HHS Public Access

Author manuscript

Pediatrics. Author manuscript; available in PMC 2017 December 01.

Published in final edited form as:

Pediatrics. 2017 August ; 140(2): . doi:10.1542/peds.2017-0272.

Laboratory Measurement Implications of Decreasing Childhood Blood Lead Levels

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Abstract

In 2012, the Centers for Disease Control and Prevention (CDC) adopted its Advisory Committee on Childhood Lead Poisoning Prevention (ACCLPP) recommendation to use a population-based reference value to identify children and environments associated with lead hazards. The current reference value of 5 μg/dL is calculated as the 97.5th percentile of the distribution of blood lead levels (BLL) in children one to five years old from 2007–2010 National Health and Nutrition Examination Survey (NHANES) data. We calculated and updated selected percentiles, including the 97.5th percentile, using NHANES 2011–2014 blood lead data and examined demographic characteristics of children whose blood lead was ≥90th percentile value. The 97.5% percentile BLL of 3.48 μg/dL highlighted analytical laboratory and clinical interpretation challenges of blood lead measurements ≤ 5 μg/dL. Review of five years of results for target blood lead values < 11 μg/dL for U.S. clinical laboratories participating in CDC's voluntary Lead and Multi-Element Proficiency (LAMP) quality assurance program showed 40% unable to quantify and reported a non-detectable result at a target blood lead value of 1.48 μg/dL compared 5.5 % at a target blood lead of 4.60 μg/dL. We describe actions taken at CDC's Environmental Health Laboratory in the

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Conflict of Interest: The authors have no conflicts of interest relevant to this article to disclose.

Disclaimers: The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the Centers for Disease Control and Prevention. Use of trade names and commercial sources is for identification only and does not constitute endorsement by the U.S. Department of Health and Human Services, or the Centers for Disease Control and Prevention.

Contributors' Statements

Drs. Caldwell and Mortensen conceptualized and designed the work, drafted the initial manuscript and made revisions to later drafts, and approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

Dr. Cheng carried out data analysis, assisted in drafting and reviewed and revised the manuscript, and approved the final manuscript as submitted and agrees to ensure that questions related to the accuracy of any part of the work will be investigated and resolved.

Mr. Jarrett, Dr. Makhmudov and Ms. Vance collated and analyzed LAMP data and blood lead data contributed to drafting critically important data summaries and content, reviewed and revised the manuscript, and approved the final manuscript as submitted and agree to be accountable for the work.

Ms. Ward contributed to collation of and analyzed lot screening data, assisted with drafting and reviewed and revised the manuscript, and approved the final manuscript as submitted. Ms. Ward agrees to be accountable for all aspects of the work and will ensure and questions related to the accuracy or integrity of any part will be investigated and resolved.

Dr. Jones consulted on the design of the work and assisted with interpretation of the data, he assisted with the initial draft of the article and he assisted with review and revision of the manuscript, and approved the final manuscript as submitted. Dr. Jones agrees to be accountable for all aspects of the work and will ensure and questions related to the accuracy or integrity of any part will be investigated and resolved.

All authors approved the final manuscript as submitted.

Division of Laboratory Sciences, which measures blood lead for NHANES, to improve analytical accuracy and precision and to reduce external lead contamination during blood collection and analysis.

Introduction

No safe blood lead concentration in children has been identified.[1,2] Lead can affect nearly every system in the body and is especially harmful to the developing central nervous systems of children.[3]. Chronic lead exposure may occur with no obvious symptoms, but it has been associated with developmental delay, sluggishness and fatigue, weight loss, irritability and difficulties learning.[3] In 2012, the Centers for Disease Control and Prevention's Advisory Committee on Childhood Lead Poisoning Prevention (ACCLPP) recommended using a population-based reference value, calculated as the 97.5th percentile of blood lead in children one to five years old in the U.S., instead of a blood lead "level of concern" to identify children and environments associated with lead hazards.[2] Based upon the 2007–2010 National Health and Nutrition Examination Survey (NHANES) blood lead results, the reference value was 5 μg/dL. The ACCLPP recommended that CDC update the reference value every four years using the most recent NHANES blood lead data for children ages one to five years old.[2] CDC concurred or concurred in principle with the ACCLPP recommendations.[4]

Using available NHANES 2011–2014 data, we calculated the 97.5th percentile at 3.48 μg/dL (95% confidence interval, 2.65, 4.29 μg/dL), approximately 30% lower than the current reference value. Our objective is to describe the laboratory implications of a decreasing trend in blood lead concentrations (referred to as blood lead levels, BLLs) in U.S. children and the clinical interpretation challenges that result from the variability of measurement of low BLLs. Because the CDC has not made a final decision about changing the current reference value of 5 μg/dL we refer to a calculated 97.5th percentile rather than a reference value.

The Challenge for Laboratories that Measure Blood Lead

As BLLs in U.S. children have declined over time (see Figure), acceptability criteria for laboratory performance of blood lead analysis in proficiency testing (PT) programs have become more rigorous, requiring laboratories to change processes and technologies. Prior to 1992, PT performance was judged satisfactory if the laboratory reported results for test samples that were within ± 6 μg/dL or ± 15% of the assigned (target) concentration for individual PT samples.[5] The Clinical Laboratory Improvement Amendments (CLIA) of 1988 tightened the acceptability criteria for blood lead measurements to ± 4 μg/dL or ± 10%, whichever is greater.[6] In 2010, the ACCLPP recommended that the criteria be reduced to ± 2 μg/dL or ± 10%, whichever is greater,[2] noting that the majority of laboratories measuring blood lead were already achieving measurement errors of ± 2 μg/dL at these concentrations.[7] However, the acceptability criteria in the CLIA regulations have not been updated.

Measuring ever-lower BLLs required laboratories to shift to newer technologies with lower method limits of detection (LODs) and improved accuracy and precision. Methodology in

the 1970's was based on flame absorption spectroscopy, later followed by methods based on electrothermal atomic absorption spectrometry, and anodic stripping voltammetry. In the 1990s inductively coupled plasma mass spectrometry (ICP-MS) was introduced and newer generations of ICP-MS have even higher sensitivity and lower background levels. These changes in analytical methodology have made it possible for laboratories to achieve lower LODs and make accurate, precise blood lead measurements significantly below 5 μg/dL. Nonetheless, achieving accurate and precise measurements at blood lead concentrations < 5 μg/dL is an analytical challenge using CLIA-exempt instruments (e.g., LeadCare® II analyzer with an LOD of 3.3 μg/dL). In addition to using highly technical measurement methods, such as ICP-MS, special precautions are needed to avoid external lead contamination of the blood collection devices and instrument reagents.

The CDC's Environmental Health Laboratory in the Division of Laboratory Sciences (EHL-DLS) plays an important public health role in blood lead measurement that includes NHANES sample analysis that serve as reference values for U.S. children and adults. Lot screening has been an important activity used by CDC's laboratory to exclude entire lots of items used in blood collection (e.g., butterfly needles, collection tubes, alcohol and iodine wipes) or analytical laboratory materials (e.g., pipette tips, reagents) with unacceptable lead contamination that could result in falsely elevated BLLs. In addition, the CDC's ICP-MS analytical method timing, calibrator placement, calibration regression type, sample introduction system, and reagent composition were optimized for accurate and precise determination of lead in blood at low concentrations. By employing all these measures, the EHL-DLS achieved a blood lead LOD of 0.07 μg/dL for the 2013–2014 NHANES survey period.

As BLLs in U.S. children continue to decrease, more laboratories will need to be able to accurately measure concentrations below their current LODs. To accomplish this, laboratories will need to consider various modifications, including selecting the optimal analytical method as well as testing for lead contamination of laboratory reagents and supplies used in the laboratory (e.g., aliquotting devices, cryovials). Lead contamination also may occur during blood sample collection because of external skin contamination and small amounts of lead in the blood collections materials (e.g., needles, vials, anticoagulants in tubes). Precautions to avoid skin contamination during blood collection are well known to clinicians and clinics that conduct lead testing. However, manufacturers of blood collection devices may need to consider screening devices for even lower levels of lead contamination that interfere with laboratory measurements and take actions to prevent lead contamination during production.

Although each device, reagent, or item that has contact with a child's blood may have only a small amount of lead, these sources are additive to a blood sample throughout the pre-analytical and analytical process. Such contamination may have little impact to measurements of blood lead at values of 10 μg/dL or more; however, the sum of contamination sources may contribute significantly to blood lead measurements near or below the current reference value. It is a principle for blood lead or any analytical measurement that as the measurement approaches the LOD, the variability around the measurement increases significantly.[8] Therefore, as BLLs continue to decline, laboratories

may need to lower their analytical LODs using analytical process improvements, technology changes, or both. We describe several approaches used by the EHL-DLS to improve analytical accuracy, precision, and to reduce lead contamination during blood collection and specimen analysis.

Methods

Data

CDC's National Center for Health Statistics (NCHS) conducts the NHANES. The design is a complex, multistage, probability cluster sample designed to represent the U.S. population based on age, sex, and race/ethnicity.[9] The survey has been continuous since 1999 and is intended to assess the health and nutritional status of the civilian, non-institutionalized U.S. population. Data is collected annually from about 5000 participants annually through interviews, surveys, physical examinations, and clinical specimens. Data are publicly released in 2-year cycles. The NHANES survey incorporates sample population weights to account for the unequal selection probabilities caused by the cluster design, non-response, and planned over-sampling of certain subgroups.[9] The NCHS Ethics Review Board approved all content, and all participants provided signed, informed consent prior to data and specimen collection. Data from NHANES 2011–2014 used for this analysis were from public release files available from the NHANES website. We used blood lead values (in μg/dL) and the following sociodemographic variables: sex; age; race/ethnicity and annual household income. Age categories were 1–2, 3–4, and 5 years; race/ethnicity categories were self-reported as non-Hispanic white, non-Hispanic black, non-Hispanic Asian, and Hispanic, which includes Mexican American and other Hispanic. Annual household income was categorized as < $20,000, $20,000–44,999, and ≥ $45,000.

Lot screening

The EHL-DLS screens a representative sample (usually 50 items) from each manufacturing lot of devices that comes into contact with patient blood during collection, analysis, storage or are used in the laboratory's analytical process for lead measurement. This screening is an essential preliminary step to accurately quantify blood lead as well as other metals. Without screening lots of collection and analytical materials and rejecting materials that are contaminated, there is a risk that one or more of the items could contain an amount of lead that is higher than LOD for the blood lead method. This can result in falsely elevated BLLs. Examples of materials screened include needles, blood tubes (evacuated blood tubes, capillary tubes, cryovial storage tubes), syringes, and lancets. Each device is set up in a manner that mimics the way it is used in the field.

Deionized water is used as the screening solution for blood collection and storage devices that are either composed of stainless steel (needles) or come into contact with the stainless steel containing devices (blood collection tubes). In general, the procedure involves rinsing a pre-determined volume of water through the device, such as a butterfly or a needle. The lead concentration is measured in each collected rinse solution. The procedure is similar for screening laboratory devices used in the analytical process, such as pipette tips and autosampler vials.

A sample of analytical reagents from the same lot are also screened by measuring the lead concentration in a pre-determined aliquot. Screen failure is defined by an equation that is based on the sample volume used, the LOD (e.g., 0.25 μg/dL for blood lead in 2011–2012) and the expected mean concentration in the population (<1 μg/dL for 1–5 year old children).[10] The equation is provided in the Supplemental Information. For each of its projects involving blood lead measurement, the laboratory either provides materials that have been screened or informs its collaborators of the manufacturer lot number that passed screening so that "clean" materials can be purchased.

Blood Lead Measurements

Whole blood specimens were collected by venipuncture using needles, disposable skin wipes, and blood collection tubes with anticoagulant. All collection supplies were lot screened and determined to be free of significant lead contamination. Samples were aliquoted with screened pipettes, and stored at ≤ −20° C until they were shipped on dry ice to the CDC's EHL-DLS, where they were stored frozen (≤ −20° C) and analyzed within three weeks of collection.

Measurements were made[11] using the ELAN® DRC II ICP-MS (PerkinElmer, Waltham, MA) and analysis tubes which had been previously lot screened. The method LOD was 0.25 μg/dL for NHANES 2011–2012 and 0.07 μg/dL for NHANES 2013–2014. The CDC ICP-MS analytical method timing, calibrator placement, calibration regression type, sample introduction system, and reagent composition were optimized for accurate and precise determination of lead at low concentrations in blood.

Lead and Multi-Element Proficiency (LAMP)

LAMP is a voluntary performance and quality assurance program designed to promote high quality whole blood lead, cadmium, mercury, selenium and manganese measurements.[12] Participating laboratories analyze a set of blood samples that CDC prepares using standard reference materials with analytical target values linked to the National Institute of Standards and Technologies Standard Reference Materials. The LAMP program ships three to four samples per challenge, four challenges a year, to the participating laboratories. After analyzing the samples in duplicate on two separate runs, each laboratory reports their results to CDC. CDC compiles the results by analytical method and reports both the laboratory group summary statistics as well as individual laboratory summary results compared to the CDC target value and the laboratory group or consensus means. The blood lead target values ranged from 0.18 to 66 μg/dL for the study period of 2011–2015. To evaluate the accuracy and precision of the participating laboratories for this report, we reviewed results with a target value <11 μg/dL and included only laboratories that were continuously participating since 2011. Approximately 180 laboratories are enrolled in LAMP, and 66 U.S. laboratories (15% academic, 6% federal government, 30% state government, 49% private) have been continuously participating since 2011, missing no more than three rounds during this period. We used an imputed value (LOD/√2) when results were submitted as <LOD. In this report, we evaluated performance in measuring blood lead at concentrations ≤11 μg/dL for the continuously participating laboratories.

Statistical analysis

Percentiles

Percentiles for blood lead in children ages 1–5 years were calculated using SUDAAN version 11.0.0 (Research Triangle Institute, Research Triangle Park, NC, USA). SUDAAN uses sample weights and calculates variance estimates that account for the complex survey design. Confidence intervals for percentiles were adapted from the methods of Korn and Graubard[13] and Woodruff.[14]

Children with BLLs at the 90th Percentile or Higher

Multiple logistic regression analysis was used to examine characteristics of children with BLLs at or above the 90th percentile, chosen to provide a larger sample size relative to the higher percentiles. Analyses were adjusted for sex, age group, race/ethnicity, and annual household income. An alpha (α) level of 0.05 was used to determine statistical significance.

Results

Lot Screening Failures

Because CDC's analytical LOD for lead in whole blood has decreased over time, and BLLs in the U.S. population have decreased over time, lot screening has resulted in more "failures" due to unacceptable lead contamination. Between January 2009 and February 2016, the laboratory screened 359 manufacturing lots of needles, blood collection tubes, cryovials, and other items for lead. The decline in LOD and BLLs in children one to five years old was accompanied by an increase in the percentage of lot screen failures. In NHANES 2009–2010, with a mean blood lead of 1.17 μg/dL and LOD of 0.3 μg/dL, less than 1% of 112 screened lots failed. In 2015, with a blood lead LOD of 0.07 μg/dL, the failure rate was 35% of 85 lots screened (Table 1).

Selected percentiles and 95% confidence intervals of blood lead concentration in children ages one to five years old from the NHANES survey periods 2011–2014 are presented in Table 2., as well as the 50th, 75th, 90th and 97.5th percentiles based on NHANES 2011–2014.

Children with BLLs at the 90th percentile or Higher

Children with BLLs at or above 3.48 μg/dL (97.5th percentile) were more likely to be younger than 3 years, male, of non-Hispanic black race/ethnicity, and reside in low income households (Table 3). However, annual household income less than $20,000 was the only significant predictor for a BLL at or above 3.48 μg/dL (p=0.0056).

Multiple logistic regression results are presented in Table 4. Both age and income were statistically significant. Relative to five year olds, children one to two years and three to four years had a 3.9 and 2.4 times higher risk, respectively, of having a BLL at the 90th percentile or higher. Children in households with annual incomes of <$20,000 and $20,000 - $44,999 had a 9.0 and 4.9 times greater risk, respectively, for having a BLL at the 90th percentile or higher, relative to children from higher income households (≥$45,000 per year).

LAMP

The LAMP challenge results for BLLs < 11 μg/dL are summarized in Table 5a. We found that overall, the participating laboratories had acceptable performance at all concentration challenges. More laboratories were accurate at determining BLLs > 5 μg/dL than at lower concentrations. On average 40% of the values reported by laboratories for samples with low BLLs (≤ 1.48 μg/dL) were reported as below the limit of detection (LOD). At 1.48 μg/dL or lower, no more than 60 % of laboratories reported actual values, and the average mean values (consensus mean) reported by the laboratories over-estimated the BLLs when the target value was <1 μg/dL. This over-estimation is due to imputation of results reported as <LOD, which uses a value of LOD/√2. Using sample ID 1503 (Table 5a) as an example, if a result was reported as <LOD, and the LOD was 3, the adjusted result was 2.1 μg/dL, whereas the target value was 0.18 μg/dL. The relative standard deviations (RSDs), an indicator of measurement precision, are also shown for each challenge sample in Table 5a. The precision of a measurement is directly related to concentration, so a measurement is more precise at a higher lead concentration than at a lower concentration. Consequently, RSDs for the challenge samples increased as the target values decreased. At the lowest BLL challenge sample (0.18 μg/dL), more than half of the laboratories reported results as <LOD. Of the 66 laboratories included in this study 21 (31%) used ICP-MS. At 1.48 μg/dL (a value close to the NHANES 2011–2012 75th percentile) or lower, approximately 50% of the laboratories reported actual values. Conversely, approximately 50% of the laboratories reported results as <LOD. The bias between CDC's target value and the consensus mean was due to the high percent of laboratories reporting < LOD at the low target concentrations.

The distribution of reported LODs for the laboratories that have continuously participated in LAMP from 2011–2015 is shown in Table 5b.

Discussion

BLLs in U.S. children one to five years old have declined (see Figure) to a point that challenges the detection limit of many laboratories. Children with BLLs at or above the 90th or 97.5th percentile for NHANES 2011–2014 have characteristics similar to what has been reported in past studies of risk factors: less than three years old; male; non-Hispanic black; and living in low income households. This suggests that lead-based paint hazards continue to be a source of childhood lead exposure, but we did not have geographic details to determine residence location or housing age.[15] We could not evaluate sources of exposure and contributions from other sources, including contaminated soil, dust, drinking water, and occasional sources such as cosmetics, remedies, hobbies, and occupational take-home. Although the NHANES 2011–2014 sample of one to five year old children was large, the 97.5th percentile and higher was comprised of only 46 children. This contributes to the wide variability around 3.48 μg/dL, with a 95% confidence interval of 2.65 to 4.29 μg/dL. Despite this limitation, NHANES is the best and possibly only data source for U.S. population-based estimates.

BLLs of 5 μg/dL also present a clinical interpretation challenge. Although reported accuracy for most laboratories is ± 2 μg/dL (Parsons et al, 2001), the current CLIA acceptability criteria for accuracy in blood lead measurements of ±4 μg/dL (at values less than 40 μg/dL)

which means that the true value of a blood lead reported as 4 μg/dL can be between 0 and 8 μg/dL. Therefore, when the child is retested, any result between 0 and 8 μg/dL includes the possibility that the true BLL is unchanged. It would be helpful for the clinician to explain to a parent or guardian the concept of variability in the measurement if, for example, a child's BLL goes from 4 to 8 μg/dL in the absence of a new or increased exposure.

Since almost 23% of LAMP-participating laboratories reported LODs between 3 and 5 μg/dL, it is likely that many laboratories will be unable to quantify blood lead at or near the 97.5th percentile value (Table 5b). Forty percent of LAMP- participating laboratories were unable to quantify BLLs at around 1.5 μg/dL, implying that surveillance data collected from clinical laboratories for the general population could be at or below the LODs of many laboratories. So that LAMP participants can improve precision and accuracy of blood lead measurements below 5 μg/dL and to assist laboratories in testing new technology, CDC will include more challenge samples with target blood lead values between 1 and 5 μg/dL in future performance challenges.

Manufacturers of items such as blood collection materials and containers, cryovials, and reagents need increased awareness and to consider actions that avoid potential lead contamination during production of these items. Screening of blood collection devices is not feasible for most laboratories that provide blood lead measurements because they do not typically provide the blood collection materials. The EHL-DLS is finding it increasingly difficult to purchase manufactured lots that pass screening, and we anticipate that the percentage of device and reagent failures is likely to increase unless changes are made in manufacturing processes.

A tightening of the blood lead acceptability criteria in proficiency testing to ±2 μg/dL (≤20 μg/dL) or ± 10% from ±4 μg/dL (≤40 μg/dL) or ± 10% will encourage laboratories to be aware of, and to proactively deal with contamination and measurement issues that often plague the analysis of blood lead at low levels. If laboratories are able to reduce contamination associated with their measurements, the limits of detection should improve. Currently, 33% of U.S. LAMP participating laboratories report a blood lead limit of detection ≥ 2 μg/dL (the 2013–2014 90th percentile for blood lead is 1.8 μg/dL). CDC will assist in reinforcing the need for blood lead laboratories to improvements contamination and measurement issues through the LAMP program. In 2017, LAMP reports will include telling participating laboratories how they would perform if a ±2 μg/dL or ±10% acceptance criteria were used.

Conclusion

The 97.5th percentile BLL based upon NHANES 2011–2014 results in children ages one to five years is 3.48 μg/dL, 30% lower than the current reference value of 5 μg/dL. Although the number of children in the sample that comprised the 97.5th percentile was small, they demonstrated previously identified risk factors for elevated BLLs: younger than three years old; male; non-Hispanic black; and living in low-income households. The continued decrease of BLLs in children presents challenges for clinicians, laboratories, and manufacturers of consumables and analytical instruments. To achieve precise and accurate

blood lead measurements with lower limits of detection, laboratories need to evaluate potential sources of external lead contamination, optimize their analytical methods for low concentration measurements, and participate in external proficiency testing programs, considering how they would perform if tighter acceptability criteria were used.

Manufacturers of devices used in blood lead sample collection could identify potential sources of lead contamination and take actions to reduce these sources. Clinicians should understand the factors affecting accurate measurements at very low blood lead concentrations to better interpret BLLs and assess whether small changes are real or indicate measurement variability.

Acknowledgments

The authors thank the following individuals whose commitment and efforts have produced high quality analytical measurements of blood metals at CDC: Melanie Franklin; Neva (Janie) Mullinix; Denise Tevis; Kristen Wallon; Sina De Leon Salazar; Yi Pan; Reba Williams; Jennifer Ysseldyke; Nolan Hilliard; Yuliya Luzinova Sommer; Cameron Kennelly; Michael Andrews; Brandi Heath; and David Kyle.

Funding source: No external funding.

Financial Disclosure: The authors have no financial relationships relevant to this article to disclose.

Abbreviations

BLL	blood lead level
CDC	Centers for Disease Control and Prevention
CLIA	Clinical Laboratory Improvements Act
EHL-DLS	Environmental Health Laboratory in the Division of Laboratory Sciences
ICP-MS	inductively coupled plasma mass spectrometry
LAMP	Lead and Multi-element Proficiency
LOD	limit of detection
NHANES	National Health and Nutrition Examination Survey
NCHS	National Center for Health Statistics
RSD	relative standard deviation

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Table of Contents Summary

This manuscript is for those pediatricians or health care professionals caring for children to aid in understanding the measurement and clinical interpretation challenges of low blood lead measurements (<5μg/dL).

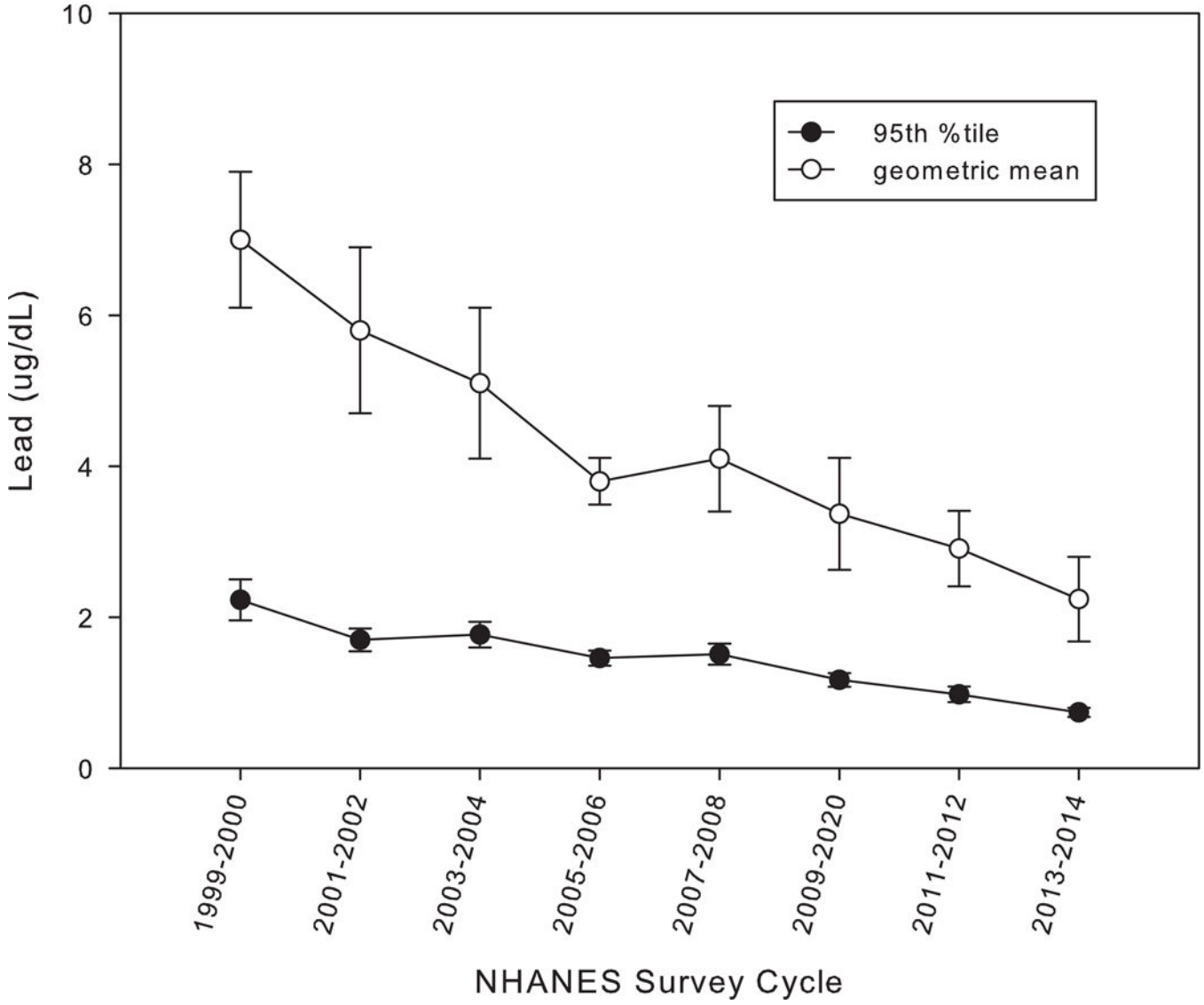

Figure.

NHANES blood (μg/dL) lead geometric mean and 95th percentile by survey cycle. Note the steady decline in the blood lead levels in U.S. children since 1999.

Table 1

Results of manufacturer lot screening (2009–2016) for multiple devices used in blood collection. Relative to the Blood Lead 97.5th Percentile in Children 1–5 Years Old (NHANES 2009–2016)

NHANES Survey years	LOD, in µg/dL	Number Lots Tested for Blood Metals	Number of Lots Failed	Percentage of Failures	Geometric mean (µg/dL) Children 1–5 yrs	97.5th percentile (µg/dL) Children 1–5 yrs
2009–2010	0.3	112	1	0.89%	1.17	4.48
2011–2012	0.25	49	2	4.08%	0.97	3.83
2013–2014	0.07	129	29	22.5%	0.76	2.80
2015–2016 *	0.07	85	30	35.3%	N/A	N/A

* from January 2015-May 2016, not a completed NHANES survey cycle

Table 2

Sample-weighted percentiles of blood lead levels (in μg/dL) for U.S. children (NHANES 2011–2014)

NHANES Survey years	Sample size (n)	Selected Percentiles				
		50th	75th	90th	95th	97.5th
2011–2012						
1–5 Years	713	0.95(0.87–1.04)	1.34(1.2–1.66)	2.26(1.88–2.65)	2.91(2.41–3.83)	3.83(2.53–6.43) *
2013–2014						
1–5 Years	818	0.74(0.68–0.80)	1.08(0.94–1.24)	1.58(1.33–1.90)	2.24(1.68–2.64)	2.80(2.31–3.93) *
2011–2014						
1–5 Years	1531	0.82(0.75–0.89)	1.21(1.09–1.32)	1.90(1.64–2.24)	2.57(2.26–3.05)	3.48(2.65–4.29) *

* n=19, 32, and 46, respectively, for sample sizes for the 97.5th percentile in NHANES 2011–2012, 2013–2014, and 2011–2014.

Table 3

Demographic distributions of the weighted-adjusted proportion (%) of U.S. children with blood lead levels (in μg/dL) at the 97.5th percentile or higher, vs. below the 97.5th percentile (NHANES 2011–2014)

	<97.5th percentile[1]	≥97.5th percentile[1]	P-value[2]
Age (years)			
1–2	38.0 (36.1—39.9)	52.6 (27.8—76.2)	0.0371
3 - 4	43.0 (40.0—46.0)	37.0 (19.3—59.1)	
5	19.0 (16.9—21.3)	10.3 (5.3—19.3)	
Gender			
Male	50.9 (48.3—53.5)	61.7 (37.8—81.1)	0.4299
Female	49.1 (46.5—51.7)	38.3 (18.9—62.3)	
Race/Ethnicity			
All Hispanic	27.4 (21.3—34.5)	13.7 (4.8—33.4)	0.0604
Non-Hispanic Blacks	14.8 (11.2—19.2)	30.9 (10.4—63.3)	
Non-Hispanic Whites	52.8 (44.2—61.2)	52.8 (19.7—83.6)	
Non-Hispanic Asians	5.1 (3.9—6.6)	2.6 (0.4—16.6)	
Annual Household Income			
< $20,000	20.6 (17.3—24.4)	40.8 (30.1—52.4)	0.0056
≥ $20,000	79.4 (75.6—82.7)	59.2 (47.6—69.9)	

[1] Results displayed are the proportion of children and (95% confidence interval).

[2] Chi square test

Table 4

Results of multiple logistic regressions to examine associations between demographics and BLLs at the 90th percentile or higher in children ages 1–5 years, NHANES 2011–2014

Category	≥90 percentile	P-value[1]
Age (years)		
1 -2	3.90 (1.69—8.99)*	0.0053
3 - 4	2.44 (1.44—4.13)	
5	1 (reference)	
Gender		
Male	1.25 (0.82—1.90)	0.2898
Female	1 (reference)	
Race/Ethnicity		
All Hispanic	0.64 (0.32—1.28)	0.141
Non-Hispanic Blacks	1.34 (0.64—2.81)	
Non-Hispanic Whites	1 (reference)	
Non-Hispanic Asians	1.19 (0.47—3.01)	
Annual Household Income		
< $20,000	8.99 (5.05—16.01)	<0.0001
$20,000—$44,999	4.93 (2.71—8.98)	
≥ $45,000	1 (reference)	

[1] odds ratio (95% confidence interval)

Table 5a

LAMP Results for blood lead levels <10 μg/dL reported by continuously-participating U.S. Laboratories (2011–2015)

Sample ID	Target value (±3standard deviations)	N of labs reported results	Accurate within a z-score of ±2, or reported as <LOD	N of labs reported <LOD	% of labs reported results within a z-score of ±2 or reported as <LOD	Consensus mean (standard deviation)	Relative standard deviation (%)
1503	0.18 (0.03–0.33)	46	46	25	100	0.96 (0.81)	84
1402	0.20 (0.00–0.44)	48	48	25	100	0.94 (0.77)	82
1205	0.31 (0.22–0.40)	53	48	20	91	0.86 (0.78)	91
1304	0.34 (0.25–0.43)	52	50	20	96	0.92 (0.78)	85
1210	0.38 (0.35–0.41)	51	51	21	100	0.94 (0.64)	68
1101	0.42 (0.06–0.78)	54	53	18	98	0.85 (0.86)	101
1409	0.45 (0.36–0.54)	45	45	19	100	1.08 (0.76)	70
1212	1.20 (1.14–1.26)	51	50	25	98	1.33 (0.5)	38
1201	1.28 (1.16–1.40)	54	50	25	93	1.33 (0.7)	53
1207	1.48 (1.42–1.54)	55	53	22	96	1.45 (0.53)	37
1302	4.60 (3.94–5.26)	55	53	3	96	4.15 (0.77)	19
1407	4.69 (4.33–5.05)	45	45	2	100	4.52 (0.45)	10
1505	5.02 (4.15–5.89)	45	44	1	98	4.73 (0.87)	18
1404	5.30 (4.73–5.87)	47	47	2	100	4.86 (0.77)	16
1203	5.43 (5.03–5.82)	55	51	1	93	5.15 (0.997)	19
1312	6.11 (5.60–6.62)	46	42	1	91	5.4 (1.14)	21
1204	6.40 (5.74–7.06)	53	53	0	100	6.15 (0.68)	11
1506	6.67 (5.59–7.75)	45	43	0	96	6.23 (0.73)	12
1305	8.75 (8.48–9.02)	52	51	0	98	8.44 (1.18)	14
1310	8.97 (8.67–9.27)	46	43	0	93	8.27 (1.23)	15
1502	9.16 (7.66–10.66)	47	47	0	100	8.25 (0.68)	8
1508	10.13 (8.84–11.42)	45	45	1	100	9.7 (0.96)	10
1411	10.32 (8.73–11.91)	47	44	0	94	9.66 (1.37)	14
1405	10.35 (7.32–13.38)	47	46	1	98	9.42 (1.36)	14
1209	10.37 (9.44–11.30)	55	54	0	98	10.26 (1.02)	10

Sample ID	Target value (±3standard deviations)	N of labs reported results	Accurate within a z-score of ±2, or reported as <LOD	N of labs reported <LOD	% of labs reported results within a z-score of ±2 or reported as <LOD	Consensus mean (standard deviation)	Relative standard deviation (%)
1403	10.90 (10.0–11.8)	48	46	0	96	10.42 (1.34)	13

Table 5b

Blood Lead Limits of Detection (LODs) for laboratories continuously participating in LAMP, 2011–2015

LOD Range (µg/dL)	N of labs (percent)
<1	15 (22.7)
1 - <2	29 (43.9)
2 - <3	7 (10.6)
3 - 5	15 (22.7)