Environmental Health Perspectives
Vol. 89, pp. 35-42, 1990

Lead Effects on Postural Balance of Children

by A. Bhattacharya,* R. Shukla,* R. L. Bornschein,* K. N. Dietrich,* and R. Keith†

The postural sway responses of 63 children with a mean age of 5.74 years were quantified with a Force Platform technique. The average maximum (max) blood lead (PbB) of these children during the first 5 years of life was 20.7 μg/dL (range 9.2 to 32.5). The backward stepwise regression analysis for sway area response during the eyes-closed, no-foam test with all the covariates and confounders and the PbB parameters showed a significant relationship with peak or max PbB during the second year of life. These results are consistent with our previous study with a smaller group of children. The data have been analyzed to provide some insight into the role of various afferents for the maintenance of postural balance. The results suggests a hypothesis that if the max PbB had caused some level of impairment in the functional capacities or interconnectivity of the vestibular and/or proprioception systems at 2 years of age, then it is reasonable to assume that the redundancy in the postural afferent systems would naturally adapt to rely more on the remaining intact afferent system (in this case, vision).

Introduction

A considerable amount of research related to chronic lead exposure and its impact on neurocognitive behavior has been conducted by various investigators. Some of these investigators reported results from inner city children who were exposed to low levels of environmental lead. Other studies were conducted on children residing at the lead smelter site (*1*). Because of close proximity to the lead sources, these children had high blood lead (PbB) burdens. Earlier studies by Needleman et al. (*2*) documented the lead-induced impairment of psychologic and classroom performance of children from the first and second grades. More recently, the results from longitudinal studies by Bellinger et al. (*3*), McMichael et al. (*4*), Fulton et al. (*5*), Shukla et al. (*6*), and Dietrich et al. (*7*) support the earlier findings that lead exposure is associated with some impairment in early cognitive development and early growth rate. These investigators found these effects at different age groups and at different exposure levels. Bellinger et al. (*3*), in a prospective study of children from birth to 2 years of age, found an association between prenatal and postnatal lead exposure and cognitive development as assessed by Mental Development Index of the Bayley Scales of Infant Development. The umbilical cord PbB levels ranged between less than 3 μg/dL and as high as 25 μg/dL. Dietrich et al. (*7*), in their prospective study of 3- and 6-month-old infants, reported that prenatal lead exposure (maternal PbB) was significantly releated to 3- and

exposure (maternal PbB) was significantly releated to 3- and
6-month Bayley Mental Development Index. For this study, the mean prenatal PbB was 8.0 μg/dL (range, 1–27 μg/dL). In 1988, the Port Pirie, Australia, cohort study (*4*) showed an inverse relationship between postnatal PbB values, particularly at 2 and 3 years and cognitive scores at the age 4. A detailed literature review of lead effect on function can be found in another paper by one of the co-authors in this issue (*8*).

While the above investigators reported associations between pre- and/or postnatal lead exposure and cognitive development, others (*9*) indicated that the low-level exposure effects on the cognitive system are still not well documented. Therefore, controversy regarding lead effects on cognitive function still exists. However, the topic of cognitive development is important enough to warrant continued research. While studies of lead effects on the cognitive system are continuing, the literature on lead-induced neuromotor effects have not been comprehensive. A few studies have shown fine motor impairment at high PbB levels (> 40 μg/dL). Recent studies by Benetou-Marantidon (*1*) reported retardation of gross motor maturation as recorded by a short version of Oseretsky test for motor maturation in children 6 to 11 years of age living near a lead smelter. These children had PbB levels in the range of 35 to 60 μg/dL, (mean, 44.5 μg/dL). Earlier studies by Canadian investigators (*10*) also showed subtle neurological impairment at PbB greater than 40 μg/dL in a small subgroup of the children studied.

The measurement of neuromotor function in the assessment of neurotoxicants may be equally important as measures of cognitive development. This is plausible because the portions of the higher center of the central nervous system (CNS), which contribute toward cognitive development, also play a significant role in neuromotor development in young children (*11,12*).

*Department of Environmental Health, University of Cincinnati, M.L. #056, Cincinnati, OH 45267-0056.
†Department of Audiology, University of Cincinnati Medical Center, M.L. #528, Cincinnati, OH 45267-0056.
Address reprint requests to A. Bhattacharya, University of Cincinnati Medical Center, Biomechanics-Ergonomics Research Laboratory, Department of Environmental Health, M.L. #056, Cincinnati, OH 45267-0056.

It is possible that, with the availability of newer state-of-the-art techniques, one can detect early symptoms of neuromotor function impairment. Our research group (*13*), with the help of a microprocessor-based Biomechanics Force platform system for noninvasively measuring postural balance, showed a significant relationship between postnatal PbB level and postural balance characteristics. This study was conducted on a small group of 31 children of approximately 6 years of age who had an average maximum PbB of 23.5 μg/dL. This study was pilot in nature, and we are currently pursuing the testing of additional children from our cohort. This report will present some interim results from our ongoing study.

Methods

This study used subjects from the Cincinnati Lead Program Project Cohort Children (*14*). So far, 87 children have been tested for the quantification of postural equilibrium using a microprocessor-based force platform Balance Evaluation Testing System (BETS). Four out of 87 children did not complete the test due to behavioral characteristics which prevented them from successfully completing the test procedure. Twelve out of 87 children had a middle ear pressure (MEP) reading of < −150 mm H_2O during tympanometry test on the postural sway testing day. Any reading < −150 mm H_2O is considered to be associated with acute dysfunction of eustachian tube, and they were considered to be the children with high MEP. Eight out of 87 children repeatedly needed help in preventing a fall during one of the postural sway tests (standing eyes closed on foam). Some of these children fell (i.e., needed help to prevent a fall) even during a 6-month repeat test. These children were placed in the "fallers" category. For the data analysis purposes, the data from the high MEP group, faller group, and uncooperative group were not included in the final analysis. Therefore, the results presented are from 63 children. Twenty-six out of 63 children were retested after a 6-month period and 9 out of 26 children were retested a second time after a 12-month period to determine the stability and reproducibility and/or aging effect on postural sway over a prolonged period.

The mothers of the study subjects were recruited prenatally. Special care was taken to exclude mothers who were diabetic, alcoholic, mentally retarded, or drug addicts. Furthermore, infants with genetic and serious medical impairments were also excluded from the study. A detailed description of exclusion criteria are given in Dietrich et al. (*7*). The Cincinnati Lead Program Project Cohort undergoes a thorough and periodical medical checkup, PbB evaluation, and a series of age-appropriate standard neuromotor and neurocognitive tests. Measures of particular relevance to this report include PbB, the Bruininks-Oseretsky (BO) neuromotor tests administered at 6 years of age, the Hollingshead Four Factor Index of Social Status (SES), birth length and weight, Home Observation for Measurement of Environment (HOME) at 3 years of age, maternal intelligence (IQ), and the number of known occurrences of bilateral otitis media only (B-OM) and combined number of occurrences of bilateral and unilateral otitis media (BU-OM) for the subjects used in our study.

The postural sway measurement was performed using a strain-gauge-type force platform (Model OR6-3, Advanced Mechanical Technology, Inc., Newton, MA). This platform provides direct measurements of three forces and three moments around three orthogonal axes during the postural sway test. An algorithm is used to calculate the X and Y location of the body's center of pressure in the horizontal plane (*15*). Details of calibration and accuracy of measurement of this platform have been documented in our earlier publication (*15*).

The test procedure involved standing quietly on the force platform for 30 seconds for each of the four testing conditions. The four testing conditions were standing on the platform with eyes open (EO) and then with eyes closed (EC); and standing on a foam (compliant surface) placed on the platform with eyes open (FO) and then eyes closed (FC). These four testing conditions were designed to indirectly challenge (and/or enhance and minimize) various afferents (vision, proprioception, cutaneous receptors, and vestibular system) relevant for the maintenance of postural balance. The tests were administered in the following sequence, EO, EC, FO, FC, FC, FO, EC, and EO with a 2-min rest between tests. The average of each pair of repeat tests was used for later analysis. The force platform system and associated software provides a quantifiable picture of the movement pattern of the body's center of pressure, known as a stabilogram. This pattern is then processed to calculate a variety of sway characterizing parameters. One such parameter is called the sway area, which is the area of the projection of the body's center of pressure on the X-Y horizontal plane.

The BETS and our custom software allow calculation of postural sway area, which was transformed to natural logarithmic units for statistical analysis purposes. Standard descriptive statistics such as means and standards deviations and inferential statistics such as Pearson bivariate correlation and stepwise multiple regression analysis were computed with the SAS statistical package (*16*).

Results

The descriptive statistics for the demographic data and maximum (max) PbB level are given in Tables 1 and 2. As demonstrated in our previous pilot study (*13*), all four testing conditions were sufficiently adequate for challenging various afferents. In order to illustrate the comparison between adult postural sway response and those of study children, in Figure 1 we have provided postural sway area data from the present study as well as those from two adult studies conducted in our laboratory. It can be observed that for both children and adult subjects, as the vision and proprioception were removed and/or modified in the EC, FO, and FC tests, the maintenance of postural equilibrium became progressively more difficult as illustrated by an increase in sway area. For adults, the postural sway area was several-fold smaller than those for the children. The children in the faller category consistently showed the highest postural sway area values

Table 1. Descriptive statistics for the sample: demographic data.

Variable	Mean ± SD	Minimum	Maximum
Age, years	5.74 ± 0.51	5.05	7.02
Birth weight, g	3047.10 ± 421.20	1990.02	4139.00
Birth length, cm	48.80 ± 2.40	41.50	53.00
Middle ear pressure, mm H_2O[a]	−39.1 ± 49.4	−150.00	42.00
Sex	43% Males 57% Females		
Race	16% Whites 84% Blacks		
Number of subjects	63		

[a]Anything less than −150 mm H_2O is considered indicative of eustachian tube dysfunction.

Table 2. Descriptive statistics: maximum blood lead values.

Period of blood sampling[a]	Mean ± SD, μg/dL	Minimum value, μg/dL	Maximum value, μg/dL
Prenatal	8.8 ± 1.53	1.99	22.00
1st year of life	17.1 ± 1.65	5.40	56.30
2nd year of life	21.8 ± 1.57	8.50	53.50
3rd year of life	20.1 ± 1.50	8.84	49.90
4th year of life	18.0 ± 1.53	8.60	52.50
5th year of life	15.3 ± 1.54	7.40	36.20

[a]Four measures per child per year.

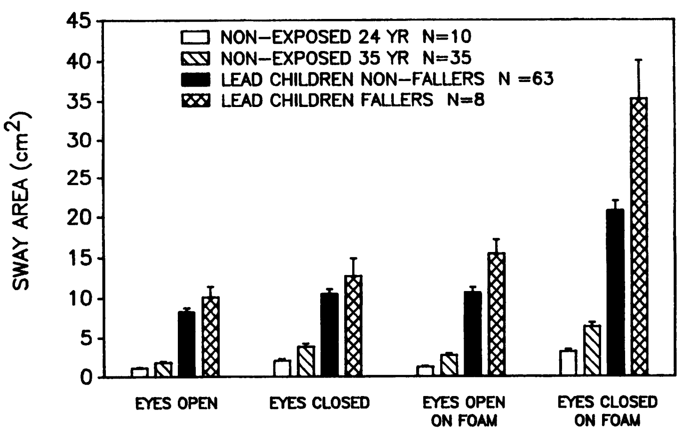

FIGURE 1. Postural sway area of children in the present study compared to those of children "fallers" and adult subjects.

for all the testing conditions. Furthermore, the coefficient of variation was considerably smaller for the adults (ranged between 25.6 and 39%) as compared to the children (ranged between 46.8 and 53.9%). However, the values for the 35 year olds were higher (50 to 65.2%).

To evaluate the test-retest reliability, the data from test 1, test 2, and test 3 were compared. The mean difference of sway area values (−0.5 cm^2 for EO; 0.3 for EC; −0.7 for FO) between test 1 and test 2 (6 months later) was not significantly different than zero (p values were 0.5, 0.7, and 0.5 for EO, EC, and FO respectively) for all test conditions except FC. For the FC test condition, the mean difference was −5.15 cm^2 (p = 0.01). The mean difference of sway area values between test 1 and test 3 (12 months later) always showed negative values [−3.5 cm^2 (p = 0.09) for EO; −3.9 (p = 0.02) for EC; −1.9 (p = 0.4) for FO and −8.5 (p = 0.06) for FC], indicating improvement in sway with age. This finding is consistent with data reported by the other investigators (*17*).

A Pearson bivariate correlation analysis indicated that the sway area was significantly related to the second year max PbB (r = 0.31, p = 0.01) and marginally related to the fourth year max PbB (r = 0.24; p = 0.06) (Tables 3 and 4), for the test condition of EC. In other words, higher Pb exposure during the second year was associated with greater sway. No other test condition showed any statistically significant correlation for the PbB parameters. For FO test condition, birth length and B-OM and OME1 (B-OM/age) showed significant correlations with sway area. The parameters of B-OM and OME1 were also correlated with sway area for the FC test condition. Other parameters such as age, sex, race, SES, maternal IQ, HOME scores, birth weight, and MEP were found to be not significantly related to the sway area. This finding essentially supports results from our previous study which was carried out with a smaller but overlapping group of subjects (*13*).

A stepwise regression analysis was carried out with backward elimination of nonsignificant variables (p > 0.10) for the EC condition. The extraneous variables included potential confounders and covariates of PbB-sway relationship, i.e., prenatal PbB, max first year PbB, max second year PbB, MEP, maternal IQ, SES, age, race, sex, HOME, birth weight, birth length, and OME1.

In the stepwise regression analysis, the variables were dropped out except for certain bonafide confounders/covariates that were forced to remain in the model even if they were not statistically significant. These variables were MEP, OME1, and max first year PbB. The final regression model was:

$$\text{Log sway area} = 1.69 - 0.0014 \text{ min MEP} + 0.09 \text{ OME1} - 0.30 \log \text{max 1st year PbB} + 0.44 \log \text{max 2nd year PbB}$$

The only statistically significant PbB parameter was max second year PbB at p = 0.03 and r = 0.34. This finding is consistent with our previous results (*13*), and Figure 2 shows this relationship. Our regression results suggests that for every 1 log unit increase in the max second year PbB, the area of sway increased on the average by 5.2 cm^2.

To determine the association between the postural sway test and the balance subtest of Bruininks-Oseretsky neuromotor test battery, a Pearson bivariate correlation analysis was performed (Table 5). The correlations were significant for all postural sway test conditions, with EC having the highest correlation coefficient value (r = −0.49). In other words, the children who performed poorly on the balance subtest of Bruininks-Oseretesky test battery had larger sway area. It is interesting to note that it is the EC condition that also showed a significant relationship between the sway area and the second year max PbB.

To better understand the role of various afferents for the maintenance of postural balance, three physiological ratios (or factors) were defined. These ratios are the sole effect

Table 3. Bivariate correlation matrix for blood lead and bouts of otitis media versus postural sway area.

	Test condition			
Parameters	Eyes open, no foam	Eyes closed, no foam	Eyes open, foam	Eyes closed, foam
Prenatal PbB	-0.011	-0.04	-0.08	-0.10
	(0.93)[a]	(0.77)	(0.56)	(0.44)
Max PbB lst year	-0.05	0.09	0.04	0.08
	(0.65)	(0.47)	(0.77)	(0.54)
Max PbB 2nd year	0.17	0.31	0.18	0.18
	(0.18)	(0.014)	(0.15)	(0.15)
Max PbB 3rd year	0.08	0.19	0.10	0.12
	(0.51)	(0.12)	(0.44)	(0.34)
Max PbB 4th year	0.07	0.24	0.12	0.18
	(0.56)	(0.06)	(0.33)	(0.17)
Max PbB 5th year	-0.04	0.09	0.06	0.09
	(0.76)	(0.48)	(0.66)	(0.49)
Bilateral episodes of	0.21	0.08	0.30	0.27
otitis media only (B-OM)	(0.09)	(0.52)	(0.02)	(0.04)
Bilateral and unilateral	0.08	0.02	0.15	0.15
episodes of otitis media (BU-OM)	(0.53)	(0.85)	(0.23)	(0.22)
OME1 (B-OM/age)	0.22	0.08	0.30	0.26
	(0.08)	(0.51)	(0.02)	(0.04)
OME2 (BU-OM/age)	0.09	0.02	0.16	0.16
	(0.48)	(0.87)	(0.21)	(0.22)

[a]The numbers in parentheses are p values.

Table 4. Bivariate correlation matrix for demographic data versus postural sway area.

	Test condition			
Parameters	Eyes open, no foam	Eyes closed, no foam	Eyes open, foam	Eyes closed, foam
Age	-0.13	-0.013	-0.07	-0.067
	(0.30)[a]	(0.92)	(0.55)	(0.60)
Sex	0.02	-0.14	-0.09	-0.16
	(0.88)	(0.25)	(0.50)	(0.20)
Race	0.11	0.08	0.15	0.15
	(0.40)	(0.52)	(0.24)	(0.22)
Socioeconomic status	0.13	-0.07	0.12	-0.01
	(0.32)	(0.56)	(0.33)	(0.93)
Maternal IQ	-0.09	-0.13	-0.18	-0.13
	(0.46)	(0.32)	(0.15)	(0.29)
HOME	-0.19	-0.08	-0.13	-0.17
	(0.14)	(0.52)	(0.29)	(0.19)
Birth weight	-0.04	-0.03	-0.19	-0.11
	(0.75)	(0.80)	(0.13)	(0.37)
Birth length	-0.16	-0.06	-0.25	-0.13
	(0.20)	(0.63)	(0.04)	(0.29)

[a]The numbers in parentheses are p values.

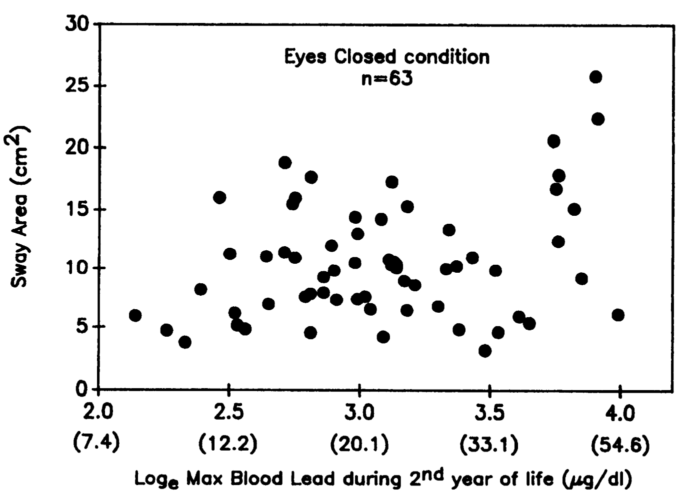

FIGURE 2. Scatter plot of the postural sway of children at 5.74 years of age versus lead exposure during second year of life. PbB is presented as natural logarithm.

Table 5. Bivariate correlation between Bruininks-Oseretsky balance subtest and sway area.[a]

Test condition	Correlation coefficient
Eyes open, no foam	-0.41
	(0.01)[b]
Eyes closed, no foam	-0.49
	(0.0016)
Eyes open, on foam	-0.41
	(0.01)
Eyes closed, on foam	-0.36
	(0.025)

[a]So far only 38 children out of 63 have been tested on the Bruininks-Oseretsky balance subtest.
[b]The numbers in parentheses are p values.

of change in vision (vision ratio = EC/EO), sole effect of change in proprioception (proprioception ratio = FO/EO), and the effect of highest reliance on the vestibular system (vestibular ratio = FC/EO). The process of presenting the data as ratios effectively minimizes the possible effect of extraneous variables such as height and body weight. The importance and usefulness of presenting data with these ratios can be explained by discussing data from our cohort and subjects who repeatedly needed assistance in preventing a fall during the FC test. There were eight children in our cohort who were considered fallers, and their data were not included in the remaining data analysis. It was hypothesized that fallers must have different postural balance characteristics for all test conditions and not only just the one in which they fell. As per the literature on adult elderly fallers, it has been found that elderly persons with a history of falls have larger sway as compared to those with no history of falls (*18*). This finding is substantiated in our children fallers as well, who showed higher sway area for all four test conditions as compared to the remaining subjects in our population (Fig. 1). Furthermore, it was also found that these eight fallers had below average performance on the standard balance subtest of Bruininks-Oseretsky neuromotor tests (Table 6).

In Figure 3, we have compared various ratios between fallers and nonfallers. Fallers showed slightly lower reliance on vision than the nonfallers and considerably greater reliance on the vestibular system. Therefore, the response to the vestibular reliance test (FC) produced considerably higher values in the fallers compared to others. Figure 3 also shows the use of ratios to better understand the roles of various afferents in maintaining balance for our study children as compared to the nonexposed adults. Adults showed considerably larger values for vision ratio compared to those for children, whereas for the proprioception ratio the values were reversed.

The sway area responses were also investigated by dividing our population into two subgroups, i.e., high and low PbB groups. These groupings were based upon the median second year max PbB = 20.9 μg/dL. The mean value of

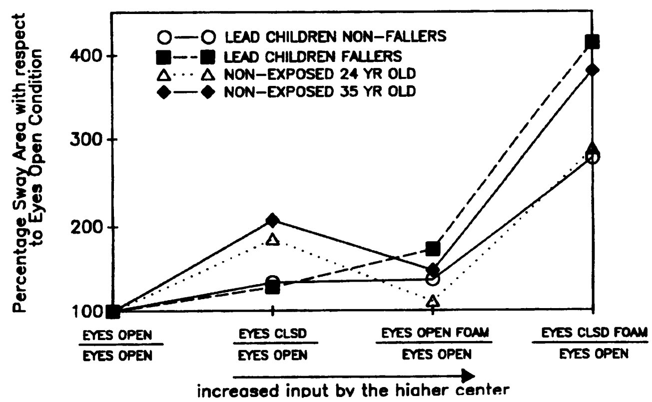

FIGURE 3. Percentage change in sway area for various ratios, i.e., vision ratio (EC/EO) proprioception ratio (FO/EO), and vestibular ratio (FC/EO).

second year max PbB for high PbB group was 30.9 ± 1.3 SD μg/dL and for the low PbB group was 14.9 ± 1.2 SD μg/dL and for the low PbB group was 14.9 ± 1.2 SD μg/dL. These data are presented in Figure 4. For all four testing conditions, the absolute sway area values were higher in the high PbB group than that of the low PbB group. Because of the small number of subjects in each group, the differences in sway areas were not significant. In order to investigate the role of various afferents for these two groups, the results are presented in terms of ratios in Figure 5. The absolute value of the vision ratio was higher in the high PbB group than that of the low PbB group. The vestibular ratio was smaller in the high PbB group than that for the low PbB group. The implications of these results are explained in the discussion section.

Discussion

The results from our present study essentially support the findings from our previous pilot study (*13*) with 31 children. The test-retest results from test 1, test 2 (performed 6 months later), and test 3 (performed 12 months

Table 6. Comparison of sway area values with scores from Bruininks-Oseretsky (BO) tests.

Variables	Mean ± SEM		
	Fallers[a] (n = 8)	Nonfallers (n = 63)	p-Value
Sway area, cm^2			
Eyes open, no foam	10.1 ± 1.34	8.24 ± 0.50	0.20
Eyes closed, no foam	12.7 ± 2.16	10.50 ± 0.61	>0.20
Eyes open, on foam	15.4 ± 1.76	10.62 ± 0.71	<0.02*
Eyes closed, on foam	35.2 ± 4.81[b]	20.7 ± 1.24	<0.01
BO balance subtest score	8.00 ± 1.34 (n = 6)	10.52 ± 0.73 (n = 50)	>0.20
BO bilateral coordination	12.66 ± 0.61 (n = 6)	14.9 ± 0.69 (n = 50)	>0.20
BO strength	12.66 ± 1.92 (n = 6)	15.7 ± 0.76 (n = 50)	0.10
BO upperlimb coordination	12.5 ± 2.53 (n = 6)	15.3 ± 0.77 (n = 50)	>0.10
BO response speed	10.83 ± 2.45 (n = 6)	10.9 ± 0.71 (n = 49)	>0.50

[a]Fallers have been excluded from analyses of the sway area-PbB relationship.
[b]This value may actually underestimate the sway area since children fell during the test.
*Significant difference between fallers and nonfallers.

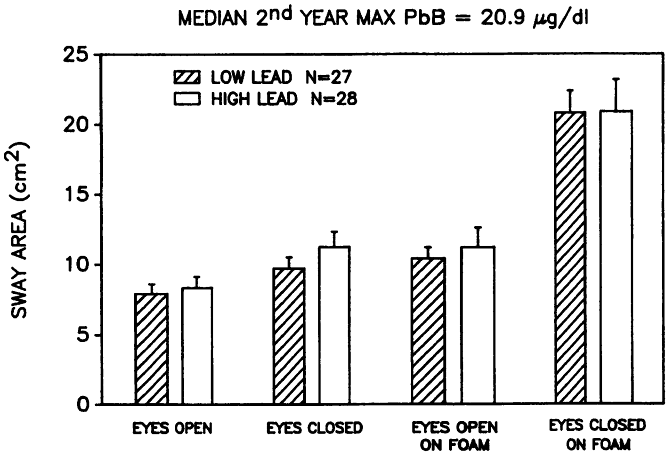

FIGURE 4. Comparison of postural sway area response between the high lead group and the low lead group.

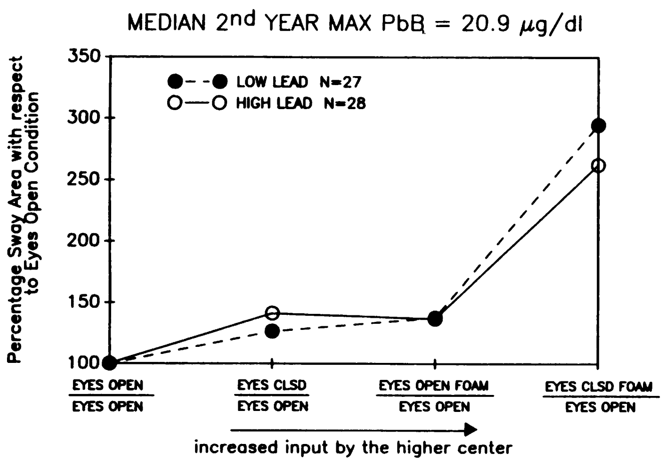

FIGURE 5. Comparison of vision, proprioception, and vestibular ratios between the high lead group and the low lead group.

later) indicate that the sway area values remain fairly stable during the 6-month period. However, after a 12-month period, these values show significant decrement. Although these changes were not statistically significant, the direction of sway area changes are suggestive of an age-associated maturation of the neuromuscular system relevant for postural balance. Previous studies (*17,19–21*) have shown that generally, children reach adultlike sway performance at around age 12 years. Based on the pilot results, we can suggest that to avoid the influence of aging on the sway area, it is necessary to test the subjects no more than 6 months apart.

Like the results from our previous study (*13*), the present overlapping data also show significant correlation between sway area and the max second year PbB for the EC condition only. The B-OM and OME1 parameters were significantly correlated with sway area for the FO and FC test conditions. These parameters provide a measure of bouts of bilateral episodes of otitis media during the life of the child. In other words, B-OM and/or OME1 parameters are indicators of a chronic condition of middle ear disease, while the measurement of MEP on the sway testing day provide evidence regarding the presence of any acute or recent ear infection. With any middle ear problems, it is expected that the function of the vestibular system may be affected, and therefore we might find significant correlations with sway area for the tests that require increased reliance on the vestibular system (i.e., FO and FC tests). Although the EC test requires some level of vestibular reliance, it was not challenging enough to detect the effect of bilateral episodes of otitis media. This finding is consistent with the results of Birren et al. (*22*), Graybiel et al. (*23*), and Fregley et al. (*24*), which indicated that a patient with bilateral labyrinthine defect can perform the eyes-closed on a firm surface test without any difficulty, but the patient had considerable difficulty during a heel-to-toe test, which minimized the support surface and therefore placed excessive demand on the vestibular system. In our study, a comparable situation is presented to the child when he or she is asked to stand on the compliant (foam) surface with or without eyes open.

The only other variable that showed correlation with sway area was the birth length for the FO test. This was a negative correlation, implying that children with smaller stature at birth showed poorer balance. The significance of this association is not clear, but may reflect overall influence of intrauterine developmental factors on postnatal neurobehavioral development. To determine the correlation between height and body weight and weight/height at the time of sway test and EO, EC, FO, and FC performance, a bivariate analysis indicated that no correlation existed. Also, there were no correlations between height and body weight and max second year PbB. Although age did not show any significant correlations with sway area, it is interesting to note that for all testing conditions the associations were negative (i.e., sway area decreased with increase in age). This finding is consistent with other studies (*17*).

The stepwise regression analysis for sway area response during the EC test with all the covariates and confounders and the PbB parameters showed that the only parameter that showed significant correlation was the max second year PbB. However, since we are still not finished collecting data from the entire cohort, it is important to realize the significance of some of the established covariates and/or confounders that are known to have an influence on sway performance. Some of these parameters have shown correlations in the proper direction even though they were not significant for our small sample of 63 subjects. Because of these reasons, the regression model presented in the results section includes variables such as bouts of bilateral otitis media, MEP, and max first year PbB in addition to the max second year PbB. The regression coefficient for the first year PbB, although not significantly different from zero, was negative. This finding, together with a positive regression coefficient for the max second year PbB, suggests that the rate of change in PbB history might be a better index of lead exposure.

To facilitate the discussion of the various ratios or physiological factors, it will be necessary to describe the physiological significance associated with each of the testing conditions. The EO test implies that the response during this assessment reflects the availability of vision and proprioception but the least amount of vestibular input or reliance. The sway area value for this condition therefore should be the smallest, since all the afferents are available.

The response to the EC test condition is due to availability of cues from the proprioceptors and a slightly increased level of vestibular input compared to EO. The sway area value for this test is larger than that for the EO condition because of the lack of vision.

In the case of FO test, the response reflects the availability of vision and incorrect cues from the proprioceptors and slightly increased level of vestibular input compared to EO, but probably similar to that for EC condition. The results of sway area for the FO test are dependent on the subject's ability to process incongruent cues from vision and the proprioceptors. The processing of these kinds of conflicting signals generally requires input from the higher centers.

Finally, the response to the FC test reflects incorrect cues from the proprioceptors with no vision and therefore places considerably higher reliance on the vestibular system compared to EO, EC, and FO test conditions. Therefore, for this test condition, conflicting signals from the proprioceptors and the vestibular system will require significant input by the higher centers. In general, tests such as FC produce conflicting signals from the somatosensory system and place relatively higher reliance on the vestibular system. The sway area response to this test always produces the largest values in all age groups (*12*) (Fig. 1) compared to respective responses to EO, EC, and FO tests. To understand better the role or the contributions by these afferents, we have used the ratios of the sway area values obtained for each of the test conditions with respect to the EO condition. As explained in the results section, this process provided three ratios such as vision ratio, proprioception ratio, and vestibular ratio. We now discuss our data in the light of these ratios.

As shown in Figure 3, since fallers demonstrate somewhat less reliance on vision (faller has a value of 128.6% compared to 134% for nonfallers), it can be postulated that they would have to compensate by placing higher reliance on the other ratios (i.e., proprioception and vestibular), which require more dependence on higher centers. It is indicated in the literature that children's supraspinal pathways responsible for processing the interactions among multiple afferents mature at a later age (*25*). Therefore, children relying on this pathway for the maintenance of balance would have difficulty with postural tests such as eyes closed on a compliant surface (on foam), which requires predominantly higher reliance on the supraspinal processing. Such was the case in our small group of subjects who repeatedly required help in preventing a fall during the FC testing condition.

We found that there exists a correlation between bouts of bilateral episodes of otitis media and the sway area. Since chronic middle ear disorder may affect vestibular function, it is reasonable to expect a higher vestibular ratio for the children with otitis media episodes compared to those with no episodes. When the subjects in our population were placed in such groups, sway area did show a higher (278%) vestibular ratio for the otitis group than those (265%) with no episodes.

The use of ratios in clarifying the role of various afferents may be a worthwhile avenue to explore further in indentifying the influence of lead on various afferents important for postural balance control. In the following paragraphs, the ratio data are further discussed for the high and low PbB groups, which were grouped as per second year PbB median value of 20.9 μg/dL. The following discussion, although based on a small number of subjects, does provide preliminary insight into the possible role of environmental lead effect on the postural balance characteristics of the children.

The results from the regression analysis suggest that with an increase in max second year PbB, the sway area also increases for the EC testing condition. In our small sample of 63 children, average sway area was higher for the high PbB group compared to that of the low PbB group (Fig. 4). This difference was relatively more pronounced for the EC condition than for the remaining tests. Keeping in mind the physiological implications of EC testing, it can be said that an increase in sway response in the EC test during which postural control is maintained only by the proprioceptive and vestibular systems implies impairments in either proprioception function and/or vestibular function. Furthermore, since the body has to compensate by shifting its reliance to other unaffected afferents to maintain balance, it can be postulated that the high PbB group will have higher reliance on the vision than that for the low PbB group. In Figure 5, it can be seen that the high PbB group did show a somewhat higher vision ratio compared to that for the low PbB group. On the other hand, it is interesting to note that the high PbB group showed a lower value for the vestibular ratio compared to the low PbB group. This finding suggests an interesting hypothesis that if the max PbB had caused some level of impairment in the functional capacities or interconnectivity of the vestibular and/or proprioception systems at 2 years of age, then it is reasonable to assume that the redundancy in the postural afferent systems would naturally adapt to rely more on the remaining intact afferent system (in this case, vision). This process of placing higher reliance on the vision probably started at age 2; however, its time course of adaption, until age 5 (when we measured the postural sway) is not known. It will be worthwhile to identify from the neuromotor test battery administered during the early infant years the measured variables that might reflect the vestibular and/or proprioception status at that age. Clearly, more data analyses will be needed to test this hypothesis further.

The results from our study indicate that the force platform technique can be effectively used in young children for quantifying the lead effects on their postural equilibrium. We believe that this technique has promise in the field of neurotoxicology for detecting a subtle change induced by low-level, long-term exposure to neurotoxic agents. In particular, this technique may provide a simple and quick method for screening large populations for evidence of neurotoxic effects of environmental pollutants.

The authors appreciate and thank the families and the children for their participation and cooperation. Thanks are due Cyndy Cox, Terry Mitchell, JoAnn Grote, Ronnie Ratliff, Jill Edwards, Jolanda Johnson, Joyce Frondorf, Suzanne Liebee, Mariana Bier, Susan Naraine, George Robinson, and Kathleen Krafft of the Lead Program Project. Thanks are also due Jon Kopke and Salman Nawaz of the University of Cincinnati Computing Center for their assistance in the development of the software. This project was supported by a Program Project Grant from the National Institute of Environmental Health Sciences (Grant #ES-01566-09) and the National Institute of Environmental Health Sciences Center Grant #P30 ES-00159.

REFERENCES

1. Benetou-Marantidou, A., Nakou, S., and Micheloyannis, J. Neurobehavioral estimation of children with life long increased lead exposure. Arch. Environ. Health 43(6): 392–395 (1988).
2. Needleman H. L., Gunnoe, C., Leviton, A., Reed, R., Peresie, H., Maher, C., and Barrett, P. Deficits in psychologic and classroom performance of children with elevated dentine lead levels. N. Engl. J. Med. 300: 689–695 (1979).
3. Bellinger, D., Leviton, A., Waternaux, C., Needleman, H., and Rabinowitz, M. Longitudinal analysis of prenatal and postnatal lead exposure and early cognitive development. N. Engl. J. Med. 316(17): 1037–1043 (1987).
4. McMichael A. J., Baghurst, P. A., Wigg, N. R., Vimpani, G. V., Robertson, E. F., and Roberts, R. J. Port Pirie Cohort Study: environmental exposure to lead and children's abilities at the age of four years. N. Engl. J. Med. 319(8): 468–475 (1988).
5. Fulton, M., Thomson, G., Hunter, R., Raab, G., Laxen, D., and Hepburn, W. Influence of blood lead on the ability and attainment of children in Edinburgh. Lancet i: 1221–1226 (1987).
6. Shukla, R., Bornschein, R. L., Dietrich, K. N., Buncher, C. R., Berger, O. G., Hammond, P. B., and Succop, P. A. Effects of fetal and infant lead exposure on growth in stature. Pediatrics 84(4): 604–612 (1989).
7. Dietrich, K. N., Krafft, K. M., Bornschein, R. L., Hammond, P. B., Berger, O. G., Succop, P. A., and Bier M. Low-level fetal lead exposure effect on neurobehavioral development in early infancy. Pediatrics 80(5): 721–730 (1987).
8. Dietrich, K. N., Succop, P. A., Bornschein, R. L., Krafft, K. M., Berger, O., Hammond, P. B., and Buncher, C. R. Lead exposure and neurobehavioral development in later infancy. Environ. Health Perspect. 89: 13–19 (1990).
9. Ernhart, C. B., Morrow-Tlucak, M., Marler, M. R., and Wolf, A. W. Low-level lead exposure in the prenatal and early preschool period: early preschool development. Neurotoxicol. Teratol. 9: 259–270 (1987).
10. Roberts, T. M., Hutchinson, T. C., Paciga, J., Chattopadhyay, A., Jervis, R. E., and Van Loon, J. Lead contamination around secondary smelters: estimation of dispersal and accumulation by humans. Science 196: 1–20 (1979).
11. Njiokikjien, C. H., DeRijke, W., Dieker-Van Ophem, A., and Voorhoeve, O. Stabilography as a diagnostic tool in child neurology. Agressologie 17D: 41–48 (1976).
12. Horak, F. B., Shumway-Cook, A., Crowe, T. K., and Black, F. O. Vestibular function and motor proficiency of children with impaired hearing, or with learning disability and motor impairments. Dev. Med. Child Neurol. 30: 64–79 (1988).
13. Bhattacharya, A., Shukla, R., Bornschein, R. L., Dietrich, K. N., and Kopke, J. Postural disequilibrium quantification in children with chronic lead exposure. Neurotoxicology 9(3): 327–340 (1988).
14. Bornschein, R. L., Hammond, P. B., Dietrich, K. N., Succop, P., Krafft, K., Clark, S., Berger, O., Pearson, D., and Que Hee S. The Cincinnati prospective study of low-level lead exposure and its effects on child development: protocol and status report. Environ. Res. 38: 4–18 (1985).
15. Bhattacharya, A., Morgan, R., Shukla, R., Ramakrishanan, H. K., and Wang, L. Noninvasive estimation of afferent inputs for postural stability under low levels of alcohol. Ann. Biomed. Eng. 15(6): 533–550 (1987).
16. SAS User's Guide: Statistics. SAS Institute, Inc., Cary, NC, 1985.
17. Woollacott M. H., Shumway-Cook, A., and Nashner, L. Postural reflexes and aging. In: The Aging Motor System, Vol. 3 (J. Mortimer, Ed.), Praeger Publishing, New York, 1982, pp. 98–119.
18. Overstall, P. W., Exton-Smith, A. M., Imms, F. J., and Johnson, A. L. Falls in the elderly related to postural imbalance. Br. Med. J. 1: 261–264 (1977).
19. Zernicke, R. F., Gregor, R. J., and Cratty, B. J. Balance and visual proprioception in children. J. Hum. Move. Studies 8: 1–13 (1982).
20. Odendrick, P., and Sandstedt, P. Development of postural sway in the normal child. Hum. Neurobiol. 3: 241–244 (1984).
21. Ornitz, E. M., Atwell, C. W., Walter, D. O., Hartmann, E. E., and Kaplan, A. R. The maturation of vestibular nystagmus in infancy and childhood. Acta Otolaryngol. 88: 244–256 (1979).
22. Birren, J. E. Static equilibrium and vestibular function. J. Exp. Psychol. 35: 127–133 (1945).
23. Graybiel, A., and Fregly, A. R. A new quantitative ataxia test battery. Acta Otolaryngol. 61: 292–312 (1966).
24. Fregly, A. R., and Graybiel, A. Labyrinthine defects as shown by ataxia and caloric tests. Acta Otolaryngol. 69: 216–222 (1970).
25. Bawa, P. Neural development in children: a neurophysiological study. Electroencephalogr. Clin. Neurophysiol. 52: 249–256 (1981).