacharya *et al.*, 1995; Kuo *et al.*, 1996). The measurements of postural stability increase with the test condition difficulty. These 6 test conditions each lasted 30-sec., and were preceded by one practice trial.

Test Conditions 1 and 2

Participants stood on a hard surface platform with the eyes open (HEO) followed by eyes closed (HEC). These test conditions have the proprioceptive and vestibular afferents intact, but remove the visual system in the HEC test.

Test Conditions 3 and 4

Participants stood on a soft surface (e.g., 4-in thick foam pad) with eyes open (SEO) followed by eyes closed (SEC). These test conditions modify the proprioceptive feedback and remove visual feedback in the SEC test, with the vestibular afferents intact.

Test Conditions 5 and 6

Standing on the right leg with eyes open (RL) followed by standing of left leg (LL) with eyes open. These conditions would be expected to further challenge all the afferents responsible for maintaining balance, possibly including cerebellar input.

The software calculates the x-y co-ordinates using center of pressure calculations and produces several measurements useful for postural balance. Two measures, sway area and sway length, have proven the most reliable (Dick *et al.*, 1990; Bhattacharya *et al.*, 1995) and

were chosen for analysis. Sway area represents the area within the sway path in sq cm, and sway length is the length of the sway path in cm.

Worker testing took place in portable buildings with linoleum surface floors at each factory site that required frequent calibration of each postural sway test system. Equipment was calibrated using a known mass over 45 kg (e.g., the weight of the test administrator) each morning of a test session and after the testing of every three subjects. Acceptable error between the measured mass and known mass was < 5%. This value was slightly above the requirements in the laboratory (e.g., < 2%), where the platforms can be mounted permanently, but is very good for a building without a firm foundation.

Workers were instructed to remove their shoes and the test administrator took their height, weight and foot measurements. The test conditions were explained and workers were instructed to place their feet, aligned heel-to-heel, inside footprints drawn both on the hard surface of the platform and the foam used in the soft surface conditions. The footprints were drawn with an approximate 30° separation angle. Hands were to be at their sides and they were to look straight ahead with no forceful movements during each test session. They were also advised that tests would be re-taken if unnecessary head or foot movements were observed, if they departed from the platform, or touched a raised leg to the platform during the one leg test conditions. For the standing on one leg conditions, workers were instructed to stand close to the center of the platform with their feet parallel and slightly apart. When comfortable, they were to slowly raise one leg, bending at the knee, and try and maintain balance for at least 30-sec. Arm movements to maintain balance were allowed.

The postural stability test systems used Advanced Mechanical Technology Inc. (AMTI) strain gauge type force platform (Model OR6-6-1) that measured inputs from 6 channels producing three force components and three moment components (Dick *et al.*, 1990). The signals from each channel were amplified by AMTI amplifiers (Model SGA6-4) and then fed into Dell 433p microcomputers using Data Translation (DT-2801) analog to digital converter boards. All testing was microcomputer controlled at a 30-Hz sampling rate using The Body Balance Software[®] developed by the University of Cincinnati (Bhattacharya *et al.*, 1995) for data collection and analysis.

STATISTICAL ANALYSIS

Several analyses were undertaken to evaluate the large data set collected in this study. Initially, 80 tests of the standing on one leg condition were re-analyzed because of potential problems identified by experimenter(s) during testing of participants (i.e., movement, stepped off platform). At least 20-sec. of useable data was required and 13 tests had to have a new length

measurement (e.g., velocity of sway times 30-sec.) calculated. The area measurement for these 13 tests was dropped because the calculation of sway area uses an algorithm that was not amenable to correction after data had been collected. Finally, 17 subjects were eliminated from the study because they did not meet study requirements (e.g., not invited or not employed for greater than 6 months-9 subjects) or had a medical problem (e.g., foot or ankle injury, inner ear infection, severe diabetic with suspected neuropathy-8 subjects) that might affect sway results. Consistent with previous research (Dick *et al.*, 1990), the area and length measurements were log transformed to provide a more normal distribution of the data for analysis purposes.

The independent variables used for analysis purposes were: (1) group assignment (e.g., exposed battery workers versus non-exposed comparison workers); (2) blood lead concentrations (BLL) at the time of testing. Comparison workers BLL that was less than the limits of detection (2.0 µg/dl) were set to the limit of detection divided by the $\sqrt{2}$ or 1.41µg/dl; (3) zinc protoporphyrin concentrations (ZPP) at the time of testing; (4) total cumulative blood (CBL) levels (e.g., lead exposed only); and, (5) time-weighted average blood lead (TWBL) levels (e.g., lead exposed only).

Analysis of variance and chi-square analysis was used to compare the mean values of the covariates (see tables 3 + 4) of the comparison and exposed groups and to test for overall exposure effects. A separate stepwise regression analysis was done for each sway test condition to determine which covariates to include in the final models. The probability to enter or leave the model at each step in the stepwise regression was 0.05. If a covariate remained in the model for more than one test condition, that covariate remained in the final model. Mixed models were used as the final models to test for exposure effects and estimate slope coefficients. All the two-legged test conditions were included in one model and all the one-legged conditions were included in another. An equation for the two-legged model is:

$$y_{ijkl} = \mu + \alpha + \beta + \gamma + \delta + \zeta_i + \eta_j + \theta_k + \eta\theta_{jk} \\ + \alpha\eta_j + \beta\eta_j + \gamma\eta_j + \delta\eta_j + \zeta\eta_{ij} + \\ + \alpha\theta_k + \beta\theta_k + \gamma\theta_k + \delta\theta_k + \zeta\theta_{jk} + \\ + \alpha\eta\theta_{jk} + \beta\eta\theta_{jk} + \gamma\eta\theta_{jk} + \delta\eta\theta_{jk} + \zeta\eta_{ijk} + \epsilon_{ijkl}$$

μ is the grand mean, α is the effect of exposure, β is the effect of age, γ is the effect of height, δ is the effect of mass, ζ_i is the effect of race, η_j is the effect of pad, θ_k is the effect of eyes, and ϵ_{ijkl} is a random error. Multiplied terms indicate interactions and subscripted terms indicate classification variables. An equation for the one-legged model is:

$$y_{ijk} = \mu + \alpha + \beta + \gamma + \delta + \zeta_i + \eta_j + \\ + \alpha\eta_j + \beta\eta_j + \gamma\eta_j + \delta\eta_j + \zeta\eta_{ij} + \epsilon_{ijk}$$

μ is the grand mean, α is the effect of exposure, β is the effect of age, γ is the effect of height, δ is the effect of mass,

ζ_i is the effect of race, η_j is the effect of leg, and ϵ_{ijk} is a random error. In both models, y_{ijk} represents the log transformed postural sway measurements, area and length. These models were estimated using restricted maximum likelihood. The variances and covariances of the repeated measurements were modeled using an unstructured covariance matrix. All calculations were done with SAS® Version 6.1 (SAS Institute, Inc., Cary, NC, USA).

RESULTS

The results of the blood lead measurements are presented in Tables 1 and 2. Table 1 lists the medians, means, standard deviations, maximums and minimums for the measurements. Table 2 shows the Pearson correlation coefficients between the various lead measurements used in the study. All of the correlation coefficients are significant, $p < 0.05$. Table 3 lists the results of the analysis of variance (e.g., continuous variables) and chi-square analysis (e.g., categorical variables) of the study co-variables for independent variables with greater than 10% reporting. Table 4 lists the means, standard

deviations, and analysis of variance p-values of the sway measurements for each test condition. The only statistically significant group mean differences from exposure were detected with the standing on one leg conditions; specifically the area measurement for the right leg and the length measurement for both the right and left leg.

The final analysis of the exposure effects with the test conditions and the significant co-variables was performed using mixed models. Confirming the analysis of variance results, the only statistically significant main effects due to lead exposure occurred in the one leg conditions; both for area ($p = 0.0022$) and length ($p = 0.0002$). Because the only quantitative lead measurement that showed a statistically significant effect with the postural sway measurements was current blood lead, only the results using these measurements are reported in Table 5, panels A and B. Table 5, panel A, which provides the parameter estimates (e.g., intercept and slope values) for all workers confirms that the significant exposure effects were primarily in the one leg conditions. For standing on the left leg, both exposure slope estimates for area ($b = 0.0067$, $t = 3.88$, $p = 0.0001$) and length ($b = 0.0046$, $t = 4.11$, $p = 0.0001$) were significant. For standing on the right leg, only the slope estimate for

TABLE 1. Independent Measurement Variable Parameters.

Variable (values rounded to 0.1)	N ¹	Median	Mean	SD	Minimum	Maximum
Blood Lead (BLL) ² Comparison Workers	83	1.4µg/dl	2.3µg/dl	1.7	<2µg/dl	12.0µg/dl
Blood Lead (BLL) ³ Lead Exposed Workers	136	39.0µg/dl	38.9µg/dl	8.5	15.0µg/dl	55.0µg/dl
Zinc Protoporphyrin (ZPP) ⁴ Comparison Workers	83	17µg/dl	18.7µg/dl	10.0	1.0µg/dl	59.0µg/dl
Zinc Protoporphyrin (ZPP) Lead Exposed Workers	135	46.0µg/dl	55.3µg/dl	42.2	2.0µg/dl	227.0µg/dl
Total Cumulative Blood Lead (CBL) ⁵ Lead Exposed Workers	138	55866µg/dlD	84085µg/dlD	79532	3459.5µg/dlD	355414µg/dlD
Time-Weighted Average Blood Lead (TWBL) ⁶ Lead Exposed Workers	138	36.2µg/dl	35.2µg/dl	8.5	14.2µg/dl	55.8µg/dl
Duration of Exposure ⁷ Lead Exposed Workers	138	1745	2198 D	1719 D	191 D	6734 D

¹N= number of subjects with usable data for the analysis.

²Blood lead values for comparison and lead workers measured on day of testing. Comparison workers BLL that was less than the limits of reported detection (2.0 µg/dl) were set to the limit of reported detection divided by the /2 or 1.41µg/dl.

³Blood lead values for lead exposed workers only.

⁴ZPP (zinc protoporphyryn) values for comparison and lead workers measured on day of testing. Limit of reportable detection was 5.0µg/dl.

⁵Total cumulative blood lead measurement for lead exposed workers only in µg/dlD (e.g., D = days). Value was calculated (see text).

⁶Time-weighted average blood lead measurement lead exposed workers only. Value was calculated by dividing the cumulative blood lead value by duration (days) of exposure.

⁷Time period in days (D) covered by available historical BLL samples in lead exposed workers only

length ($b = 0.0033$, $t = 3.02$, $p = 0.0029$) was significant. The one significant exposure slope estimate (panel A, $b = 0.0017$) in a two-leg condition occurred with blood lead for length in the soft surface eyes open condition. The soft surface eyes closed condition slope estimate, however, is not significant (panel A, $b = -0.0003$) and in the wrong direction (e.g., negative). Because the soft surface eyes closed condition is more difficult the expected direction would be an increase (e.g., positive). Table 5 also reveals that the contribution of other variables in the model, such as age, height, mass and race on sway were sometimes greater than the contribution of exposure. Height probably represents the only variable that is consistently significant (e.g., increased height with increased sway) in the two leg conditions. Neither age, mass, or race were consistently statistically significant and the direction (positive versus negative) of the parameter estimates frequently changed with increasing task difficulty (e.g., eyes open versus eyes closed and hard surface versus soft surface).

The data analysis showed (Table 5, Panel B) that the dose-response exposure effect was not significant in the one leg conditions when only the lead exposed workers BLL values were analyzed, although there was one two leg test condition (hard surface, eyes closed) where the

exposure effect approached significance ($b = 0.0063$, $t = 1.92$, $p = 0.0576$) for the length measurement. BLL values for the lead exposed workers ranged from 15 $\mu\text{g}/\text{dl}$ to 55 $\mu\text{g}/\text{dl}$, and the significant exposure effect was not observed when comparison workers, whose blood lead values were less than 12 $\mu\text{g}/\text{dl}$ were removed. Efforts to evaluate the exposure-response curve and to determine if a threshold level exists were hampered by the small number of workers with blood lead values between 15 $\mu\text{g}/\text{dl}$ and 25 $\mu\text{g}/\text{dl}$ ($n=8$) and above 50 $\mu\text{g}/\text{dl}$ ($n=14$).

Examination of the log transformed sway values in Figures 1 and 2 shows that the postural sway measurements increased with increasingly challenging test conditions (hard surface to soft surface to one leg) and eye conditions (eyes open to eyes closed). The axis intercepts demonstrate more sway (top to bottom) for each test condition (hard surface, soft surface, one leg) and eye condition (right to left). Figures 1 and 2 also show that there is an exposure effect occurring with the left leg area measurement and for both the right and left leg length measurements. The one leg condition is obviously more challenging to the worker and may be possibly showing some evidence of an association with lead exposure.

TABLE 2. Correlations Between the Independent Measurement Variables.

Variable	Exposure ¹	BLL ² (All Workers)	BLL ³ (Lead Workers)	ZPP ⁴ (All Workers)	TC BLL ⁵ (Lead Workers)	TWA BLL ⁶ (Lead Workers)	Duration of Exposure ⁷ (Lead Workers)
Exposure (All Workers)	1.000						
Blood lead (All Workers)	0.934	1.000					
Blood lead (Lead Exposed Workers)	--	1.000	1.000				
Zinc Protoporphyrin (All workers)	0.466	0.611	0.573	1.000			
Total Cumulative BLL (Lead Exposed Workers)	--	0.184	0.184	0.173	1.000		
Time-weighted Average BLL (Lead Exposed Workers)	--	0.678	0.678	0.410	0.629	1.000	
Duration of Exposure (Lead Exposed Workers)	--	--	--	--	0.959	0.467	1.000

¹Non-lead exposed worker or a lead exposed worker.

²Analysis used blood lead values in $\mu\text{g}/\text{dl}$ for comparison and lead exposed workers measured on day of testing.

³Analysis used blood lead values in $\mu\text{g}/\text{dl}$ for lead exposed workers only.

⁴Analysis used ZPP (zinc protoporphyrin) values in $\mu\text{g}/\text{dl}$ for comparison and lead exposed workers measured on day of testing.

⁵Analysis used a total cumulative blood lead measurement in $\mu\text{g}/\text{dl} \cdot \text{day}$ for lead exposed workers only. Value was calculated (see text).

⁶Analysis used a time-weighted average blood lead measurement in $\mu\text{g}/\text{dl}$ for lead exposed workers only. Value was calculated by dividing the total cumulative blood lead value by duration (days) of exposure.

⁷Time period in days covered by available historical BLL samples in lead exposed workers only.

DISCUSSION

Postural sway testing was carried out on a group of workers exposed to lead in a secondary lead smelter and a group of workers not exposed to lead in a hinge manufacturing plant. All workers were measured for BLL concentrations and ZPP concentrations at the time of testing and both a total cumulative (CBL) and time-weighted average blood lead (TWBL) value was constructed for the lead exposed workers. The lead exposed workers blood lead values at the time of testing ranged from 15 to 55

$\mu\text{g}/\text{dl}$ with a mean of $38.9 \mu\text{g}/\text{dl}$ (md = $39 \mu\text{g}/\text{dl}$) and the non-exposed workers values ranged from <2.0 to $12 \mu\text{g}/\text{dl}$ with a mean of $2.3 \mu\text{g}/\text{dl}$ (md $1.4 \mu\text{g}/\text{dl}$). The only measure of exposure which showed a significant association with the sway measurements was the blood lead concentrations measured at the time of testing. None of the measurements (ZPP) or estimates (CBL, TWBL) of longer term exposures to lead showed any significant associations with the measurements of sway.

Correlation analysis indicated that the relationship between current BLL and ZPP, the short-term measure of

TABLE 3. Results of the Analysis Between the Lead Exposed Workers and the Comparison Workers on the Study Co-variables.

Study Variable ¹	Group	N	Mean	SD ²	Statistic	P Value
Duration of Employment	Lead Exposed Workers	145 ³	5.3 yr.	4.8	F=2.36	0.126
	Comparison Workers	84 ³	4.3 yr.	4.3		
Age	Lead Exposed Workers	138 ⁴	32.7 yr.	8.7	F=4.46	0.036
	Comparison Workers	83 ⁴	30.1 yr.	9.3		
Height	Lead Exposed Workers	138	175.6 cm	6.9	F=8.03	0.005
	Comparison Workers	83	178.26 cm	6.4		
Mass	Lead Exposed Workers	138	85.8 kg	17.5	F=0.24	0.624
	Comparison Workers	83	87.1 kg	20.1		
Sleep	Lead Exposed Workers	138	6.71 hours	1.8	F=0.53	0.467
	Comparison Workers	83	6.89 hours	1.57		
Race	Lead Exposed Workers	138	37.6 %White		$\chi^2=10.78$	0.001
	Comparison Workers	83	62.4% White			
Shift	Lead Exposed Workers	138	23% second shift		$\chi^2=9.91$	0.002
	Comparison Workers	83	43% second shift			
Back injury	Lead Exposed Workers	138	5.8%		$\chi^2=0.52$	0.470
	Comparison Workers	83	3.6%			
Broken hip, leg, or foot	Lead Exposed Workers	138	15.2%		$\chi^2=0.02$	0.878
	Comparison Workers	83	14.4%			
Knee, ankle, leg surgery	Lead Exposed Workers	138	9.4%		$\chi^2=0.12$	0.732
	Comparison Workers	83	10.8%			
Ever smoke cigarettes	Lead Exposed Workers	138	45.7%		$\chi^2=4.42$	0.036
	Comparison Workers	83	60.2%			
Currently smoke cigarettes	Lead Exposed Workers	138	31.9%		$\chi^2=2.96$	0.085
	Comparison Workers	83	43.4%			
Drink alcohol	Lead Exposed Workers	138	61.2 %		$\chi^2=1.17$	0.281
	Comparison Workers	83	54.2 %			

¹Independent variables with less than 12% reporting a medical condition in both the lead exposed and comparison worker populations are not listed in the table. These variables include: (1) diabetes; (2) diabetic neuropathy; (3) other neuropathy; (4) arthritis of the spine; (5) tardive dyskinesia; (6) scoliosis; (7) club feet; (9) hammer toes; (10) missing toes; (11) myasthenia gravis; (12) reflex sympathetic dystrophy; (13) muscle disease; (14) difficulty walking; (15) difficulty standing; (16) standing or balance problems; (17) caffeine intake; (18) severe head injury; (19) Parkinson's syndrome; (20) back surgery; (21) back pain; (22) back problems; (23) arthritis; (24) recent injury to legs or feet; (25) one leg longer; (26) smoke marijuana; (27) pipe smoking.

²Standard Deviations; SDs not reported for categorical variables.

³Number of subjects in the final study group.

⁴Values < 145 or 84 represent the number of subjects with usable data for the analysis of the covariates.

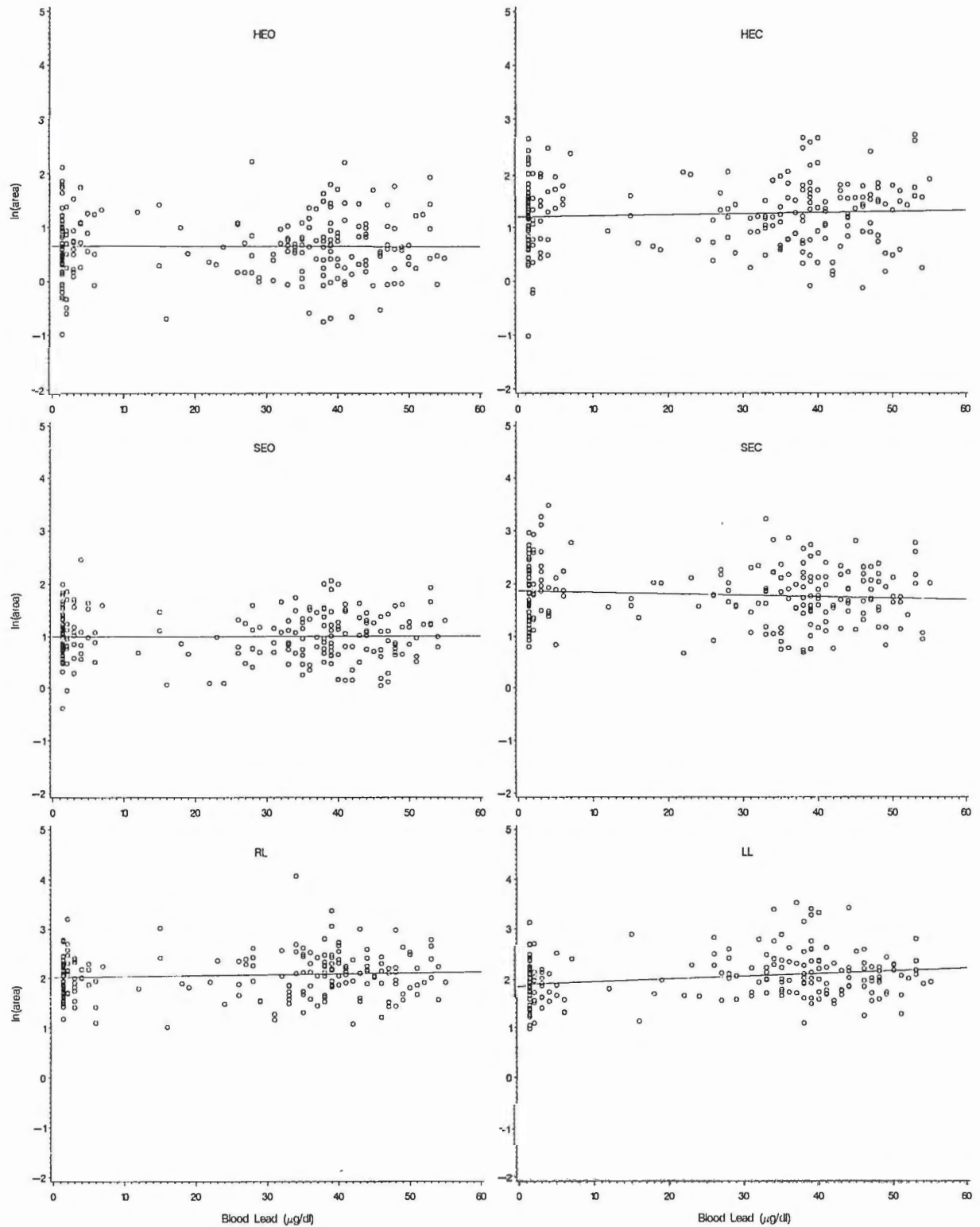


FIG. 1. Scatter plot showing the natural log transformed area measurements (cm^2) with current Blood Lead Levels ($\mu\text{g/dl}$) for each test condition. HEO=Hard surface-eyes open; HEC=Hard surface-eyes closed; SEO=Soft surface-eyes open; SEC=Soft surface-eyes closed; RL=Standing on right leg; LL=Standing on left leg.

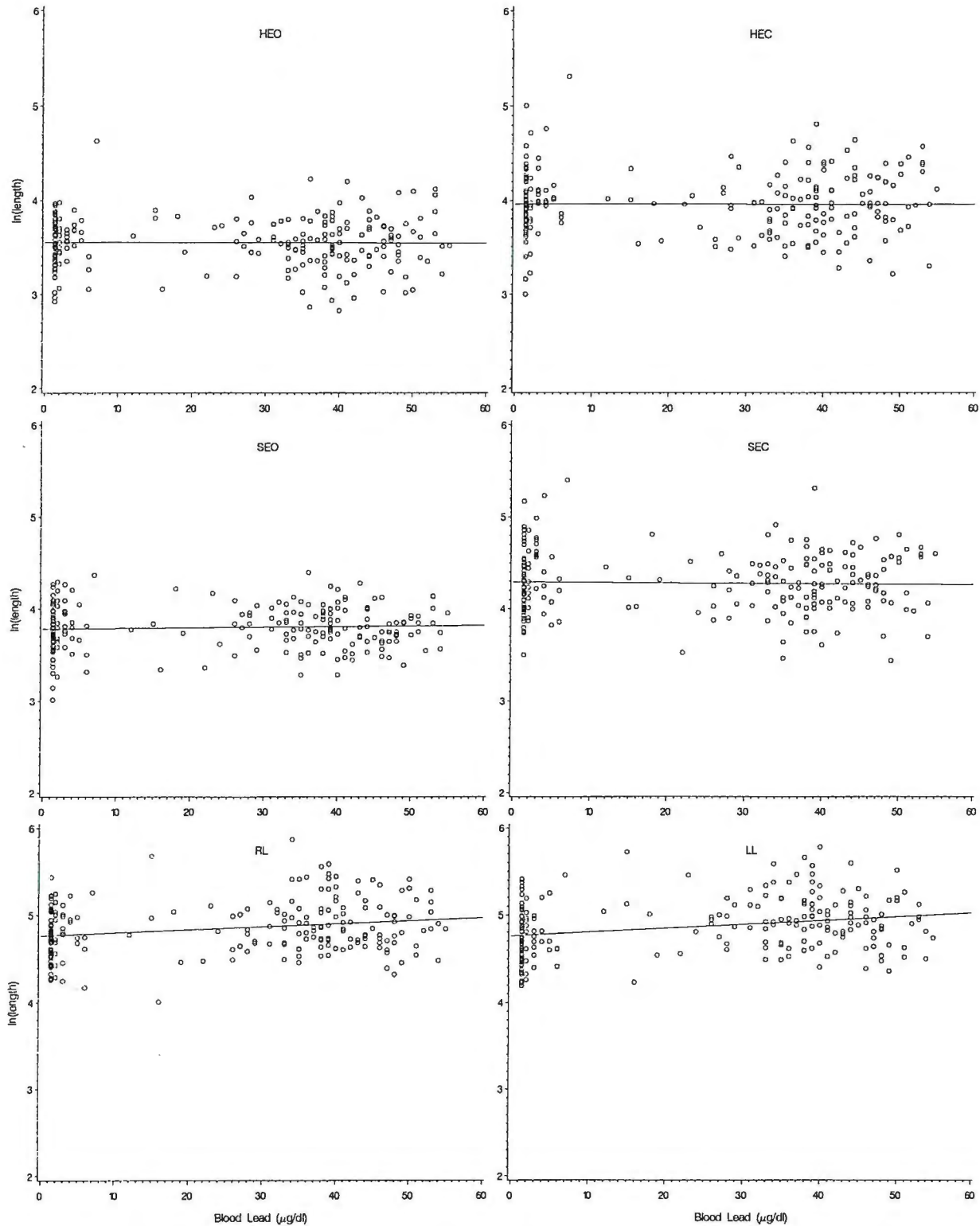


FIG. 2. Scatter plot showing the natural log transformed length measurements (cm) with current Blood Lead Levels ($\mu\text{g}/\text{dl}$) for each test condition. HEO=Hard surface-eyes open; HEC=Hard surface-eyes closed; SEO=Soft surface-eyes open; SEC=Soft surface-eyes closed; RL=Standing on right leg; LL=Standing on left leg.

exposure, and the longer term chronic measure (CBL) of exposure, although statistically significant, were indicative of different measures of lead exposure because the coefficients were low (<0.20). The best correlation between a current measure and a long term exposure measure was between current BLL and TWBL at 0.678.

Analysis of the data showed that possible exposure effects occurred only in the standing on one leg test condition. The two leg test conditions, which are the more standard test conditions and have been used in previous adult lead exposure studies (Chia *et al.*, 1994; 1996) did not show any increases in sway with exposure to lead. The exposure effect in the one leg conditions was significant for both the area measurement and the length measurement and was linear, but only when blood measurements for all workers were analyzed. The effect was not present when only the blood lead measurements of the lead exposed workers, which ranged from 15 µg/dl to 55 µg/dl were analyzed.

The results of this study only partially replicate the postural sway results reported by Chia *et al.*, 1994, 1996, which reported significant postural sway effects comparing lead exposed workers to control workers in a two leg, hard surface eyes closed condition. These effects reported by Chia *et al.*, however, were not significantly related to current blood lead concentrations in the

regression analysis. Soft surface and one leg conditions were not used in the Chia study. A follow up study by Chia *et al.*, (1996) using data from the same workers, developed cumulative estimates for each year of exposure; and while they reported no significant effects with the total cumulative estimate (e.g., blood lead years), they did report a small significant relationship with the cumulative blood estimate for year two. Our results also showed no significant relationship between the cumulative measures of lead and postural sway,

Major differences between the test methods and analysis procedures that could account for the lack of agreement with the Chia *et al.*, 1994 results are not apparent. The mean blood lead levels of the two exposure groups are comparable (38.91 versus 36.0 µg/dl), as are the test equipment and test procedures. The Chia study took three measurements for each test condition, which probably produced a more precise measurement; our study was limited to one measurement per test condition because of time constraints. Age ranges of the subjects were similar (e.g., first half of third decade), but the Chia study group averaged a slightly longer mean exposure (7 yr. versus 6 yr.) and upper range of exposure (30.5 yrs. versus 18.5 yrs.) than the US study workers. The US study workers were on the average 12 cm taller and 20 kg heavier. Both studies, however, controlled for weight and

TABLE 4. Means¹, Standard Deviations and ANOVA P-values for the Comparison Workers Versus the Exposed Lead Workers By Sway Test Condition.

Sway Variable ¹	Log (Area-cm ²)					Log (Length-cm)		
	N ²	Mean ³	SD	P =	N	Mean ³	SD	P =
Hard Surface-Eyes Open								
Lead Workers	138	0.63	0.56	0.5523	138	3.54	0.27	0.7587
Comparison Workers	84	0.67	0.59		84	3.55	0.27	
Hard Surface-Eyes Closed								
Lead Workers	138	1.25	0.59	0.7332	138	3.94	0.33	0.4207
Comparison Workers	84	1.23	0.65		84	3.98	0.36	
Soft Surface-Eyes Open								
Lead Workers	138	0.99	0.45	0.6542	138	3.80	0.22	0.4192
Comparison Workers	84	1.02	0.47		84	3.78	0.27	
Soft Surface-Eyes Closed								
Lead Workers	137	1.75	0.52	0.0954	137	4.26	0.31	0.3265
Comparison Workers	84	1.87	0.58		84	4.31	0.37	
Standing on Right Leg								
Lead Workers	134	2.09	0.47	0.2833	136	4.89	0.31	0.0024
Comparison Workers	79	2.02	0.39		80	4.76	0.28	
Standing on Left Leg								
Lead Workers	132	2.10	0.47	0.0002	138	4.94	0.30	0.0001
Comparison Workers	82	1.85	0.41		83	4.75	0.30	

¹Measurements of postural sway.

²N=the number of subjects with usable postural sway data for the analysis.

³Mean of the log transformed scores for each test condition using natural logarithms.

TABLE 5. Parameter Estimates Using Lead Exposure Measurements on Postural Sway Measurements.

PANEL A												
Measurement: Blood Lead - All Subjects: N = 216												
Condition	HEO		HEC		SEO		SEC		LL		RL	
	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)
Model Variable												
Intercept	-2.2360	2.4154	-3.3150	1.5306	-0.3801	3.3917	-1.8362	2.3680	0.4760	4.1932	0.6305	4.1560
Exposure	0.0002	0.0005	0.0027	0.0005	0.0009	0.0017	-0.0026	-0.0003	0.0067	0.0047	0.0032	0.0033
Age (months)	0.0008	0.0004	-0.0002	0.0003	0.0005	0.0001	0.0004	0.0003	0.0002	0.0004	-0.0001	0.0006
Height (cm)	0.0154	0.0076	0.0255	0.0143	0.0082	0.0045	0.0219	0.0126	0.0085	0.0032	0.0098	0.0031
Mass (kg)	0.0003	-0.0025	-0.0002	-0.0016	0.0017	-0.0034	-0.0052	-0.0047	-0.0002	-0.0001	-0.0026	-0.0004
Race	-0.1168	-0.1087	0.0643	-0.0428	-0.0814	-0.1231	0.1001	-0.0113	-0.1152	-0.0869	-0.1375	-0.0908

PANEL B												
Measurement: Blood Lead - Lead Exposed Workers Only: N = 134												
Condition	HEO		HEC		SEO		SEC		LL		RL	
	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)	Ln(A)	Ln(L)
Model Variable												
Intercept	-2.7094	2.6053	-2.6255	2.4264	0.3254	3.9074	-1.3589	3.1226	1.1523	4.8244	1.1476	4.7343
Exposure	0.0042	0.0009	0.0095	0.0063	0.0071	0.0001	0.0030	0.0035	-0.0026	-0.0025	0.0029	0.0014
Age (months)	0.0005	0.0004	-0.0005	0.0002	-0.0000	0.0001	-0.0002	0.0002	0.0000	0.0005	-0.0003	0.0007
Height (cm)	0.0197	0.0068	0.0219	0.0080	0.0048	0.0018	0.0209	0.0084	0.0085	0.0011	0.0087	0.0002
Mass (kg)	-0.0025	-0.0037	-0.0029	-0.0033	-0.0031	-0.0035	-0.0087	-0.0066	-0.0020	-0.0008	-0.0036	-0.0011
Race	-0.1805	-0.0812	0.0734	0.0341	-0.1206	-0.1053	0.0819	0.0174	-0.1531	-0.0537	-0.1674	-0.0641

KEY: N=number of subjects with usable data for the analysis using the final model. HEO = Hard surface, eyes open; HEC = Hard surface, eyes closed; SEO = Soft surface (pad), eyes open; SEC = Soft surface (pad), eyes closed; LL = Standing on left leg; RL = Standing on right leg; Ln(A) = Log transformation of the area measurement; Ln(L) = Log transformation of the length measurement. Bold Type = Parameter estimates significant with p < 0.05.

height in the statistical analysis. Our study did have a larger number of workers in both the lead (151 versus 60) and control (86 versus 60) populations, but a larger number of test subjects usually improves the probability of detecting effects. Because the Chia studies reported 20 sec. samples and our study used 30 sec. sway samples, a comparison of the study group sway means is limited.

We did not examine the cumulative data similar to the Chia *et al.*, 1996 study for three reasons. (1) Their correlation analysis did not adjust for co-variables; (2) the alpha levels were not adjusted to protect against type I error; and (3) data points are lost when individual years are examined because not all workers have worked the same number of years. In the Chia study, data from 10 workers was lost in calculation of the year 2 cumulative measure versus the total cumulative measure.

The expected increase in sway from the eyes open condition to the eyes closed condition is consistent in both our study and the Chia *et al.* studies. Examination of Figure 1 in our study does show a slight increase in sway with increasing blood lead concentrations for the hard

surface area measurement with eyes closed, but the parameter estimate was not statistically significant (b = 0.0028, t = 1.25, p = 0.2119). This condition (hard surface, eyes closed) also approached significance (p = 0.0576) for the length measurement in the analysis of only the lead exposed workers. These results, however, were not supported by the results of the soft surface test conditions, which were more challenging.

The findings from this study may be explained by an effect of lead on the peripheral nervous system. Given the range of blood lead levels detected in the battery workers, a peripheral nervous effect involving some weakness affecting extensor muscle groups is possible (Baker, 1995). According to Baker (1995) this weakness may occur before abnormalities are detected on nerve conduction testing. Peripheral nerve dysfunction measured by nerve conduction testing tends to develop in individuals with BLLs in the range of 60 µg/dl (Baker, 1995). The influence of cortical structures (e.g., cerebral cortex, cerebellum, hippocampus), seems remote given that these effects have been reported at very high con-

centrations in animals (Cory-Slechta and Pounds, 1995) and not at the workplace concentrations measured in this study. A recent study by Yokoyama *et al.* (1997), using frequency analysis from postural sway measurements in lead sterate workers reports lead effects at workplace concentrations with possible links to effects on the cerebellum, may indicate otherwise.

Because the effects disappear when only the lead exposed workers data were analyzed, threshold or bi-modal effects are also suggested. Threshold effects have been found in lead exposed children (Bhattacharya *et al.*, 1995), who have developmentally sensitive nervous systems, and bi-modal effects have been reported in animal studies (Cory-Slechta and Pounds, 1995). These limited findings, however, could not be adequately evaluated because of the small number of workers whose BLLs were between 5 µg/dl and 25 µg/dl, which limited the dose response range.

While there is some evidence of an exposure effect with the one leg test conditions, the results need to be interpreted with some caution. (1) The one leg test condition did produce evidence of being a more challenging test condition than the two leg test conditions because of the greater sway produced by the test condition, but this test condition unlike the more standard Romberg (eye open versus eyes closed) test is still a new condition with unknown parameters. Analysis of one-leg sway data collected on two successive days in a NIOSH laboratory project has shown a test-retest correlation coefficient of 0.74 for the right leg and 0.69 for the left leg length measurements, which were comparable to the standard Romberg conditions. However, correlation coefficients for the area measurement were less than 0.50. (2) Although the number of tests that had to be re-analyzed and data dropped because subjects could not complete the one leg test condition for a full-30 sec. was minimal, there is still the possibility of increased experimental error. (3) The exposure effect was only significant across the entire dose-response range and disappeared when only the lead exposed workers data was analyzed. While this may be suggestive of a threshold effect or a bi-modal effect, or possible population differences between the lead exposed workers and non-exposed workers, further research with a dose-response range containing more workers with BLLs between 5 and 25 µg/dl would be needed to confirm the strength of the exposure effects. (4) Because the study was designed and carried out as an epidemiological study, the exposure effects have to be interpreted as associative rather than as causative.

In summary, the results of this study indicate possible sub-clinical effects from current lead exposures on measures of postural stability at average concentrations slightly below 40 µg/dl. The effects were not related to either a short-term (3-4 months) indicator of lead exposure (ZPP) or to the longer-term cumulative measure of lead absorption (CBL).

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