Exposure to Lead by the Oral and the Pulmonary Routes of Children Living in the Vicinity of a Primary Lead Smelter

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Yearly from 1974 to 1978, a medical survey was carried out among 11-year-old children attending schools situated less than 1 and 2.5 km from a lead smelter. Age-matched control children from a rural and urban area were examined at the same time. The blood lead levels (PbB) of the children living in the smelter area (mainly those attending schools located less than 1 km from the smelter) were higher than those of rural and urban children. The mean PbB levels were usually lower in girls than in boys, especially in the smelter area. Despite a slightly decreasing trend in the annual mean airborne lead concentration at less than 1 km (mean PbA: 3.8 μg/m³ in 1974 to 2.3 μg/m³ in 1978) the PbB levels there did not improve, whereas 2.5 km from the plant a significant tendency to normalization of PbB became apparent. Therefore, in the third survey, the medical examination was combined with an environmental study which demonstrated that lead in school-playground dust and in air strongly correlated. Lead on the children’s hands (PbH) was also significantly related to lead in air or lead in dust. Less than 1 km from the factory boys and girls had on the average 436 and 244 μg Pb/hand, respectively, vs 17.0 and 11.4 μg Pb/hand for rural boys and girls, respectively. Partial correlations between PbB, PbA, and PbH indicated that in the smelter area the quantitative contribution of PbA to the children’s PbB is negligible compared to that of PbH. Thus, the control of airborne lead around the lead smelter is not sufficient to prevent excessive exposure of children to environmental lead. In view of the importance of lead transfer from dust and dirt via hands to the gastrointestinal tract remedial actions should be directed simultaneously against the atmospheric emission of lead by the smelter and against the lead particulates deposited on soil, dust, and dirt.

INTRODUCTION

In 1973, several cases of cattle death around a lead smelter in Belgium drew the attention to environmental pollution by heavy metals. The first environmental surveys within 1 km from the smelter demonstrated levels of lead in air, in soil, and in grass which were at least 10 to 100 times the background values currently found in nonpolluted areas of Belgium being for air 0.23 μg Pb/m³ (Janssens and Dams, 1975), for soil <25 μg Pb/g (surface layer), and for grass <15 μg Pb/g (dry matter) (Cottenie et al., 1975). Since 1974, the inhabitants and the environment around the plant were extensively surveyed to estimate the biological effects of lead, particularly on children, to pinpoint the major lead-emitting sources within the plant and to evaluate the effects of various preventive measures.

Our first medical survey in 1974 (Roels et al., 1976) revealed markedly
increased—compared to rural children—lead absorption among 11-year-old children attending schools situated less than 1 and 2.5 km from the lead smelter. The undue lead absorption was accompanied by early biochemical indications of disturbed heme biosynthesis. Eighteen months after major improvements had been introduced in the factory to reduce its lead emission, a second medical survey (Roels et al., 1978) was carried out in the same schools (lead smelter and rural areas) on other groups of children which were comparable with those of the first survey. The continuous air monitoring revealed for the smelter area a decrease in airborne lead, but high lead levels in school-playground dust were found at less than 1 km (3000 to 5000 µg Pb/g) and at 2.5 km (about 400 µg Pb/g) compared to the rural school (about 150 µg Pb/g). By comparison with the results of the first survey, a significant tendency to normalization of PbB was found at 2.5 km, but at less than 1 km the biological parameters (particularly PbB, ALAD, FEP) did not improve.

Two hypotheses have been put forward to explain the lack of significant improvements in the biological parameters of the children living less than 1 km from the lead smelter (Roels et al., 1978; Braux et al., 1978). Ingestion of lead-containing dust and dirt (probably related to hand contamination) from their surroundings may represent, in addition to air, a supplementary source of increased lead accumulation in these children. The alternative explanation is that a continuous resuspension of dust and dirt particles from the highly contaminated soil around the lead smelter may maintain a very high airborne lead concentration at the breathing height of children. This second hypothesis, however, can be ruled out since a subsequent comparative analysis of air lead levels at 1.6 and 4 m above ground level, performed from June 1977 till September 1978 less than 1 km from the plant, demonstrated that the monthly mean air lead levels at 1.6 m were only 10 to 15% higher than those measured at 4 m as usually.

We have therefore attempted to estimate the relative importance of air and dust on the overall exposure to lead of the children nearest to the smelter. Hence, after the second survey, three more medical surveys (1976, 1977, 1978) were carried out among 11-year-old children living in the smelter area as well as in a rural and an urban area. Between each survey airborne lead (PbA) was continuously monitored and, moreover, during the third survey, hand contamination by lead (PbH) was evaluated in order to study the relationships between PbB, PbA, and PbH.

SUBJECTS AND METHODS

Study populations and their environment. Yearly from 1974 to 1978 a biological monitoring survey was carried out among children living in the vicinity of a large lead smelter (annual lead production about 100,000 metric tons). The first (1974) and the fifth (1978) study were performed at the end of spring (May–June), while the second (1975), the third (1976), and the fourth (1977) were conducted in autumn (mainly October). Each time, a control group of age-matched children from a rural area was examined, except during the fourth survey. The third and the fifth survey also included a group of urban children comparable in age to the lead smelter and rural groups. The overall age for the different groups ranged from 9 to 14 years (mean age 11 to 12 years) and the length of residence at the current dwelling place varied from 0.5 to 14 years (mean 7–10 years). The boys and the
girls of the study populations from the lead smelter, the urban (Brussels), and the rural (Herent near Leuven) areas were invariably recruited in the same five schools: one in the urban and rural area and three in the smelter area where two of them (school 1 and 2) are located less than 1 km northeast and the other one 2.5 km east of the plant. A description of the industrialized area and some data reflecting the degree of the environmental pollution (air, soil, grass) around the lead smelter have been published previously (Roels et al., 1976, 1978). Although the lead concentration of suspended particles in the air has been decreasing since 1977, recent studies (Vanderboorthy and Adams, 1978; IHE, 1979) confirmed that the environmental pollution by lead (and even other heavy metals) remains important, particularly within a distance of 1 km from the high stack: indeed, top-soil (0–10 cm) contained about 2000 to 6000 µg Pb/g, grass about 200 to 800 µg Pb/g dry matter, and in the dwelling areas of the children attending schools 1 and 2, the lead content of the atmospheric dust fallout averaged around 16.4 to 22.0 mg Pb/m²/day at 500 m from the high stack, 5.8–7.2 mg Pb/m²/day at 700 m, decreasing to about 2 mg Pb/m²/day at 1000 m and fluctuating around 0.5–1 mg Pb/m²/day at 1.5 km and above. The size distribution of the lead-containing airborne particles in the smelter area demonstrated that particles with a diameter of about 2 µm constituted the most important fraction, while a secondary maximum was found for particles with a diameter between 4 and 8 µm that progressively decreased when the distance to the plant increased from 0.7 to 2.4 km (Degussem et al., 1978). In total, 661 children (328 boys, 333 girls) were examined of whom 214 children (98 boys, 116 girls) attended schools 1 and 2 less than 1 km from the lead smelter, 169 children (115 boys, 54 girls) attended school 3 at 2.5 km from the plant, 55 children (35 boys, 20 girls) lived in the urban and 223 children (80 boys, 143 girls) in the rural area. All the children were in good health and no striking socioeconomic difference was found between the rural, urban, and lead-smelter groups.

Air sampling. Since September 21, 1973, the airborne lead levels 0.7 km (site I) northeast of the 152-m stack have been nearly continuously monitored (IHE, 1977, 1979). The sampler, which is installed on the roof of school 1 at 4 m above the playground, represents the dwelling area of the children attending schools 1 and 2. A second air-sampling station operates 1.2 km (site II) southeast of the high stack and is close to the principal dwelling area of the children attending school 3. By June 21, 1977, a new air sampler 2.5 km east of the high stack was installed 1.6 m above the playground of school 3. However, since the airborne levels at this sampling point were on the average nearly identical with those measured at site II, the air monitoring at 2.5 km was stopped by March 1978. Therefore, the airborne lead concentrations measured at site II were considered also representative for the children attending school 3.

Since June 1977, the air sampling sites I and II were integrated in a network of 13 air-sampling stations operating at different locations within 3.3 km from the high stack. The suspended particles in the air of the smelter zone are collected on Sartorius cellulose nitrate membrane filters (0.45-µm pores) by means of vacuum pumps. The sampling head with the membrane filter is mounted upside down so that the air is aspirated in an upward vertical direction and the filter protected from direct impact of rainfall and atmospheric fallout of heavy particles. About 15
m³ air is aspirated per day (24-hr samples) through the membrane filter and at 0 hr GMT the vacuum pump is automatically connected to a new filter (IHE, 1977). The air sampling in the school of the urban area (10-hr samples) and the analysis of the filters with the collected particles were performed as previously described for the rural area (Roels et al., 1978). Both methods gave similar results as checked by a comparability test in the urban area.

Dust and dirt. Samples of dust and dirt collected on the children’s school playgrounds were analyzed for lead as described previously (Roels et al., 1978). The samples were collected at the time the hand contamination by heavy metals was determined in the course of the third survey.

Contamination of hands. In order to estimate the contamination of the children’s hands by trace metals (lead, cadmium, manganese, arsenic), 500 ml of HNO₃ 0.1 N was poured slowly over the palm of one hand (dominant hand) while the fingers are slightly spread. The diluted nitric acid was collected in a metal-free polyethylene bottle (500 ml) by means of a metal-free polyethylene funnel. After each “hand-rinsing,” the funnel was rinsed with 500 ml HNO₃ 0.1 N. Bottle and funnel blanks were taken in each school before and after the “hand-rinsing” operations which took place in the afternoon (between 2 and 4 PM) on sunny days. The children had not been told before that their hand contamination would be evaluated.

The heavy metal concentrations in the diluted nitric acid “hand-rinsings” were measured by electrothermal atomic absorption spectrophotometry using Perkin-Elmer instruments, Model 305, 360, or 420, equipped with a deuterium background corrector, a HGA-74 or HGA-76B graphite furnace (Perkin-Elmer), and an automatic sampling device Perkin-Elmer Model AS-1 for the injection of 20-μl aliquots. Appropriate dilutions and standard curves in HNO₃ 0.1 N (except for arsenic, see: Buchet et al., 1980) were run and the amounts of the metals are expressed in micrograms per hand.

Blood analysis. A sample of blood was taken from each child by venipuncture using standardized disposable syringes and hypodermic needles free from heavy metal contamination. Aliquots of 5 ml blood were immediately transferred into two heparinized metal-free polyethylene or polystyrene tubes for blood lead analysis and for routine hematological measurements including hematocrit, hemoglobin, and blood cell counts with a Hemalog 8 (Technicon). The remainder of the blood sample was kept in a glass tube to separate serum for determination of its iron level (except first survey). The blood samples were kept at 4°C and all the analyses were performed within 24 hr. From the examination of the hematological data, it could be concluded that none of the children suffered from iron deficiency anemia.

Throughout the five surveys electrothermal atomic absorption spectrophotometric methods were used for blood lead analysis. The blood lead of the children was determined over the whole study period independently by the laboratory of the Ministry of Public Health and our laboratory: the average blood lead levels reported by these laboratories for each population group were very close and usually differed less than 10%. Moreover, they participated regularly in quality control programs organized on national or European scale in order to ascertain their proficiency in measuring blood lead.
Statistical analysis. The statistical difference between subgroups was ascertained by one-way variance analysis. Pearson’s and Spearman’s correlation coefficients were also calculated.

RESULTS

Correlation between Air Lead and Blood Lead: An Indirect Relationship

An overview of the mean airborne and blood lead levels corresponding to the several children population groups examined during the five surveys is presented in Table 1. The reported airborne lead levels are the averages of the monthly mean values observed during the 9 months preceding the first survey and during the time interval between the following surveys. Hence, the PbA values given in Table 1 are somewhat different from the calendar year mean values; this applies particularly to the sampling station located less than 1 km from the lead smelter where mean PbA amounted to 3.79 µg Pb/m³ in 1974, 3.32 µg Pb/m³ in 1975, 3.59 µg Pb/m³ in 1976, 2.84 µg Pb/m³ in 1977, and 2.27 µg Pb/m³ in 1978. Since 1977 the airborne lead concentrations in the dwelling areas of the children attending the school at 2.5 km are comparable with those recorded in the urban school. Most likely due to less motor vehicle traffic in the vicinity of the rural school the airborne lead level there is lower than in the urban school.

Table 1 indicates that the mean PbB level is usually lower in girls than in boys, particularly in the smelter area (the highest individual PbB value recorded was 49 µg/100 ml). Less than 1 km from the lead smelter no improvement in the mean

<table>
<thead>
<tr>
<th>Study populations</th>
<th>Pb~Air (µg/m³)</th>
<th>Total population</th>
<th>Boys</th>
<th>Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n</td>
<td>Mean ± SD</td>
<td>n</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>1 Survey (&lt;1 km)</td>
<td>4.06</td>
<td>37</td>
<td>30.1 ± 5.7</td>
<td>14</td>
</tr>
<tr>
<td>(1974)</td>
<td>Rural</td>
<td>0.29</td>
<td>92</td>
<td>9.4 ± 2.1</td>
</tr>
<tr>
<td>2 Survey (&lt;1 km)</td>
<td>2.94</td>
<td>40</td>
<td>26.4 ± 7.3</td>
<td>19</td>
</tr>
<tr>
<td>(1975)</td>
<td>Rural</td>
<td>0.74</td>
<td>29</td>
<td>13.6 ± 3.3</td>
</tr>
<tr>
<td>3 Survey (&lt;1 km)</td>
<td>3.67</td>
<td>45</td>
<td>9.1 ± 3.1</td>
<td>14</td>
</tr>
<tr>
<td>(1976)</td>
<td>Rural</td>
<td>0.31</td>
<td>18</td>
<td>24.6 ± 8.7</td>
</tr>
<tr>
<td>4 Survey (&lt;1 km)</td>
<td>2.5 km</td>
<td>0.80</td>
<td>40</td>
<td>13.3 ± 4.4</td>
</tr>
<tr>
<td>(1977)</td>
<td>Urban</td>
<td>0.45</td>
<td>26</td>
<td>10.4 ± 2.0</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>0.30</td>
<td>44</td>
<td>9.0 ± 2.0</td>
</tr>
<tr>
<td>5 Survey (&lt;1 km)</td>
<td>2.68</td>
<td>36</td>
<td>27.8 ± 9.3</td>
<td>20</td>
</tr>
<tr>
<td>(1978)</td>
<td>2.5 km</td>
<td>0.54</td>
<td>46</td>
<td>16.0 ± 3.8</td>
</tr>
<tr>
<td></td>
<td>Urban</td>
<td>0.56</td>
<td>29</td>
<td>12.7 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>Rural</td>
<td>0.37</td>
<td>42</td>
<td>10.7 ± 2.8</td>
</tr>
</tbody>
</table>
blood lead concentration was observed throughout the 5-year observation period. On the other hand, the mean PbB levels of the children attending the school 2.5 km from the lead smelter never exceeded 20 μg/100 ml since 1975, although the PbB values were still higher than those measured in the urban and rural schools, particularly for the boys. The two surveys among urban children demonstrated for boys as well as for girls slightly higher PbB values than for the corresponding rural groups. The apparent relationships between the mean blood lead levels (total population, boys, girls) and lead in air are presented in Fig. 1. Similar correlations were obtained whether parametric (Pearson) or nonparametric (Spearman) statistics were used. These results tend to indicate that when Pb-air increases by 1 μg/m³ PbB would increase by approximately 5 μg/100 ml. This figure, however, largely exceeds the fractional contribution of Pb-air to Pb-blood which is estimated in the range 1 to 2 μg Pb/100 g blood per 1 μg Pb/m³ on the basis of experimental and epidemiological results principally obtained on adults (Mahaffey, 1977). According to Chamberlain et al. (1978), there is conflicting evidence as to whether the effect of Pb-air on Pb-blood is greater for children than for adults. Analysis of literature data by these authors points to little difference, although epidemiological studies (Johnson et al., 1975; Tsujiya et al. 1977) suggest a more important effect in children, possibly connected with indirect uptake of lead from other sources correlated with Pb-air. A similar indirect mechanism (probably hygienic) may explain differences observed in blood lead levels between boys and girls (Table 1). Indeed, since boys and girls of 11–12 years old have almost similar respiratory ventilation (Geigy Scientific Tables, 1973) another cause associated with Pb-air must be invoked to explain the greater apparent fractional contribution of Pb-air to Pb-blood in boys than in girls (Fig. 1).

Interrelationships between Pb-Air, Pb-Dust, and Pb-Hand

A simple extrapolation of the relationship found between air lead and blood lead in urban and suburban situations may not be valid in heavily contaminated areas.

![Fig. 1. Apparent relationship between the mean concentrations of lead in blood and lead in air as observed for the distinct groups of 11-year-old children examined from 1974 to 1978.](image-url)
near lead smelters, where fallout of lead and high lead levels in dust may contribute significantly to the overall exposure. Therefore, in order to pinpoint the most important factor contributing to the blood lead of children in the smelter area, an environmental survey (air, dust, lead on hand) coupled with blood lead analysis was carried out in 1976 (Table 1, Fig. 2). The rural air lead level of 0.30 μg/m³ was the lowest of the four geographic areas. The urban air lead concentration amounted to a somewhat higher value of 0.45 μg/m³, whereas 0.80 and 3.67 μg/m³ were measured, respectively, 2.5 km and less than 1 km from the lead smelter. Lead concentration of school-playground dust was similar in the urban and rural area, namely 112 and 114 μg/g, respectively, but was about four times higher in the school at 2.5 km (466 μg/g) and even more than 20 times in the schools less than 1 km (2560 μg/g) from the lead smelter. The average amounts of lead found on the hands of the children from the distinct areas followed the air and dust lead levels characteristic for the children’s environment. Boys were found to have invariably higher amounts of lead (μg(hand) on their hands than girls: the rural school, boys 17.0 μg vs 11.4 μg for girls; the urban school, boys 20.4 μg vs 12.7 μg for girls; the school 2.5 km from the lead smelter,

![Fig. 2. Lead in air, in dust, in blood, and on hand found during the third survey (1976) among 11-year-old children living less than 1 or 2.5 km from the lead smelter, or living in an urban or rural area.](image-url)
boys 62.2 μg vs 20.0 μg for girls; and schools less than 1 km from the lead smelter, boys 436 μg vs 244 μg for girls.

These environmental parameters are interrelated. Lead in dust (PbD) is highly correlated with lead in air \( (r = 0.999, P < 0.001; \text{PbD} = -151.4 + 739.0 \text{PbA}) \). Lead on hand is also significantly related to lead in air or lead in dust showing moreover significantly higher \( (P < 0.001) \) slopes for boys than for girls (Table 2). The multiple regression coefficients of PbH \( \cdot \text{PbA} \cdot \text{PbD} \) are \( R = 0.999 \) and \( R = 0.995 \) for boys and girls, respectively. The higher degree of hand-cleanness in girls than in boys probably results from differences in their everyday activities.

**Interrelationships between Pb–Air, Pb–Hand, and Pb–Blood**

Yankel *et al.* (1977) deduced from a multiple regression analysis that five factors significantly influenced the probability of a child experiencing an excess in blood lead level: (1) ambient air lead concentration, (2) lead concentration of the soil, (3) age of the child, (4) cleanliness of the home, (5) occupation of the parents. In our study, the third factor cannot be considered a variable influencing PbB since children within a definite age range were chosen. The fifth factor is of little importance to our study, since there were no major socioeconomic differences between the various study populations. Only 5 children out of 78 lead-smelter children examined during the third survey had their father employed at the smelter. Their PbB values (11.7, 14.2, 18.0, 18.7, and 30 μg/100 ml, respectively) were in the same range as those of the other children living in the same area. This may be due to the fact that in Belgium, workers are not allowed to return home with their work clothes.

The population of the smelter area was also aware of the environmental lead pollution and was advised since 1973 to avoid consumption of home-grown vegetables and fruit. The drinking water in the four geographical areas did not contain more than 0.05 mg Pb/liter. Taking into account these conditions, the assumption can be made that the PbB level of the children primarily reflects uptake by inhalation of airborne lead and by ingestion of lead from hands contaminated through lead fallout and dust (in our age groups pica did not occur, however, nail-biting and finger-sucking was still frequently observed).

As for lead on hands, the average blood lead levels of the boys in the four distinct geographical areas were also consistently higher than those of the corresponding groups of girls as shown in Table 1 (see third Survey, 1976) and Fig. 2.

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**TABLE 2**

**INTERRELATIONSHIPS BETWEEN LEAD IN DUST (PbD) OR LEAD IN AIR (PbA) AND LEAD ON HAND (PbH) AS FOUND IN THE GROUPS OF BOYS AND GIRLS EXAMINED DURING THE THIRD SURVEY (1976)**

<table>
<thead>
<tr>
<th>Population groups</th>
<th>Number</th>
<th>Correlated parameters*</th>
<th>( r )</th>
<th>( P )</th>
<th>Regression equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boys</td>
<td>4</td>
<td>PbH ( \cdot \text{PbA} )</td>
<td>0.999</td>
<td>&lt;0.001</td>
<td>PbH = -32.1 + 127.2 PbA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PbH ( \cdot \text{PbD} )</td>
<td>0.999</td>
<td>&lt;0.001</td>
<td>PbH = -5.9 + 0.172 PbD</td>
</tr>
<tr>
<td>Girls</td>
<td>4</td>
<td>PbH ( \cdot \text{PbA} )</td>
<td>0.995</td>
<td>&lt;0.005</td>
<td>PbH = -21.8 + 71.8 PbA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PbH ( \cdot \text{PbD} )</td>
<td>0.994</td>
<td>&lt;0.010</td>
<td>PbH = -6.8 + 0.097 PbD</td>
</tr>
</tbody>
</table>

* The parameters are expressed in μg Pb/g for PbD, in μg Pb/m³ for PbA, and in μg Pb/hand for PbH.
For the lead-smelter groups the differences in blood lead between boys and girls were even highly significant ($P < 0.001$ at 2.5 km and $P < 0.005$ at less than 1 km) and paralleled the differences in lead on hand found between boys and girls in each of these two groups. It is interesting to notice that, during the third survey, only the girls at less than 1 km from the plant demonstrated an elevated mean PbB value, whereas the other three groups of girls (at 2.5 km, urban, rural), in spite of a different air lead, exhibited low and similar PbB values. This could be related to their low hand contamination showing relatively small difference among these groups. However, the mean PbB values in the rural and urban boys were clearly different from the mean PbB value found in the boys attending the school 2.5 km from the lead smelter. The quantity of lead on the hands of these boys amounted to about 60 µg/hand and is three times the quantity found for rural or urban boys and for girls attending the same school 2.5 km from the factory. This might suggest that lead ingestion from hand contamination significantly influences blood lead concentration when lead on hand becomes higher than 20 µg/hand. In order to examine the interrelationship between lead in blood, lead in air, and lead on hand we assumed as many other authors a linear relation between PbB and PbA, but a curvilinear relation between PbB and PbH since recent studies on the relation between water lead and blood lead (Lauwerys et al., 1977; Moore et al., 1977) suggest a nonlinear relationship between oral lead intake and blood lead. The multiple regression coefficient of PbB · PbA · log PbH, calculated for the four geographic groups of boys and girls combined ($n = 8$), is highly significant ($R = 0.976$; $P < 0.001$). Standardization for PbA resulted in a still significant partial correlation between PbB and log PbH, whereas the partial correlation coefficient between PbB and PbA becomes insignificant when standardized for log PbH (Table 3). This means that ingestion of lead from lead-contaminated hands is a much more important factor contributing to PbB than does PbA. That the influence of PbA on the relationship PbB · log PbH appears to be very weak in our study populations is emphasized by the fact that the regression equation of the simple correlation between PbB and log PbH (Table 3) has practically a similar slope and intercept as the partial regression equation neglecting the partial contribution of PbA to PbB. According to this finding, it is possible to draw a simple correlation regression line for the relationship PbB · log PbH as calculated for the combined groups ($n = 8$) of boys and girls (Fig. 3).

Of course, due to the fact that PbA strongly correlates with PbH, very significant indirect correlations between PbB and PbA are to be expected for boys ($r = 0.983$, $P < 0.025$) and for girls ($r = 0.995$, $P < 0.005$). However, from the results discussed above, we know that these correlations are primarily due to the influence of PbH on PbB. This leads to an erroneous estimate of the fractional contribution of PbA to PbB as suggested by Fig. 1. Thus, it may not be concluded that in this study PbB is directly related to PbA in terms of a cause and effect relationship.

DISCUSSION

Increased lead concentrations in the ambient air of large cities mostly due to vehicle emissions—and near lead smelters have been the subject of concern because of the possible health effects particularly in children (NAS, 1972; Lin-Fu,
TABLE 3
Relationship between Lead in Blood (PbB), Lead in Air (PbA), and Lead on Hand (PbH) as Found in the Combined (n = 8) Groups of Boys and Girls Examined during the Third Survey (1976)

<table>
<thead>
<tr>
<th>Correlated parameters</th>
<th>Constant parameter</th>
<th>$r$</th>
<th>$P$</th>
<th>Regression equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PbB: PbA</td>
<td>log PbH</td>
<td>0.002</td>
<td>$&gt;0.05$</td>
<td>$\text{PbB} = -4.27 + 11.50 \log \text{PbH}$</td>
</tr>
<tr>
<td>PbB: log PbH</td>
<td>PbA</td>
<td>0.810</td>
<td>$&lt;0.025$</td>
<td>+0.007 PbA$^b$</td>
</tr>
<tr>
<td>PbB log PbH</td>
<td></td>
<td>0.976</td>
<td>$&lt;0.001$</td>
<td>PbB = 4.33 + 11.54 log PbH</td>
</tr>
</tbody>
</table>

$^a$ The parameters are expressed in µg Pb/100 ml for PbB, in µg Pb/m³ for PbA, and in µg Pb/hand for PbH.
$^b$ The partial contribution of PbA to PbB has to be neglected ($r = 0.002$, not significant).

1973, 1975; Roberts et al., 1974a; Landrigan et al., 1975a, 1976; Roels et al., 1976, 1978; Tsuchiya et al., 1977). However, lead in ambient air which increases lead concentration in dust due to fallout has been suspected to cause a considerable enhancement in the daily oral lead intake of children who developed increased blood lead in those areas (NAS, 1972; Sayre et al., 1974; Lepow et al., 1975; Day et al., 1975; Yankel et al., 1977; Roels et al., 1978).

Angle et al. (1974) concluded from an environmental study in Omaha, that blood lead of urban school children, all past the age of pica, showed significant correlations with exterior “fallout” lead, but little or no correlation with air lead. Roberts et al. (1974b) stated that the major route of lead absorption by children living in different areas of Toronto contaminated by secondary lead smelters appeared to be ingestion of dirt and dust rather than inhalation of suspended particles. Around the El Paso ore-smelter it appeared that the more mobile fractions (air, dust) of environmental particulate lead, rather than soil lead, were those most closely associated with human uptake (Landrigan et al., 1975b).

![Fig. 3](image.png)

**Fig. 3.** Relationship between the mean concentration of lead in blood and on hand as observed for the combined ($n = 8$) groups of boys and girls examined during the third survey (1976).
Unlike many North American cities where ingestion of lead-based peeling paint is considered an important cause of excessive lead absorption (Lin-Fu, 1972), in Belgium this kind of lead problem does not exist. Therefore, the present paper deals with environmental lead pollution (air, dust) which in the smelter area is mainly due to airborne lead-containing effluents from the plant (fumes from stack and smelting-ovens, ore dust) and in the other areas to combustion of leaded gasoline.

The study of Yankel et al. (1977) among children near a lead smelter in Kellogg, Idaho, is actually one of the most extensive environmental analysis providing a relationship—based on epidemiological data—to predict blood lead from given air lead concentrations in an environment with excessive lead contamination. PbA (ranging up to 17 μg/m³) and lead in surface soil (up to 7500 ppm) were found to be the most significant factors. Yankel et al. (1977) calculated that the blood lead contribution from a 1 μg Pb/m³ increment of air lead exposure would amount for children to about 1.1–1.4 μg Pb/100 ml blood over a range of ambient air lead exposure of 1 to 5 μg/m³, while lead in soil up to 5000 μg/g would rather weakly influence PbB (cf. also Landrigan et al., 1975b; Barltrop, 1975).

The environmental lead contamination in the surroundings of the Kellogg and our lead smelter seemed to be comparable. Although the lead concentration of air and surface soil around the Kellogg smelter appears to be somewhat higher, particularly for air, we assumed that Yankel's relationship between childhood PbB levels and environmental lead exposure could be applied to our school children. Accordingly, the difference in PbA levels (first survey) between the rural and lead smelter (less than 1 km) areas would predict for the lead smelter children a mean PbB level at the most 5.3 μg/100 ml higher than that of the rural children: for the fifth survey, the PbB enhancement would be no more than 3.3 μg/100 ml. The discrepancy between the predicted PbB value—which would never exceed 15 μg/100 ml—and the measured mean PbB levels of 25 to 30 μg/100 ml strongly suggests an additional pathway of lead intake near the lead smelter. As mentioned above, lead of industrial origin transported home from the workplace is not likely to play an important role. Since pica did not occur in our study populations, it must be inferred that lead particulates deposited by the smelter in the environment are ingested mainly via excessively lead-contaminated hands. This lead exposure mechanism is indirectly supported by the finding that the PbB levels in nine teachers of the schools less than 1 km from the lead smelter were in the normal range (mean ± SD, 18.0 ± 1.3 μg/100 ml; range, 15.1–19.5 μg/100 ml), although significantly higher than those observed in nine teachers of the rural and urban schools (mean ± SD, 12.8 ± 3.3 μg/100 ml; range 8.6–18.4 μg/100 ml). The difference in blood lead between these two groups of adults more or less reflects the difference in air lead as calculated according to Yankel et al. (1977). It seems thus that the principal route of lead absorption differs greatly between children and adults. Our results suggest that inhalation of airborne lead constitutes by far the most important source of a slightly increased PbB in adults from the smelter area. In children of this area, however, a considerably enhanced oral daily intake of lead via soiled hands seems to be the main factor explaining their increased PbB. Indeed, the dose-effect relationship between log PbH and PbB (Table 3)
would—irrespective of PbA—predict for a PbH = 10 µg/hand (like in the rural area) a PbB of about 7.2 µg/100 ml and for a PbH of 50, 100, 500, and 1000 µg/hand PbB of 15.3, 18.8, 26.8, and 30.3 µg/100 ml, respectively. In the present study, the quantitative contribution of PbA to PbB was found to be rather negligible compared to that of PbH. That lead on hands appears to be a useful environmental indicator of the degree of lead ingestion is also supported by the fact that the higher PbH level for boys than for girls are closely reflected in their respective PbB levels, even in the rural and urban areas.

Yankel et al. (1977) considered only in the third place lead containing dust as a possible source of exposure to environmental lead. They observed a fairly weak correlation with PbB (r = 0.21), but this is most likely to be attributed to their less quantitative and rather subjective assessment of cleanliness of the homes simply in terms of clean, moderate, or dusty. Furthermore, the lack of a significant correlation between PbB and the lead concentration in house dust samples obtained from vacuum cleaner bags is not surprising, because it is not the concentration but the absolute amount of lead recovered as dust per surface unit which is related to the cleanliness of the houses. In our present study, we attempted to assess objectively the factor cleanliness related as close as possible to ingestion of environmental lead. This may explain the very strong correlation between blood lead and hand cleanliness which provides a quantitative basis for assessing to what extent lead ingestion from contaminated hands may contribute to blood lead levels in children living around a lead smelter.

CONCLUSION

The overall influence of environmental lead contamination (suspended particles, dust fallout, and pollution of surface soil) on children living around a lead smelter should take into account their physiological characteristics and habits. Therefore, the environmental control strategy should be directed to all routes of exposure bringing about significantly enhanced lead absorption. Measures aiming only at the decrease of airborne lead inhalation would be to a large extent insufficient in the smelter area. Since intake of lead from contaminated hands roughly contributes to the children's PbB by at least with a factor of 2 to 4 more than does air lead, it can be stated that the actual airborne lead concentrations in the smelter area does not represent as much an indicator of exposure as does lead contamination of hands. Therefore, in a lead smelter area, the enforcement of a permissible limit for airborne lead alone may not necessarily prevent an excessive exposure of children to environmental lead, since past emission of lead and possibly direct transfer of lead-containing dirt (e.g., through road transport) will maintain a high level of lead in soil-dust and dirt irrespective of the current concentrations of atmospheric lead.

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REFERENCES


