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RESEARCH ARTICLE

Lead exposure from households and school settings: influence of diet on blood lead levels

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Abstract

Lead is known as a potent toxicant to human health, particularly for children while their central nervous system is developing. The aim of this study was to investigate the associations between blood lead levels (BLLs) and lead exposure in the children's diet, home, and school environments. A cross-sectional study was conducted with 153 children aged 1–4 years, in four day care centers (DCCs), where a high prevalence of lead exposure was previously found. Lead determination by graphite furnace atomic absorption spectrometry (GF-AAS) was performed for venous blood, drinking water collected in the DCCs, and the 24-h diet ($n = 64$). Environmental screenings were conducted to evaluate lead concentrations in the tableware, buildings, and playground items in all DCCs and children's homes ($n = 18$) by using a field-portable X-ray fluorescence analyzer (FP-XRF). The BLL mean was 2.71 μg dL^{-1}. Means for 24-h lead concentrations in the diet were 1.61 and 2.24 μg kg^{-1} of body weight (BW) in two DCCs. Lead concentrations in the water supply were lower than 2 μg L^{-1}. More than 11% of the DCCs' environmental analyses presented lead concentrations higher than or equal to 1 mg cm^{-2}, as defined by the USEPA. The diet was not found to be a risk factor for lead exposure, but households and DCC settings raised concern. Children's exposure to lead in DCC environments, where they spend the most part of their weekdays, appeared to be relevant.

Keywords Children's health · Lead exposure · Diet and environments · Blood lead levels

- More than 75% of children had a lead ingestion higher than EFSA limits.
- There was no significant correlation found between lead ingestion through the diet and BLL.
- BLL were not associated with the mean of lead found in the household screenings.
- There was a significant correlation found between BLL and lead in DCC screenings.
- Children's exposure to lead in DCC environments appeared to be relevant.

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Introduction

Children's lead (Pb) exposure is a worldwide public health concern. The number of children at risk of lead poisoning in developing countries, such as in Latin America and the Caribbean, is unknown (Olympio et al. 2017). Vulnerability to lead is higher in childhood, not only because of children's habit of putting hands in the mouth often but also because the organs and body systems, which are metal targets, are still developing (Olympio et al. 2009; Turgeon O'Brien et al. 2014; Li et al. 2016; Tamayo y Ortiz et al. 2016). Children may absorb up to five times more Pb than adults or even higher amounts, depending on the nutritional status of some minerals (CDC 2009, 2012).

The main source of Pb exposure for most individuals is through diet (González-Muñoz et al. 2008; Li et al. 2016). Taking into account the overall exposure, diet may contribute to an average of 83% of the metal intake, followed by dust and soil with 15%, and less than 1% by air or water (Li et al. 2016). However, lead may be present in several places in the household items and structure of the buildings such as wall painting, toys, furniture, objects, and old plumbing (EPA 1990). Environmental exposure may pose special importance for children due to habits of eating or imbibing non-nutritional materials (pica-habit) such as paint chips, colored pencils, and toys. With this contact, the quantity of metal present, for example in jewelry and toys, may be taken in through saliva and, in the case of small pieces, ingested. After ingestion, some of the existing metal may be bioavailable, causing harmful effects on children's health (Cui et al. 2015). Lead concentration in the children's blood increases about 0.16 μg dL^{-1} for each 1 μg of lead they ingest (Tamayo y Ortiz et al. 2016).

Some dietary nutrients can interfere with the intestinal absorption process of lead, such as iron and calcium. When iron deficiency is present, lead absorption is increased because they compete for the same gastrointestinal carrier (Shah-Kulkarni et al. 2016). In the presence of calcium, lead has a decreased intake, probably because it also has the same mechanism of absorption. It is estimated that for every 100 mg of calcium increased in the diet, BLLs decrease by 3.8% (Turgeon O'Brien et al. 2014). Appropriate protein ingestion is also related to lower BLLs (Penuela et al. 2006).

Therefore, the environment and diet can be considered relevant lead-exposure sources. Moreover, diet is also a source of important nutrients that may act as a protective factor for lead absorption. This study aims to investigate the association between BLLs and children's lead exposure by diet, school, and household environments.

Material and methods

Subjects

This study was conducted among 1–4-year-old children from four DCCs, two of them located in the East Zone (coded VA and PF) and two in the South Zone (coded NR and PS) of the city of Sao Paulo, where high BLLs had been found in a previous study (Olympio et al. 2018). This study was reviewed and approved by the Ethics Committee of the School of Public Health of the University of Sao Paulo, Brazil (Protocol #1.127.698). The children's parents/guardians were invited to a meeting with the investigators to discuss the potential sources of lead exposure and its health effects. All children whose parents/guardians signed an informed consent form were included in the study. Thus, out of 580 children from the four DCCs, 153 participated in the study.

Blood collection

Phlebotomists with extensive experience in collecting blood from children carried out the blood collections. Venous blood samples (5 mL) were collected from all the study children and were collected in metal-free and heparinized Vacutainer tubes and stored at − 22 °C prior to lead determinations. The blood sampling was performed after the 24-h diet sampling recorded on the same day. The collections were scheduled in advance to be held in the DCCs, at the end of the class period, followed by the parents or caregivers.

Diet sampling

The diet sampling was conducted in a subsample from 64 children attending two DCCs (PF and PS). Daily lead intake from the diet for each child, considering solid foods and drinks, was estimated using a 24-h duplicate plate method, including one weekday. The parents and guardians were instructed to maintain the usual dietary habits of their children and to duplicate the dietary intake as precisely as possible by observing the amounts that the children really ate and drank. The parents and guardians were asked to use household measures, such as a tablespoon, teaspoon, or cupful, to approximate the quantities of children's food ingested. They were also asked to remove the foods' parts that are not normally eaten, such as bones, skin, and seeds, before storing the duplicate food and drink in containers in a refrigerator until the researchers collected the 24-h diet samples. For cooked meals, parents were asked to make a similar plate, with the same portion of the children's plates, and wait until the children finish the meal and then to add or remove comparable amounts of food from the duplicate plate.

The same protocol was accomplished at the DCCs, and the investigators, who monitored the children during the whole day, recorded the portions. After a duplicate sample for an individual child had been collected, it was transported to the laboratory and thoroughly homogenized using a homogenizer (Arno model 600W, Sao Paulo, SP, Brazil). The weight was recorded using a weighing scale (Shimadzu, Barueri, SP, Brazil). Diets were aliquoted and stored at − 22 °C until the chemical analysis was performed for the lead.

To avoid contamination, all polypropylene flasks used in the collections were previously cleaned with a detergent solution, rinsed in HNO_3 10% overnight, rinsed with deionized water 18.2 MΩ cm at 25 °C, dried, and stored in a closed polypropylene container. High-purity water produced by a Milli-Q water purification system (Millipore, Bedford, MA) was used throughout. A sub-boiling system (Distilled, Berghof, Germany) was employed to produce high-purity nitric acid.

Drinking water sampling

The first drinking water of the day from the DCCs was collected from the DCCs' kitchens on the same day as the diet sampling. The water samples were stored in a decontaminated plastic container at 4 °C until the lead determinations were made.

Sample preparation for chemical analyses

All the sample preparation procedures were conducted in a clean room (ISO 8 Class, Vidy, Brazil) to avoid contamination from the air. The reagents were of analytical grade. Each matrix required different sample preparation: the blood samples were emulsified, the diets were digested, and the drinking water did not need any previous treatment.

The blood emulsions were prepared with 500 μL of blood, 3 mL of a solution containing Triton X-100™ 0.2%, and nitric acid 5%. The resulting emulsion was submitted to ultrasonic agitation for 30 min. The diet samples were previously dried by lyophilization (Thermo Fischer Scientific, USA) up to constant mass. After, 1 g of each one was separately digested with a solution containing 0.3 g Triton X-100™, 2.0 mL of hydrogen peroxide (30%), and 28 mL of nitric acid (40%) in a water bath, using closed vessels. The heating program for the water bath involved two steps: (i) 70 °C for 30 min and (ii) 120 °C for 4 h.

Lead determination

All samples (blood, diet, and drinking water) were analyzed by graphite furnace atomic absorption spectrometry (GF-AAS), model Varian GTA120 AA 240FS. It used a lead hallow cathode lamp at 217.0 nm, slit at 1.0 nm, current at 15 mA, automatic autosampler (which introduces 20 μL of samples or standards), and deuterium lamp background correction. The heating program was used as recommended elsewhere (Luz et al. 2013). All the measurements were made in triplicate.

Accuracy of the lead determination methods was checked during the sample analysis, using a calibration curve with the traceable lead reference solution and certified reference materials: TORT-3: Lobster Hepatopancreas from the National Research Council (NRC) for the diet analysis and Seronorm Trace Elements Whole Blood L-2 from Sero for the blood analysis. Recovery means were about 100%, with relative standard deviations lower than 5%.

Environmental screenings

Environmental screenings were conducted from July 2015 to April 2016 to evaluate lead concentrations in all DCC buildings ($n = 4$), playgrounds, and individual toys, and in household items from homes ($n = 18$) that the parents and guardians accepted to receive the investigators' visit. A field-portable X-ray fluorescence spectrometer (FP-XRF) was used for the screenings, in lead-paint-mode (Innov-X System™). This equipment detects the presence of metals in different materials and, according to their levels of detection, indicates that the values found are within or higher than the adopted standards. FP-XRF enables short-term analysis without the need to collect samples of the object being analyzed and thus allows more analyses. In residential lead inspections, the Lead Paint Mode method is used to identify lead levels in materials of minimum thickness (i.e., layers of paint). Their concentration values are given in mg cm^{-2}. We considered the values high when lead concentrations in paints were higher than or equal to 1 mg cm^{-2} or 5000 μg g^{-1}, as defined by the US Department of Housing and Urban Development (EPA 1997).

Painted walls, floors, doors, windows, toys, tableware items (plastic plates, glasses, and cutlery used by children), and playgrounds with metallic structures, among others, were analyzed. For 30 s, the XRF was positioned firmly against the area to be measured for lead and the surface was analyzed, in the Lead Paint Mode, by depressing the trigger mechanism. The objects and structures had triplicate analyses in each of measurements performed on different parts. The analysis considered colors, structure, and materials; therefore, multiple analyses were performed if an object was composed by different colors or materials. At the end of the visits (DCCs and children's homes), the data was stored in the device's memory and downloaded to the computer.

Possible sources of exposure in the environment or in the home itself, such as vehicle flow, the presence of factories in the surroundings, type of construction, and recent renovations, among others, were registered on a form, according to a checklist during home visits.

Anthropometric measurements

The children's height was measured by a stadiometer fixed to the wall, and they were weighed on a portable digital scale, model Tec-Black (Techline, China). The height and weight of the child were measured once, without shoes. They also used lightweight clothing, and the heaviest pieces of clothing were taken off at the time of measurement. Body mass index was calculated using the formula of weight height^{-2}.

Statistical analysis

Statistical analyses included one-way ANOVA, Spearman's correlation tests, and multiple logistic regression models. STATA software 13.0 was used. A cutoff point of 3 μg dL^{-1} was adopted for blood lead concentration for all analyses, because neurobehavioral deficits have been associated with this concentration (Chiodo et al. 2004).

Results

Anthropometric characteristics of the children from the two day care centers, whose diets had been collected, are presented in Table 1.

The means of daily lead intake, by DCC and age group, are shown in Table 2. The mean of daily lead intake for the PS DCC was 82.44% higher than the PF DCC for children from 1 to 3 years old and 28.65% lower for the 4-year-old children. Table 3 shows the BLL means and the prevalence of children with BLLs higher than or equal to 3 μg dL^{-1}* and lower than 3 μg dL^{-1} (Chiodo et al. 2004).

Table 4 depicts the total number of analyses and the analyses with values above the USEPA reference (≥ 1.00 mg cm^{-2}), according to each DCC. More than 16% of the structure analyses performed in the NR DCC were above the USEPA reference value (≥ 1.00 mg cm^{-2}), followed by the VA DCC (13.1%), PF DCC (10.2%), and PS DCC (9.8%).

Comparing the mean of BLLs and the mean of lead in the environmental screenings for each DCC, the NR DCC presented the highest mean of BLLs and environmental screening ($p < 0.05$). Similarly, the mean of BLL found in the VA DCC is statistically superior to the PF and PS DCC means (Table 5).

The BLLs found were not associated with lead intake by diet ($p = 0.40$) or with the mean of lead found in the household screenings ($p = 0.15$). However, we found a positive correlation ($r = 0.4631, < 0.0001$) between the concentration of BLLs and the lead found in the environmental screenings in the DCCs, besides a positive association between BLLs and the children's age ($p = 0.02$).

Discussion

To the best of our knowledge, the present study is the first that investigated the dietary exposure to lead, using the 24-h duplicate diet protocol for one weekday in Brazil. Therefore, there are no dietary exposure historical values.

The present study found 78% of children 1–3 years old and 84% of 4-year-olds above the Benchmark Dose Lower Confidence Limit (BMDL) of 0.5 μg kg^{-1} BW^{-1} daily for children established by the European Food and Safety Authority (EFSA) (EFSA 2010). Moreover, 64 children presented BLLs above 3 μg dL^{-1}, a concentration that is already related to neurobehavioral deficits (Chiodo et al. 2004; Olympio et al. 2009).

A mean of 14.66 and 13.88 μg kg^{-1} BW^{-1} of Pb week's intake was found for the 1–3 and 4-year-old age groups, respectively. The Joint FAO/WHO Expert Committee on Food Additives (JECFA) had previously established the Provisional Tolerable Weekly Intake (PTWI) at 25 μg kg^{-1} BW^{-1} per week. However, it was withdrawn. Scientific evidence from epidemiological studies of associations between dietary lead exposure lower than that limit and negative effects such as intelligence quotient (IQ) decrease for children and increased systolic blood pressure for adults led the World Health Organization (WHO) eventually to affirm that there is no tolerable limit for lead intake that could be considered safe for human health (WHO 2011).

Table 1 Anthropometric characteristics of children from two day care centers (coded PS DCC and PF DCC) in Sao Paulo, 2015

	PS DCC		PF DCC		Total	
	Male ($n = 26$) mean ± SD	Female ($n = 15$) mean ± SD	Male ($n = 8$) mean ± SD	Female ($n = 15$) mean ± SD	Male ($n = 34$) mean ± SD	Female ($n = 30$) mean ± SD
Age (year)	3.6 ± 0.6	3.3 ± 0.7	2.6 ± 0.9	3.4 ± 0.7	3.4 ± 0.8	3.4 ± 0.7
Height (cm)	98 ± 7	95 ± 6	93 ± 12	101 ± 6	97 ± 8	98 ± 7
Weight (kg)	17 ± 4	15 ± 2	15 ± 4	17 ± 3	16 ± 4	16 ± 3
BMI (kg/m^2)	17 ± 2	17 ± 1	18 ± 1	16 ± 2	17 ± 2	17 ± 2

BMI body mass index

Table 2 Lead (Pb) daily and weekly intake (μg kg^{-1} bw^{-1}) and percentage of children with the lead intake above the BMDL and PTWI limits, by age group, of children from two day care center in São Paulo, Brazil, 2015

	PS DCC		PF DCC		Total	
	1–3 years mean ± SD (n = 28)	4 years mean ± SD (n = 13)	1–3 years mean ± SD (n = 17)	4 years mean ± SD (n = 6)	1–3 years mean ± SD (n = 45)	4 years mean ± SD (n = 19)
Lead daily intake (μg kg^{-1} $BW^{-1)}$	2.4 ± 2.3	1.9 ± 2.1	1.3 ± 1.4	2.5 ± 1.9	2.0 ± 2.0	2.1 ± 2.0
Pb weekly intake (μg kg^{-1} $BW^{-1)}$	16.7 ± 15.9	13.4 ± 14.9	9.2 ± 10.0	17.3 ± 13.4	13.9 ± 14.30	14.7 ± 14.2
% > BMDL[a]	86	77	65	100	78	84
% > PTWI[b]	18	15	18	17	16	16

[a] EFSA-Benchmark Dose Lower Confidence Limit (BMDL) of 0.5 μg kg^{-1} BW^{-1} daily for Pb for children

[b] Previous and currently withdrawn WHO-Provisional tolerable weekly intake (PTWI) of 25 μg kg^{-1} BW^{-1} per week

A weekly Pb intake value closer than our findings for the 4-year-old age group (Table 2) was found by Wang et al. (2009), who reported values higher than 15 μg kg^{-1} BW^{-1} weekly for Chinese children aged around 3–6 years. A low weekly lead intake (0.84 μg kg^{-1} Pb BW^{-1} week) was reported by Watanabe et al. (2013) in a study conducted with Japanese children aged 3–6 years, a value that is 17 times lower than the mean weekly intake of lead by the 4-year-old children in the present study.

A substantial decrease in the dietary exposure to lead and cadmium (Cd) was reported in Lublin, a city from southeast Poland. The technique of 24-h dietary recall and duplicate analog diets were used in that study, which involved 850 students from three universities. From 2008 to 2010, students from the medical university presented a decrease in weekly intake of Cd (65.19% in females and 70.21% in males), suggesting a diminishing concentration of this element in the environment, and the Cd intake was correlated with the total energy of daily food meals. For lead intake, the decrease of weekly intake was 64.69% for females and 63.64% for males and, similarly to Cd, the study showed that the lead intake was correlated with the total energy of daily food meals and the constant reduction of lead emission in the environment (Marzec et al. 2014).

An adequate intake of essential elements is recommended as a component of intervention in lead toxicity (Ros and Mwanri 2003). The dietary calcium intake influences the susceptibility to lead toxicity (Mahaffey 1995; Sargent 1994), so that a higher calcium intake reduces lead absorption in the intestine (Moreira and Moreira 2004) due to the competition between lead and calcium for attachment to an intestinal transport protein (Ros and Mwanri 2003). A negative association between BLLs and calcium intake was found in a study performed with 245 preschool Inuit children (p = 0.0001) in Nunavik (Quebec, Canada), where the BLL mean was 2.07 μg dL^{-1} (n = 190), lower than our finding (2.71 μg dL^{-1}), and the mean for calcium intake was 896 mg (n = 217) (Turgeon O'Brien et al. 2014).

A study conducted in Korea quantified lead and cadmium in the dietary intake and urine and identified associations between the urine concentration of both elements and the concentration in the dietary intake among 108 children living in urban and rural areas. The 24-h food duplicate and the morning spot urine were analyzed. A negative correlation for cadmium and an insignificant correlation for lead between the dietary intake and the urine concentration of these elements were found. The geometric mean for Cd and Pb in diet duplicate samples were 0.58 and 0.27 μg kg^{-1} BW^{-1} daily, respectively, the latter being seven times lower than our finding for

Table 3 Mean of BLLs according to the day care center, by age, and prevalence of children with BLLs higher than or equal to 3 μg dL^{-1} and lower than 3 μg dL^{-1}, São Paulo, 2015–2016

	PF DCC (n = 23)	PS DCC (n = 41)	VA DCC (n = 60)	NR DCC (n = 29)	Total (n = 153)
1–3 years[a] (mean ± SD)	1.5 ± 1.0	1.8 ± 1.1	3.2 ± 1.7	4.6 ± 0.9	2.9 ± 1.7
4 years (Mean ± SD)	1.7 ± 1.2	1.3 ± 1.4	2.4 ± 0.6	4.0 ± 2.5	2.0 ± 1.3
BLLs ≥ 3 μg dL^{-1*}	9%	17%	43%	100%	42%
BLLs < 3 μg dL^{-1*}	91%	83%	57%	0%	58%

*Chiodo et al. 2004

[a] p = 0.02

Table 4 The total number of analyses and the analyses with values above 1.00 mg cm^{-2}, according to the day care center (DCC), 2015

DCC	Total number of analyses	Number of analyses ≥ 1.00 mg cm^{-2} [a]
VA (East Zone)	329	43
PF (East Zone)	499	51
PS (South Zone)	408	40
NR (South Zone)	257	43

[a] EPA 1997

Pb μg kg^{-1} BW^{-1} daily for the 1–3-year-old age group (Watanabe et al. 2015).

A significant positive correlation between the BLLs and the concentration of lead in the DCC screenings was found in the present study. Other studies have also reported associations between lead paint and children's BLLs (Lanphear et al. 1998; Gulson et al. 2013; Etchevers et al. 2015; Silva et al. 2018). Despite the small number of homes evaluated ($n = 18$), to our knowledge, before the present study, no home structural screening had been performed in Brazil, even for lead, a highly toxic element of worldwide concern.

Environmental screenings to quantify the presence of lead have been performed in different countries (Takaoka et al. 2006; Turner and Solman 2016). One study, aiming to verify the contribution of paint chips to soil lead levels, evaluated 31 public playgrounds in Tokyo and found high lead concentrations in the soil surface (mean = 55.5 mg kg^{-1}). A positive correlation was found between the degrees of peeling of paint on the surface of the public playgrounds with lead concentrations in the soil ($r = 0.366$, $p = 0.043$) (Takaoka et al. 2006). Plymouth, in southwest England, had the exterior paints from public environmental structures, such as railings, gates, telephone kiosks and bridges, and playgrounds, analyzed for lead levels, because 38% of all analyses exceeded the abatement action level established by the US Department of Housing and Urban Development (1990), Environmental Protection Agency (EPA), of 5000 μg g^{-1} or 1 mg cm^{-2} (Turner and Solman 2016). In our study, around 11.9% of all analyses performed in the DCCs showed lead concentrations higher than or equal to those limits defined by the EPA.

Table 5 BLLs means and lead levels found in the day care centers (DCCs) screenings, Sao Paulo, 2015

DCC	Mean ± SD of BLL (μg dL^{-1}) (n)	Median of BLL (μg dL^{-1}) (Min–Max)	Mean of lead in the screening (mg cm^{-2}) (*n*)
VA (East Zone)	3.0 ± 1.5 (60) [a]	2.8 (1.0–88.0)	0.25 (329) [a]
PF (East Zone)	1.5 ± 1.0 (23) [b]	1.7 (0–3.5)	0.24 (499) [a, b]
PS (South Zone)	1.6 ± 1.2 (41) [b]	1.6 (0–4.6)	0.21 (408) [b]
NR (South Zone)	4.5 ± 0.8(29) [c]	4.3 (3.4–7.5)	0.49 (257) [c]

Superscript lowercase letters mean statistically significant differences between schools, considering the same column ($p < 0.0001$)

In Brazil, there is no systematic annual testing of children's BLLs. There is still a lack of information about children's BLLs in many Brazilian states; even the hot spots are not all identified and investigated. Studies conducted in developed countries, such as the Child Blood Lead Surveillance System from the United States, to assess the BLLs in children aged 1 to 2 years, show the importance of early identification of children at risk, allowing potential prevention of neurological damage and behavioral disorders in thousands of children (Raymond et al. 2014).

The Brazilian policy approaches urgently need to be revised, updated, and aligned with contemporary international standards; otherwise, we will continue to overlook the future of our children.

There are some limitations to be considered in the present study. A small number of parents ($n = 18$) agreed to receive the researchers for the environmental screening in their homes. Moreover, because of the deadline of the project, the 24-h duplicate diet was applied for a subsample ($n = 64$) and for only 1 day of the week. This is a good and important point at which to start a list of recommendations for further studies, that is, to consider more sampling days, comparing week and weekend days, to get more representative data on the usual children's diet.

Conclusions

In the present study, diet was not found to be a risk factor for lead exposure, although households' and DCCs' settings raised concern. Children's exposure to lead in DCC environments, where they spend the most part of their weekdays, appeared to be relevant. Thus, public authorities must be alert to acquire lead-free materials for DCCs' painting and maintenance and for the objects offered to children. It is fundamental to pay attention to the maintenance of these DCC structures to prevent children's contact with lead paint fragments, causing accidental ingestion and consequent toxicity. Such a warning should be seriously addressed because the DCC playgrounds were the places with higher lead exposure risks.

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Compliance with ethical standards

This study was reviewed and approved by the Ethics Committee of the School of Public Health of the University of Sao Paulo, Brazil (Protocol #1.127.698).

Conflict of interest The authors declare that they have no conflicts of interest.

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