

Effect of lead exposure from electronic waste on haemoglobin synthesis in children

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Abstract

Background

Primitive electronic waste (e-waste) recycling is ongoing in Guiyu, so toxic heavy metals may continue to threaten the health of children in the area.

Objective

This study aimed to evaluate the effect of e-waste exposure on haemoglobin (Hb) synthesis in preschool children.

Methods

Medical exams were conducted with the consent of children's guardians and the approval of the Shantou University Medical College Ethics Committee. This study recruited 224 and 204 children in 3–6 years old from Guiyu (exposed group) and from a town without e-waste pollution (control group), respectively. Blood levels of lead, Hb, ferritin, folate and vitamin B12 were tested in all children. Furthermore, all children were assessed for thalassemia, and their parents were asked to complete questionnaires.

Results

There was no significant differences in ferritin, folate, or vitamin B12 levels between the exposed and control groups ($P > 0.05$). All children were excluded thalassemia. Blood lead level (BLL) and the rate of children with $BLL \geq 10 \mu\text{g/dL}$ were higher in the exposed group than control group (both $P < 0.01$). Both groups were further divided into three sub-groups according to BLL (Group A: $< 5.0 \mu\text{g/dL}$; Group B: $5.0\text{--}9.9 \mu\text{g/dL}$; Group C: $\geq 10.0 \mu\text{g/dL}$). Hb levels were negatively correlated with BLL in exposed group ($F = 3.52$, $P = 0.03$), but not in control group ($F = 1.98$, $P = 0.14$). Hb levels in group B and group C were significantly lower in exposed group than in control group (Group B, $P = 0.01$; Group C, $P = 0.03$). In addition, the prevalence of anaemia in children with lead poisoning in exposed group were significantly higher than those in control group (4.0% versus 0.5%, $P < 0.05$). The prevalence of anaemia in children without lead poisoning and without iron deficiency in exposed group were also higher than those in control group (6.5% versus 2.0%, $P < 0.05$).

Conclusion

Lead exposure significantly inhibits Hb synthesis in children living in e-waste dismantling areas compared to those living in non-e-waste dismantling areas. Other toxins released from e-waste may also contribute to the inhibition of Hb synthesis and may lead to anaemia in local children. Further investigations are needed to provide evidence for the development of relevant protective measures.

Introduction

Childhood is a period of rapid growth and development of all the organs and systems of the body. In addition to genetic factors that may lead to disorders of the blood system, the lack of various haematopoietic substances, such as dietary nutrients, proteins, and vitamins, can seriously impact it. Haemoglobin synthesis requires the coordinated production of haeme and globin. Haeme is the prosthetic group that mediates reversible binding of oxygen by haemoglobin. Globin is the protein that surrounds and protects the haeme molecule. Haeme or globin synthesis disorders can cause haemoglobin synthesis to decline. Moreover, the toxic effects of harmful environmental substances may inhibit the synthesis of normal haemoglobin (Hb) in children and even lead to anaemia. Anaemia not only affects children's physical and mental

development but also makes children susceptible to some diseases that can pose a great threat to their health and even endanger their lives. According to a survey of anaemia in Guangdong, China, the prevalence of anaemia among children aged 3–6 years in underdeveloped rural areas in Guangdong is 10.73% [1]. There are many causes of anaemia in children. The common causes are iron deficiency, nutritional megaloblastic and thalassemia.

Except for the most common causes of anaemia in children, lead is recognized as one of the main environmental toxins that has the ability to inhibit Hb synthesis. The mechanism for this inhibition is as follows: lead can inhibit aminoethyl propionate dehydrase (ALAD), which hinders the conversion of aminoethyl propionate (ALA) into protoporphyrin and reduces Hb synthesis. In addition, lead can inhibit iron-chelating enzymes and prevent protoporphyrin and divalent iron from synthesizing haeme. Under the influence of lead, the conformation of Hb changes, and the sensitivity of Hb to proteolytic enzymes increases, thus accelerating its decomposition [2, 3].

Guiyu, Guangdong Province, known as the “World Electronic Waste Disposal Station,” has a greater than 20-year history of e-waste recycling. Every year, this town disposes of millions of tons of e-waste, electrical appliances, and plastics from various countries, such as the United States, Germany, Japan, and Korea. Local workers use simple and rudimentary disassembly methods to handle waste, such as combustion and acid washing. Without any further treatment, acid washing wastewater that has heavy metal concentrations seriously exceeding the standards is then discharged into nearby streams, which are often used for irrigation or even drunk directly by local residents. The leftover waste is incinerated. It is difficult to completely break down e-waste; hence, toxic substances, such as lead, cadmium, polychlorinated biphenyls, carbon chloride and brominated flame retardants, inevitably persist in the environment as well as in vivo [4, 5]. Long-term lead-containing food intake and environmental exposure to excessive lead can cause lead poisoning. Studies have shown that lead exposure in Guiyu had detrimental effects on the skeletal growth and neurobehavioural development of local children [6, 7]. Moreover, lead poisoning and other heavy metal poisoning are important factors leading to anaemia in children.

There are some reports related to lead exposure and anaemia. A study showed that blood lead and blood cadmium had an effect on Hb level. Blood lead and blood cadmium may interact with Hb [8]. Kutllövci-Zogaj et al used Spearman correlation analysis to analyse the relationship between BLL and Hb level in children in Mitrovica and found that there was a moderate correlation between BLL and Hb level [9]. However, previous studies did not exclude the influence of common nutritional and genetic factors in the impact of lead exposure on Hb. It is well known that nutrition and some genetic factors have a great influence on the haemoglobin of preschool children. Hence, we conducted an investigation to address the issue of e-waste and its potential effects on Hb synthesis in children on the premise of excluding common nutritional and genetic factors.

Methods

Study population

This cross-sectional study included 222 children (boys: 126; girls: 96) aged 3–6 years from two kindergartens in Guiyu, an e-waste disposal area (exposed group). In addition, 204 children (boys: 112; girls: 92) aged 3–6 years were recruited from three kindergartens in the Haojiang District (mainly engaged in agriculture and fishery, approximately 50 km from Guiyu) (control group) in 2014. This district does not conduct e-waste disassembly operations. All participants fulfilled the inclusion criteria as determined by a questionnaire survey and laboratory tests: (1) they lived in the study area for at least 3 years; (2) they had no serious haematological system disease in the past, such as aplastic anaemia and leukaemia; (3) they had no history of taking iron, folic acid or vitamin B₁₂ in the past three months; and (4) thalassemia was excluded by Hb electrophoresis screening. Medical examinations were conducted with the permission of the children’s guardians and the approval of the Ethics Committee of the Medical College of Shantou University.

Sample collection and biochemical measurements

Care was taken to ensure that the venepuncture sites (routinely the back of the child’s hand) were completely sterilized, and 5 ml of venous blood was collected by a professional nurse. One millilitre of whole blood was immediately tested for Hb by

the Hb cyanide (HiCN) method. One millilitre of whole blood was centrifuged at 5000 rpm for 5 min for Hb electrophoresis screening. Serum was obtained from two millilitre of whole blood and centrifuged at 3000 rpm for 15 min to determine ferritin, folic acid and vitamin B₁₂ levels. Hb level was measured using an automatic LH-780 haematology analyser (Beckmann, Germany). Hb electrophoresis was done using agarose gel zone electrophoresis (PN1210 electrophoresis apparatus, Sevilla, France). Ferritin, folic acid, and vitamin 12 levels were determined via chemiluminescence (Advia Centaur XP automatic immunoassay of Siemens, Germany). Because children in both areas did not get their blood drawn at the same time, to reduce the detection error, the remaining 1 ml of blood was placed in a 2-ml vacuum blood vessel containing EDTA (40 U) anticoagulant, and each blood sample was stored at -20 °C to detect the BLL. The blood collection and sample management processes were carried out by professional staff, and all laboratory indicators adhered to standard reference materials.

Measurement of BLLs

Before analyses, 100 µL of sampled blood was added to 900 µl of 0.5% nitric acid. This was then vortexed and digested at room temperature for 10 min. The resulting mixture was then used for the determination of lead levels.

Lead levels were determined using graphite furnace atomic absorption spectrophotometry (Jena Zenit 650, Germany), which was done with an autosampler (MPE60) with an injection volume set at 20 µL. The main parameters used for the detection of lead levels were a wavelength of 283.3 nm; a lamp current of 4.0 mA; a slit width of 0.8 nm; drying at 90 °C, 105 °C, and 120 °C; ashing at 600 °C; and atomization at 1500 °C. The standard calibration curve was plotted using the six working standard solutions, which were prepared from a stock lead standard solution diluted with nitric acid, to which a matrix modifier mixed with human blood was added. The linear correlation coefficient of the lead standard calibration curve was 0.9920. The accuracy of the method was controlled by the use of recoveries between 96% and 108% [10].

Diagnostic criteria

(1) Anaemia [11]: According to the World Health Organization/UNICEF 2001 standard, anaemia is represented by Hb under 110 g/L in those aged 6 months to 59 months or a Hb less than 115 g/L (level) in those aged between 6 and 11 years old.

(2) Lead poisoning [12]: According to American disease control standards, Lead poisoning is defined as a BLL of > 10 µg/L.

(3) Iron deficiency [13]: A ferritin level of < 16 µg/L indicates iron deficiency.

(4) Thalassemia [14]: Beta-thalassemia occurs when HBA2 is > 3.5%. Alpha poverty is diagnosed when HBA2 is < 2.5% or via abnormal HBH (HBBART) .

Questionnaire investigation

The parents of the children examined were asked to complete a questionnaire regarding the socio-demographic characteristics of the children. The contents of the questionnaire mainly included the child's birthplace, health status, surroundings, family economic conditions, and parental education level. Three classifications of total family income were defined according to the following levels: <1999 Chinese *yuan* (333.2 US *dollars*, 1.0 US *dollar* ≈ 6.0 Chinese *yuan* in 2014) per month equated to low income, 2000–4999 Chinese *yuan* (333.3–833.2 US *dollars*) per month equated to middle income, and 5,000 Chinese *yuan* (833.3 US *dollar*) per month equated to high-income families.

Statistical analysis

Data entry and statistical analysis were performed using SPSS 15.0 (SPSS Inc., Chicago, IL, USA). Data distribution was tested for normality with the Kolmogorov–Smirnov test. Hb level was normally distributed, and BLL, folate, vitamin B₁₂ and general characteristics were skewed. Data are expressed as arithmetic mean ± standard deviation (SD), median (25th–75th percentile), or number (percentage), depending on their distribution. Comparisons between two independent samples were performed using the t test or Mann-Whitney U *test*. Three subgroups were created according to BLL (Group A: <5.0 µg/dL; Group B: 5.0–9.9 µg/dL; Group C: ≥10.0 µg/dL) and compared by using one-way ANOVA. Categorical data were compared using the χ² test. The significance level was P < 0.05.

Results

General Characteristics and Nutritional Status of Children in the Two Towns

The general characteristics (including age, sex, family economic condition and parental education level) and nutritional status (including ferritin, folate and vitamin B₁₂) of the children in two towns are shown in Table 1. There was no significant difference in age, sex, family income, or parents' education level between the two study groups ($P > 0.05$). All children were excluded from thalassemia by Hb electrophoresis. There was no significant difference between groups in the level of ferritin, folic acid, or vitamin B₁₂ in children with anaemia ($P > 0.05$).

Table 1
Comparison of overall characteristics and nutritional status of the children in the two towns

	Exposed group (N = 222)	Control group (N = 204)	P value
Age in months	61.8 ± 9.0	60.0 ± 10.2	0.07 ^a
Boys, n (%)	126(56.8)	112(54.9)	0.70 ^c
Family income more than 2000 yuan per month, n(%)	136(61.3)	128(62.7)	0.29 ^c
Fathers with education level of senior high school and above, n(%)	166(74.8)	160(78.4)	0.37 ^c
Mothers with education level of senior high school and above, n(%)	180(81.1)	170(83.3)	0.54 ^c
Ferritin, µg/L	49.9(35.1–68.4)	49.7(36.1–66.2)	0.87 ^b
Folate, ng/mL	7.3(5.4–10.0)	8.8(6.8–11.2)	0.98 ^b
Vitamin B ₁₂ , pg/mL	720.0(577.0-851.3)	645.0(491.0-824.0)	0.06 ^b
Values are arithmetic mean ± SD, median (25th-75th percentile) and number (percentage)			

a P value calculated by t test

b P value calculated by the Mann-Whitney U test

c P value calculated using the χ^2 test

Unit measurement: 1 mg/L = 1000 µg/L (µg/L - microgram/litre); 1 mg/mL = 1000000 ng/mL (ng/ml - nanogram/millilitre); 0.001 ng/ml = 1 pg/mL (picogram/millilitre).

BLLs of Children in the Two Towns

There was a significant difference in BLL between the two groups. The average BLL in the exposed group was higher than in the control group ($P < 0.01$). In addition, the rate of children with lead poisoning in the exposed group was significantly higher than that in the control group ($P < 0.01$). The data are shown in Table 2.

Table 2
Comparison of the average BLLs and rate of lead poisoning between groups

	BLLs, µg/dL					Lead poisoning (BLLs ≥ 10.0 µg/dL)			
	N	median	25th-75th percentile	Z value	P value	n	rate(%)	χ ² value	P value
Exposed group	222	8.5	6.6–10.9	-8.71	0.00 ^a	74	33.3	19.99	0.00 ^b
Control group	204	6.0	4.8–7.9			30	14.7		

The rate (%) of lead poisoning was equivalent to the number of children with blood lead ≥ 10.0 µg/dL/the total number of children in each group.

^a P value calculated by the Mann-Whitney U test

^b P value calculated using the χ² test

Effects of Different Doses of BLLs on Hb Concentration in the Two Towns

The study participants were divided into three subgroups on the basis of their BLLs, including Group A (BLL < 5.0 µg/dL), Group B (BLL 5.0–9.9 µg/dL), and Group C (BLL ≥ 10.0 µg/dL). Table 3 shows that there was no significant difference in the Hb levels between the three subgroups of the control group ($P > 0.05$). However, a significant difference was observed in the Hb levels between the three subgroups of the exposed group by one-way ANOVA, with a tendency for a decrease in Hb level with rising BLL in the exposed group ($F = 3.52$, $P = 0.03$) but not in the control group ($T = 1.98$, $P = 0.14$). In addition, the Hb levels of group B and group C were also significantly lower in the exposed group than in the control group (Group B: 122.6 ± 9.5 g/L versus 125.8 ± 8.2 g/L, $P = 0.01$; Group C: 120.3 ± 7.3 g/L versus 123.6 ± 8.3 g/L, $P = 0.03$).

Table 3
Effects of BLL on Hb concentration in the two towns

BLLs	Exposed group (N = 222)			Control group (N = 204)			
	n	Hb (± s, g/L)		n	Hb (± s, g/L)	T value	P value ^a
≤ 5.0 µg/dL (Group A)	33	124.9 ± 8.2		62	126.9 ± 8.5	-1.140	0.26
5.0–9.9 µg/dL (Group B)	115	122.6 ± 9.5		112	125.8 ± 8.2	-2.535	0.01
≥ 10.0 µg/dL (Group C)	74	120.3 ± 7.3		30	123.6 ± 8.3	-2.262	0.03
F value		3.52			1.98		
P value ^b		0.03			0.14		
a P value calculated by t test							

^b P value calculated by one-way ANOVA

Comparison of Influencing Factors of Anaemia among Children in the Two Towns

As shown in Table 4, the prevalence of anaemia associated with lead poisoning was significantly higher in the exposed group than in the control group (4.0% vs. 0.5%, $P < 0.05$). There was no significant difference between the exposed group and the control group in the prevalence of anaemia associated with iron deficiency (2.3% vs. 2.9%, $P > 0.05$). Furthermore, the prevalence of anaemia in children without lead poisoning and without iron deficiency in the exposed group was also higher than that in the control group (6.5% vs. 2.0%, $P < 0.05$).

Table 4
Analysis of influencing factors of anaemia in children in an e-waste dismantling area

	Anaemia ^a in Exposed group (N = 222)		Anaemia ^a in Control group (N = 204)		χ^2 value	P value
	n	%	n	%		
Lead poisoning ^b	9	4.0	1	0.5	4.44	0.04
Iron deficiency ^c	5	2.3	6	2.9	0.20	0.65
Non-lead poisoning and non-iron deficiency	14	6.5	4	2.0	4.96	0.03
^a Haemoglobin (Hb) < 11.0 g/dL for children between 6 months and 59 months and Hb < 11.5 g/dL for children between 6 and 11 years old.						
^b BLL \geq 10 mg/dL						
^c Ferritin level < 16 ng/mL						

Discussion

Worldwide, the main reason for decreased Hb synthesis in children is iron deficiency [15]. Other causes include folic acid and/or vitamin B₁₂ deficiency and thalassemia [16]. In order to explore the effect of e-waste pollution on Hb synthesis in children, it is necessary to exclude these common nutritional and genetic factors. Out of this concern, normal levels of ferritin, folic acid, and vitamin B₁₂ were required for our study, and there was no significant discrepancy in these levels between groups ($P > 0.05$). There is a relatively high incidence of thalassemia in Guangdong Province, as one study found an incidence of approximately 8.53% [17]. In order to exclude any effect of thalassemia, we confirmed that no children who participated in our study had thalassemia by Hb electrophoresis screening.

It was necessary to understand the general characteristics (including social demography and cultural information) and nutritional status of children in the two regions. Families with higher maternal education may have better economic resources or engage in behaviours protective of child health, such as iron supplementation. The results showed that there was no significant difference in age, sex, family income, or parents' education level distribution between the two study groups ($P > 0.05$). This means that families in both places were unlikely to have differences in the rate of insufficient dietary intake due to economic difficulties.

As shown in Table 2, the average BLL in the exposed group was higher than that in the control group ($P < 0.01$). In addition, the rate of children with lead poisoning in the exposed group was significantly higher than that in the control group ($P < 0.01$). These results indicate that e-waste pollution had an impact on BLL in the study population. Whether lead can inhibit Hb synthesis is closely related to the child's lead load level. Research by Chen and Kutllovci-Zogaj showed that blood lead could interfere with Hb synthesis [8, 9]. The United States Centers for Disease Control (CDC) has recommended that BLL can be used for the assessment of the lead load in the body and the degree of lead poisoning. Lead poisoning has been classified as mild, moderate, or severe at BLLs of 10–19.9 $\mu\text{g/dL}$, 20–44.9 $\mu\text{g/dL}$, and 45.0–69.9 $\mu\text{g/dL}$, respectively [18]. At present, a BLL of 20–40 $\mu\text{g/dL}$ is considered the critical range at which normal Hb synthesis is affected. When the BLL is 40–60 $\mu\text{g/dL}$ or $> 60 \mu\text{g/dL}$, Hb synthesis will be inhibited, and there is an 18–40% probability of anaemia at the two former levels [19]. In this

study (Table 2), the majority of the children in both the exposed and the control groups had BLLs of less than 20 µg/dL. This indicates that low blood lead concentrations may also inhibit Hb synthesis. According to the NHANES III survey in the United States, Hb synthesis can begin to be inhibited even at a BLL of 5.0–9.9 µg/dL [20]. Data suggested that lead-induced anaemia is mediated by the inhibition of Hb synthesis [21].

This study showed that Hb levels in the exposed group decreased significantly with increasing blood lead load, but not in the control group (Table 3). Moreover, the prevalence of anaemia in children with lead poisoning in the exposed group was significantly higher than that in the control group (Table 4). This indicated that lead exposure in Guiyu is different from that in the non-e-waste disposal area, and there may be coexisting factors that enhance lead blood toxicity. In addition to lead, e-waste contains more than 700 substances, 50% of which may endanger human health, such as cadmium, mercury, hexavalent chromium, polyethylene, polystyrene, brominated flame retardants and surface coatings [22]. It has been reported that 58 kg of mercury, 24.6 kg of cadmium 340.5 kg of arsenic, and several other substances can be separated from 1 ton of randomly collected electronic cards [23]. These toxic substances may interact with lead or cause lead to inhibit Hb more strongly than when acting alone.

Studies have shown that lead can occupy iron ion sites in the intestinal mucosa or haematological system, thus increasing the absorption or reducing the excretion of lead. Therefore, with the increase in lead load in children, iron content will correspondingly decrease, which can lead to an increase in the incidence of iron deficiency anaemia [24, 25]. Unexpectedly, there was no significant difference in the incidence of iron deficiency anaemia between the exposed group and the control group ($P = 0.65$). The possible reasons might be that few children had BLLs > 20 µg/dL, and normal ferritin status does not necessarily indicate iron sufficiency because ferritin is an acute-phase reactant and may be elevated by infection or inflammatory disease [26]. Thus, some iron-deficient children may have been misclassified as iron-replete on the basis of ferritin level, which would bias the data.

This investigation also showed that the rates of non-lead-poisoning and non-iron-deficiency anaemia in the exposed group were significantly higher than those in the control group ($P = 0.03$). This finding suggests that toxic substances in e-waste besides lead may inhibit Hb synthesis and contribute to anaemia pathogenesis. Our previous study in this investigation group showed that there was a negative correlation between blood cadmium and Hb level in children in Guiyu [10], which is consistent with other findings that the Hb level in the high-cadmium group was lower than that in the low-cadmium group [27]. Other substances contained in e-waste, such as aluminium and benzene derivatives, have also been reported to inhibit Hb synthesis [28, 29, 30]. In terms of heavy metals only, the analysis of river water samples and river sediments collected in Guiyu showed that these had high contents of silver, chromium, mercury nickel, copper, lead, zinc and other heavy metals. Chromium, mercury nickel, copper, lead, zinc and other heavy metals have common target organs and molecular targets, such as affecting the haematopoietic system of bone marrow, which would result in anaemia. There are often interactions between metals due to their similar chemical properties [31]. Therefore, further study of the effects of other heavy metals on anaemia in children is required.

In conclusion, lead exposure (excluding the effects of common nutritional factors and thalassemia) more significantly inhibits Hb synthesis in children who live in e-waste dismantling areas than in those who live in non-e-waste dismantling areas. Other toxins released from e-waste may also contribute to the inhibition of Hb synthesis and may even lead to anaemia in local children. Further investigations are needed to provide evidence for the development of relevant protective measures.

Abbreviations

E-waste: Electronic waste; Hb: Haemoglobin; BLL: Blood lead level; ALAD: Aminoethyl propionate dehydrase; ALA: Aminoethyl propionate; SD: standard deviation.

Declarations

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

Hongwu Wang and Ruibiao Zhang participated in inputting data, conducting statistical analysis, and drafting the manuscript. Peng Huang and Li Zeng helped to test blood samples for biological indicators. Xueyong Feng and Qiulin Tang helped to arrange the medical examination on the study participants. Sixi Liu and Feiqiu Wen helped to revised the manuscript. Yufeng Liu, Tianyou Wang and Lian Ma conceived the overall study design. All authors have approved the manuscript as submitted.

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