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Effects of Individual and Neighborhood Characteristics on Childhood Blood Lead Testing and Elevated Blood Lead Levels, A Pennsylvania Birth Cohort Analysis

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Abstract

Background: Despite declining lead exposure among U.S. children, childhood blood lead level (BLL) undertesting and elevation remains a public health issue. This study explores the impacts of maternal, infant, and neighborhood characteristics on the receipt of lead testing and having elevated BLLs (EBLLs) among children under age two. **Methods:** Pennsylvania infants born in 2015 and 2016 were followed to 24 months. Birth certificate data were linked to 2015 through 2018 blood lead surveillance data and neighborhood data on household income, poverty, and the burden of houses built before 1970. Generalized linear mixed models were used to examine the individual and neighborhood characteristics independently and/or interactively affecting the likelihood of lead testing and of having EBLLs. **Results:** A total of 48.6% of children were tested for BLLs, and 2.6% of them had confirmed EBLLs. The likelihood of lead testing and of having EBLLs among non-Hispanic black children was respectively 7% and 18% higher than white children. Children born to mothers with the lowest educational attainment (<high school), with self-payment as a payment source for delivery, and without WIC enrollment were at higher risk of undertesting. Children living in neighborhoods of the lowest quartile of household income and the highest quartile of poverty and old housing were more likely to have EBLLs. Different neighborhood characteristics modified the associations between some individual factors (such as race/ethnicity, payment source for delivery, and WIC enrollment) and the odds of undertesting and of having EBLLs. **Conclusion:** This cohort analysis provides more accurate estimates of lead screening rates and the percentages of EBLLs than cross-sectional analysis. Some maternal and infant demographics significantly impact the risk of undertesting and of having EBLLs, and some of the effects vary across different neighborhood characteristics. These findings can help lead prevention programs to target screening and treatment resources to children with specific characteristics.

Keywords

birth cohort, blood lead test, elevated blood lead level, maternal and infant demographics, neighborhood characteristics

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Introduction

Blood lead levels (BLLs) for U.S. children have declined dramatically over the past several decades.[1] However, childhood exposure to lead and elevated blood lead levels (EBLLs) remains the important causes of various health problems, including decreased intelligence quotient, damaged nervous system, developmental delays, and neurobehavioral deficits.[2-6] The Centers for Disease Control and Prevention (CDC) updated its recommendations on the blood lead reference value to 5 μg/dL, used to identify children with EBLLs in 2012.[7] It is estimated that roughly 500 000 U.S. children under 2 years of age are still at risk of lead poisoning.[8] Therefore, state and local health departments need to identify children with EBLLs as early as possible so that they can receive follow-up cares as needed.

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Disparities in lead exposure and the burden of lead poisoning persist disproportionately among specific population groups, such as racial and ethnic minorities, parents with relatively low educational attainment, and people who participated in Medicaid or enrolled in The Special Supplemental Nutrition Program for Women, Infants, and Children (WIC).[9-13] In addition, children from deprived neighborhoods (higher proportions of homes built before 1970, lower household income, and higher levels of poverty) were associated with increased BLLs.[13-17] A recent study indicated the black-white racial gap of BLLs was exacerbated among children living in neighborhoods with higher socioeconomic positions.[13] However, limited information is available on how neighborhood characteristics modify associations between demographic characteristics and the likelihood of having EBLLs.

Childhood blood lead screening and follow-up monitoring and care provide information that forms the basis for planning, executing, and evaluation of lead poisoning prevention policies and programs. The Centers for Medicare and Medicaid Services (CMS) requires all children enrolled in Medicaid to receive blood lead screening tests at ages 1 year and 2 years[18]; however, a large proportion of uninsured or privately insured newborns are not screened. A previous study showed that approximately 57% of children who participated in Medicaid in 9 U.S. states did not receive lead testing by 2 years of age.[19] Another study showed that 50% or fewer children in New York, New Jersey, Pennsylvania, and Michigan were screened for BLLs before 6 years of age, and Pennsylvania children had the lowest screening rate and the highest burden of EBLLs.[20] Only a few studies have examined independent effects of selected characteristics such as age, race/ethnicity, parental educational attainment, Medicaid enrollment, and neighborhood characteristics on the likelihood of receipt of lead testing.[10,11] It is unclear whether community-level characteristics interact with individual risk factors on the likelihood of being tested for BLLs. More studies that combine individual and neighborhood characteristics data are needed to better depict this association.

This study uses a cohort analytic design in which newborns of Pennsylvania resident mothers were followed up to 2 years of age to estimate the rates of lead testing and the percentages of having EBLLs by maternal, infant, and neighborhood characteristics and to evaluate the independent impacts of selected characteristics on the odds of receiving lead testing and of having confirmed EBLLs. The interaction effects between maternal and infant demographics and neighborhood characteristics were also evaluated.

Methods

Data Source

Newborns born to Pennsylvania resident mothers in 2015 and 2016 were followed up to their second birthday and these birth cohorts' vital statistics data were obtained from birth certificates. Demographic information on maternal and infant characteristics was obtained from the birth certificate and categorized as follows: gender (male or female), race/ethnicity (Hispanic, non-Hispanic white, non-Hispanic black, non-Hispanic Asian, or other), maternal educational attainment ($<$ high school: less than high school graduate; high school/some college: high school graduates or had attended some college but had not received a college degree; $\geq$ college: college degree or higher; or other), principal source of payment for delivery (private insurance, Medicaid, self-payment, or other), maternal smoking (yes or no: mothers reported cigarette smoking or no cigarette smoking during the 3 months before pregnancy or during pregnancy; or unknown), WIC enrollment (yes or no: mothers participated or did not participate in WIC program; or unknown), maternal infection (yes: maternal infections, including gonorrhea, syphilis, herpes simplex virus, chlamydia, tocolysis, or external cephalic version, were present or treated during pregnancy; no: no maternal infection was present or treated during pregnancy), and maternal risk factors (yes or no: mother had or did not have risk factors, including pre-pregnancy diabetes, gestational diabetes, pre-pregnancy hypertension, gestational hypertension, previous pre-term birth, previous poor pregnancy outcomes, vaginal bleeding, pregnancy resulted from infertility treatment, or previous cesarean, during pregnancy). For children's neighborhood characteristics, census tract-level information on median household income (household income), the percentage of families and people whose income in the past 12 months is below the poverty level (poverty), and the percentage of housing units built before 1970 (old housing) were obtained from the U.S. Census Bureau 2012 to 2016 American Community Survey 5-Year Estimates.[21] Census tracts were ranked based on the percentage of each neighborhood characteristic and were assigned to a quartile for each neighborhood characteristics respectively. Census tract-level neighborhood characteristic data were linked to birth certificate data based on each child's maternal residential address which was geocoded using ArcGIS (ArcGIS Desktop: Release 10.4.1. Redlands, CA: Esri, 2016).

The Pennsylvania Department of Health (DOH) requires all health care service providers to report all blood lead test results from both venous and capillary specimens for persons under 16 years of age, and most of the reports are submitted electronically through the Pennsylvania National Electronic Disease Surveillance System (PA-NEDSS). All reported data for children who had at least 1 blood lead test from 2015 to 2018, including those collected for screening, confirmation, or follow-up purposes were included in the analyses. In accordance with CDC's current definition of an EBLL, the Pennsylvania DOH uses a single capillary or venous lead test at or above the reference value of 5 μg/dL to identify children with EBLLs. A confirmed EBLL is defined as a venous lead test ≥5 μg/dL, or 2 capillary lead tests ≥5 μg/dL drawn within 84 days of each other. An unconfirmed EBLL is defined as a capillary lead test ≥5 μg/dL with no other blood test done in the next 84 days.

Data Linkage

Deterministic linkage was used to compare several demographic identifiers (first name, last name, date of birth, gender, and zip code of the residence) across birth certificate data and blood lead surveillance data, and constructed a series of linking steps, starting with the most restrictive criteria to determine whether record pairs agree on all identifiers. If a record did not meet the first round of matching criteria, it was passed to the subsequent linking step for further comparison based on a match on partial identifiers. In situations where full or partial identifiers were incorrect, we matched based on the comparison of encrypted identifiers. For example, the first name and last name that sounded similar but had different spellings were converted by the Soundex coding system. First and last name and birth month and date were also assessed as being potentially transposed during matching.

A simple random sampling method was used to select a subset of the matched records after each step for manual review and validation. Some matched records that failed to be validated by the manual review were put back into the linkage process for subsequent comparison. After completing the linkage process, if a child whose birth certificate data linked to multiple lead test results in the same linking step, we only retained 1 matched record which was linked to the first of multiple lead test results. If a child whose birth certificate data linked to multiple lead test results in different linking steps, we only retained 1 matched record which was linked in an earlier (more restrictive) linking step. Additionally, we manually reviewed a child's multiple lead test records which were linked to different records in the birth certificate 1 by 1 and only retained 1 of them with optimal validity and reliability.

Birth certitificate data of 278 807 children born to Pennsylvania resident mothers in 2015 and 2016 were used to link to 284 755 children's blood lead test results archived in PA-NEDSS. After completing the linkage process and the manual review for validation, a total of 149 264 children's birth certificate data were successfully matched with their blood lead test results.

Statistical Analysis

Descriptive analyses were conducted to explore how the percentages of children tested for BLLs before 12 or 24 months of age and the percentages of tested children with unconfirmed or confirmed EBLLs vary by maternal and infant demographics and by neighborhood characteristics among the 2015 birth cohort and the 2016 birth cohort separately. Separate generalized linear mixed models (GLMMs) were constructed to estimate adjusted odds ratios (ORs) and 95% confidence intervals (CIs) to assess the independent relationships between each potential risk factor with the likelihood of lead testing and of having confirmed EBLLs after adjusting for the random effects of the census tract in the models. Besides all independent variables, two-way interactions between maternal and infant demographics and neighborhood characteristics were incorporated into the model 1 by 1 to explore if the impacts of individual factors on 2 outcomes of interest vary by different levels of neighborhood characteristics. All analyses were performed using SAS software version 9.4 (SAS Institute, Cary, North Carolina, USA).

Results

Overall, 48.3% of children born in 2015 received a blood lead test before 2 years of age, and this percentage increased to 49.0% in the 2016 birth cohort. Non-Hispanic black children had the highest rate of lead testing (63.4% and 63.0% in the 2015 and 2016 birth cohort, respectively), and non-Hispanic white children had the lowest rate (44.1% and 45.3% in the 2015 and 2016 birth cohort, respectively) before 2 years of age. Considering maternal educational attainment, the rate of lead testing was highest among children born to mothers with "high school/some college" educational level. Considering the principal source of payment for delivery, the rate of lead testing was the lowest among children born to mothers with self-payment. Children who enrolled in WIC, whose mothers smoked either before pregnancy or during pregnancy, and whose mothers had infections during pregnancy had higher rates of lead testing. Children who lived in neighborhoods of higher quartiles of poverty and old housing also had higher rates of lead testing (Table 1).

The percentage of confirmed EBLL among children tested for BLLs was 2.8% in the 2015 birth cohort and 2.5% in the 2016 birth cohort. In terms of racial disparities, non-Hispanic black children had the highest percentage of having EBLLs (4.4% and 4.4% in the 2015 and 2016 birth cohort, respectively), while non-Hispanic white children had the lowest percentage (2.1% and 1.9% in the 2015 and 2016 birth cohort, respectively). By maternal educational attainment, children born to mothers with "<high school" education level had the highest percentage of having EBLLs. Considering the principal source of payment for delivery, the percentage of having EBLLs was the highest among children born to mothers with self-payment and lowest among children born to mothers with private insurance. Children who enrolled in WIC, whose mothers smoked either before pregnancy or during pregnancy, and whose mothers had infections during pregnancy had higher percentages of having EBLLs. Children who lived in neighborhoods of lower quartiles of household income and higher quartiles of poverty and old housing had higher percentages of having EBLLs (Table 2).

Table 1. Number and Percentage of Children Tested for BLLs before 2 Years of Age by Maternal and Infant Demographics and Neighborhood Characteristics, 2015 and 2016 Pennsylvania Birth Cohorts.

	2015 birth cohort					2016 birth cohort				
	Total	BLL test < 1 year		BLL test < 2 years		Total	BLL test < 1 year		BLL test < 2 years	
	N[a]	N	%[b]	N	%[b]	N[a]	N	%[b]	N	%[b]
Overall	137246	37428	27.3	66233	48.3	135641	37914	28.0	66505	49.0
Maternal and infant demographics										
Sex										
Female	67169	18245	27.2	32263	48.0	65969	18515	28.1	32441	49.2
Male	70076	19183	27.4	33970	48.5	69667	19399	27.9	34064	48.9
Race										
Hispanic	14748	3753	25.5	7822	53.0	15110	3835	25.4	7873	52.1
Non-Hispanic Asian	5118	1418	27.7	2633	51.5	4990	1376	27.6	2523	50.6
Non-Hispanic black	18073	5813	32.2	11450	63.4	17730	5712	32.2	11164	63.0
Non-Hispanic white	92069	24375	26.5	40613	44.1	90363	24710	27.4	40948	45.3
Other[c]	7238	2069	28.6	3715	51.3	7448	2281	30.6	3997	53.7
Maternal educational attainment										
<High school	17483	4057	23.2	7772	44.5	16661	3760	22.6	7195	43.2
High school/some college	58822	18111	30.8	31849	54.1	57583	17616	30.6	31044	53.9
≥College	60072	15062	25.1	26268	43.7	60546	16337	27.0	27874	46.0
Other[d]	869	198	22.8	344	39.6	851	201	23.6	392	46.1
Payment source for delivery										
Private insurance	79599	20151	25.3	35306	44.4	77273	20540	26.6	35597	46.1
Medicaid	44605	14763	33.1	26627	59.7	43972	14456	32.9	25991	59.1
Self-payment	6419	608	9.5	1093	17.0	6162	455	7.4	829	13.5
Other[e]	6623	1906	28.8	3207	48.4	8234	2463	29.9	4088	49.7
WIC enrollment										
Yes	49725	17278	34.8	30525	61.4	47264	16197	34.3	28565	60.4
No	84477	19412	23.0	34344	40.7	85408	20977	24.6	36586	42.8
Unknown	3044	738	24.2	1364	44.8	2969	740	24.9	1354	45.6
Maternal smoking										
Yes	23490	7342	31.3	12610	53.7	21592	6717	31.1	11662	54.0
No	111858	29610	26.5	52741	47.2	112486	30743	27.3	54035	48.0
Unknown	1898	476	25.1	882	46.5	1563	454	29.1	808	51.7
Maternal infection										
Yes	7760	2442	31.5	4438	57.2	7740	2427	31.4	4367	56.4
No	129486	34986	27.0	61795	47.7	127901	35487	27.8	62138	48.6
Maternal risk factor										
Yes	47500	12594	26.5	22596	47.6	48510	13233	27.3	23570	48.6
No	89746	24834	27.7	43637	48.6	87131	24681	28.3	42935	49.3
Neighborhood characteristics										
Quartile of household income										
1st	37743	11982	31.8	22607	59.9	36522	11733	32.8	21798	59.7
2nd	31718	9617	30.3	15844	50.0	31849	9849	30.2	16134	50.7
3rd	34948	8568	24.5	14720	42.1	34234	8203	25.0	14323	41.8
4th	32809	7251	22.1	13042	39.8	33030	8129	22.0	14247	43.1
Quartile of poverty										
1st	31300	7288	23.3	12869	41.1	30366	7640	25.2	13258	43.7
2nd	34055	8641	25.4	14368	42.2	33086	8329	25.2	14126	42.7
3rd	31649	8882	28.1	14946	47.2	32797	9447	28.8	15672	47.8
4th	40232	12611	31.4	24041	59.8	39387	12498	31.7	23446	59.5
Quartile of old housing										
1st	35406	6788	19.2	12013	33.9	35824	6994	19.5	12659	35.3
2nd	32468	8598	26.5	14479	44.6	31764	8415	26.5	14316	45.1
3rd	32299	9735	30.1	17274	53.5	32382	9990	30.9	17584	54.3
4th	37073	12307	33.2	22467	60.6	35670	12515	35.1	21946	61.5

Abbreviation: BLLs, blood lead levels.
[a]Total number of children born in 2015 and 2016 by maternal and infant demographics and neighborhood characteristics.
[b]The percentage of children born in 2015 and 2016 with a blood lead test before the age of 1 and of 2 years by maternal and infant demographics and neighborhood characteristics.
[c]Other race includes all other races, unknown or missing race.
[d]Other maternal educational attainment includes unknown or missing maternal educational attainment.
[e]Other principal source of payment for delivery includes unknown or missing principal source of payment for delivery.

Table 2. Number and Percentage of EBLLs Among Children Tested for BLLs Before 2 Years of Age by Maternal and Infant Demographics and Neighborhood Characteristics, 2015 and 2016 Pennsylvania Birth Cohorts.

	2015 birth cohort					2016 birth cohort				
	Tested children	Unconfirmed EBLL		Confirmed EBLL		Tested children	Unconfirmed EBLL		Confirmed EBLL	
	N[a]	N	%[b]	N	%[b]	N[a]	N	%[b]	N	%[b]
Overall	66 233	1044	1.6	1826	2.8	66 505	828	1.3	1675	2.5
Maternal and infant demographics										
Sex										
Female	32 263	496	1.5	868	2.7	32 441	392	1.2	813	2.5
Male	33 970	548	1.6	958	2.8	34 064	436	1.3	862	2.5
Race										
Hispanic	7822	172	2.2	279	3.6	7873	121	1.5	238	3.0
Non-Hispanic Asian	2633	53	2.0	88	3.3	2523	47	1.9	89	3.5
Non-Hispanic black	11 450	223	2.0	505	4.4	11 164	151	1.4	488	4.4
Non-Hispanic white	40 613	554	1.4	870	2.1	40 948	479	1.2	777	1.9
Other[c]	3715	42	1.1	84	2.3	3997	30	0.8	83	2.1
Maternal educational attainment										
<High school	7772	247	3.2	355	4.6	7195	192	2.7	349	4.9
High school/some college	31 849	594	1.9	971	3.1	31 044	445	1.4	870	2.8
≥College	26 268	199	0.8	484	1.8	27 874	185	0.7	436	1.6
Other[d]	344	4	1.2	16	4.7	392	6	1.5	20	5.1
Payment source for delivery										
Private insurance	35 306	355	1.0	693	2.0	35 597	272	0.8	623	1.8
Medicaid	26 627	609	2.3	979	3.7	25 991	468	1.8	919	3.5
Self-payment	1093	25	2.3	60	5.5	829	24	2.9	35	4.2
Other[e]	3207	55	1.7	94	2.9	4088	64	1.6	98	2.4
WIC enrollment										
Yes	30 525	649	2.1	1003	3.3	28 565	493	1.7	911	3.2
No	34 344	376	1.1	782	2.3	36 586	322	0.9	737	2.0
Unknown	1364	19	1.4	41	3.0	1354	13	1.0	27	2.0
Maternal smoking										
Yes	12 610	297	2.4	373	3.0	11 662	234	2.0	358	3.1
No	52 741	732	1.4	1418	2.7	54 035	586	1.1	1285	2.4
Unknown	882	15	1.7	35	4.0	808	8	1.0	32	4.0
Maternal infection										
Yes	4438	98	2.2	140	3.2	4367	74	1.7	114	2.6
No	61 795	946	1.5	1686	2.7	62 138	754	1.2	1561	2.5
Maternal risk factor										
Yes	22 596	366	1.6	612	2.7	23 570	272	1.2	645	2.7
No	43637	678	1.6	1214	2.8	42 935	556	1.3	1030	2.4
Neighborhood characteristics										
Quartile of household income										
1st	22 607	556	2.5	1010	4.5	21 798	396	1.8	924	4.2
2nd	15 844	239	1.5	345	2.2	16 134	211	1.3	324	2.0
3rd	14 720	169	1.2	285	1.9	14 323	152	1.1	270	1.9
4th	13 042	80	0.6	186	1.4	14 247	69	0.5	157	1.1
Quartile of poverty										
1st	12 869	112	0.9	183	1.4	13 258	85	0.6	175	1.3
2nd	14 368	162	1.1	277	1.9	14 126	139	1.0	211	1.5
3rd	14 946	194	1.3	326	2.2	15 672	198	1.3	348	2.2
4th	24 041	576	2.4	1040	4.3	23 446	406	1.7	941	4.0
Quartile of old housing										
1st	12 013	102	0.9	196	1.6	12 659	86	0.7	188	1.5
2nd	14 479	170	1.2	246	1.7	14 316	156	1.1	230	1.6
3rd	17 274	271	1.6	478	2.8	17 584	246	1.4	413	2.4
4th	22 467	501	2.2	906	4.0	21 946	340	1.6	844	3.9

Abbreviation: EBLLs, elevated blood lead levels.
[a]Total number of children born in 2015 and 2016 with a blood lead test before the age of 2 years by maternal and infant demographics and neighborhood characteristics.
[b]The percentage of tested children under the age of 2 years who had unconfirmed or confirmed EBLLs by maternal and infant demographics and neighborhood characteristics.
[c]Other race includes all other races, unknown or missing race.
[d]Other maternal educational attainment includes unknown or missing maternal educational attainment.
[e]Other principal source of payment for delivery includes unknown or missing principal source of payment for delivery.

The adjusted ORs and 95% CIs were estimated from the GLMMs to identify significant independent factors of the likelihood of receipt of lead testing and of having confirmed EBLLs (Table 3). Non-Hispanic black children had 7% higher odds of receipt of lead testing (adjusted OR = 1.07, 95% CI: 1.04, 1.11) and 18% higher odds of having EBLLs (adjusted OR = 1.18, 95% CI: 1.06, 1.31) as compared with non-Hispanic white children. Children born to mothers with "<high school" educational level had 15% lower odds of receipt of lead testing (adjusted OR = 0.85, 95% CI: 0.82, 0.88) and 75% higher odds of having EBLLs (adjusted OR = 1.75, 95% CI: 1.55, 1.98) compared with those with "≥ college" education level. Compared with children born to mothers with private insurance as the payment source for delivery, children born to mothers with self-payment had 69% lower odds of receipt of lead testing (adjusted OR = 0.31, 95% CI: 0.29, 0.32) and 89% higher odds of having EBLLs (adjusted OR = 1.89, 95% CI: 1.51, 2.36), and the odds of both outcomes were higher among children born to mothers with Medicaid. Children with WIC enrollment were more likely to receive lead testing and were less likely to have EBLLs than children without WIC enrollment. The adjusted ORs of receipt of lead testing increased in a stepwise fashion for higher quartiles of old housing, reaching 1.97 (95% CI: 1.84, 2.10) for the highest quartile. The adjusted ORs of having EBLLs decreased in a stepwise fashion for higher quartiles of household income, reaching 0.58 (95% CI: 0.47, 0.72) for the highest quartile. Additionally, the odds of having EBLLs was 29% (adjusted OR = 1.29, 95% CI: 1.05, 1.58) and 44% (adjusted OR = 1.44, 95% CI: 1.24, 1.68) higher for children living in neighborhoods of the highest quartile of poverty and old housing, respectively.

Interaction terms were added to the GLMM model 1 by 1 to assess if the impacts of individual factors varied at different levels of neighborhood characteristics on the 2 outcomes of interest. Compared with non-Hispanic white children, Hispanic and non-Hispanic Asian children had lower odds of receipt of lead testing in relatively deprived neighborhoods (the first and second quartiles of household income and the third and fourth quartiles of poverty and old housing), although some comparisons were not statistically significant. Compared with children born to mothers with "≥college" education level, children born to mothers with "<high school" educational level were generally less likely to receive lead testing except those in the least deprived neighborhoods (the fourth quartile of household income and the first quartile of poverty and old housing). Compared with children born to mothers with private insurance as the payment source for delivery, children born to mothers with Medicaid had significantly higher odds of receipt of lead testing except in the most deprived neighborhoods, while the odds for children born to mothers with self-payment were significantly lower and fluctuated widely by different levels of neighborhood characteristics. Children with WIC enrollment had significantly higher odds of receipt of lead testing in each quartile of neighborhood characteristics, and the odds gradually decreased in more deprived neighborhoods (Table 4).

Compared with non-Hispanic white children, Hispanic and non-Hispanic Asian children had significantly higher odds of having EBLLs in the least poor neighborhoods, while non-Hispanic black children had significantly higher odds in the lowest household income and the poorest neighborhoods. Compared with children born to mothers with private insurance as the payment source for delivery, the odds of having EBLLs for children born to mothers with Medicaid or self-payment were significantly higher and fluctuated widely by different levels of neighborhood poverty. Children with WIC enrollment were less likely to have EBLLs only in neighborhoods of the highest quartile of old housing (Table 5).

Discussion

This cohort study indicated that approximately 49% of newborns tested for BLLs before 2 years of age which was much higher than the screening rate (29%) reported in the previous Pennsylvania childhood lead surveillance annual report based on 1 calendar year.[22] This cohort analysis, using birth certificate data linked to blood lead test data and neighborhood characteristics data, enables us to more accurately estimate the rate of receipt of lead testing and the proportion of children with EBLLs by maternal and infant demographics and neighborhood characteristics. It provides more accurate estimates than the cross-sectional study design which included blood test results reported on a calendar year view and did not include children who had been tested in the previous year or will be tested in the following year. Pennsylvania does not mandate a statewide universal screening which may result in a lower lead screening rate when compared with Philadelphia (76.5% in children under the age of 24 months) and New York state (76.7% in children under the age of 18 months) who have such mandates in place.[23,24] Estimated percentages of receipt of lead testing and of having EBLLs, which were higher among children with specific demographics and in deprived neighborhoods, may reflect a true increased risk of lead exposure or more robust and targeted lead testing among that specific group of children. We found that the rate of lead testing was relatively low among children who were non-Hispanic whites, who were born to mothers with the lowest or highest educational attainment, whose payment source for delivery was non-Medicaid (private insurance or self-payment), who didn't enroll in WIC and who lived in less deprived neighborhoods. Moreover, the percentage of having EBLLs was relatively high among children who were racial and ethnic minorities (especially non-Hispanic black), who were born to mothers with the

Table 3. Adjusted Odds Ratios (95% Confidence Intervals) for Associations between Selected Characteristics and Receipt of Blood Lead Testing and Having a Confirmed EBLL Among Children Under 2 Years of Age, 2015−2016 Pennsylvania Birth Cohort.

	Blood lead testing		Confirmed EBLL	
Maternal and infant demographics				
Sex				
Female	1.00		1.00	
Male	0.99[a]	(0.97, 1.01)[b]	0.96	(0.90, 1.03)
Race				
Non-Hispanic white	1.00		1.00	
Hispanic	0.99	(0.96, 1.02)	0.85	(0.75, 0.96)
Non-Hispanic Asian	0.95	(0.90, 0.99)	1.16	(0.98, 1.36)
Non-Hispanic black	1.07	(1.04, 1.11)	1.18	(1.06, 1.31)
Other[c]	1.14	(1.10, 1.19)	0.90	(0.76, 1.07)
Maternal educational attainment				
≥College	1.00		1.00	
<High school	0.85	(0.82, 0.88)	1.75	(1.55, 1.98)
High school/some college	1.09	(1.07, 1.11)	1.23	(1.12, 1.36)
Other[d]	0.62	(0.56, 0.69)	1.98	(1.39, 2.83)
Payment source for delivery				
Private insurance	1.00		1.00	
Medicaid	1.19	(1.17, 1.22)	1.25	(1.15, 1.37)
Self-payment	0.31	(0.29, 0.32)	1.89	(1.51, 2.36)
Other[e]	1.01	(0.97, 1.05)	1.07	(0.91, 1.25)
WIC enrollment				
No	1.00		1.00	
Yes	1.75	(1.72, 1.79)	0.89	(0.82, 0.96)
Unknown	1.05	(0.99, 1.11)	0.86	(0.66, 1.10)
Maternal smoking				
No	1.00		1.00	
Yes	1.07	(1.04, 1.09)	1.06	(0.96, 1.16)
Unknown	0.90	(0.83, 0.97)	1.16	(0.90, 1.49)
Maternal infection				
No	1.00		1.00	
Yes	1.10	(1.06, 1.14)	0.87	(0.77, 1.00)
Maternal risk factor				
No	1.00		1.00	
Yes	0.96	(0.94, 0.98)	1.01	(0.94, 1.08)
Neighborhood characteristics				
Quartiles of household income				
1st	1.00		1.00	
2nd	1.00	(0.95, 1.05)	0.71	(0.62, 0.81)
3rd	0.97	(0.90, 1.03)	0.76	(0.64, 0.91)
4th	1.02	(0.94, 1.10)	0.58	(0.47, 0.72)
Quartiles of poverty				
1st	1.00		1.00	
2nd	0.97	(0.93, 1.02)	1.08	(0.92, 1.26)
3rd	0.99	(0.94, 1.05)	1.15	(0.96, 1.36)
4th	1.05	(0.98, 1.13)	1.29	(1.05, 1.58)
Quartiles of old housing				
1st	1.00		1.00	
2nd	1.39	(1.31, 1.46)	0.87	(0.74, 1.02)
3rd	1.66	(1.57, 1.77)	1.11	(0.95, 1.29)
4th	1.97	(1.84, 2.10)	1.44	(1.24, 1.68)

Abbreviation: EBLL, elevated blood lead level.
[a]Adjusted odds ratio.
[b]95% confidence interval.
[c]Other race includes all other races, unknown or missing race.
[d]Other maternal educational attainment includes unknown or missing maternal educational attainment.
[e]Other principal source of payment for delivery includes unknown or missing principal source of payment for delivery.

Table 4. Adjusted Odds Ratios (95% Confidence Intervals) for Associations between Maternal and Infant Demographics and Receipt of Blood Lead Testing Among Children Under 2 Years of Age, by Quartiles of Each Neighborhood Characteristics, 2015−2016 Pennsylvania Birth Cohort.

	Quartiles of household income				Quartiles of poverty				Quartiles of old housing			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Race												
Non-Hispanic white	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Hispanic	0.94[a] (0.9, 0.99)[b]	0.93 (0.87, 0.99)	1.10 (1.03, 1.18)	1.09 (1.00, 1.18)	1.08 (1.00, 1.17)	1.05 (0.98, 1.13)	1.00 (0.93, 1.07)	0.95 (0.91, 1.00)	1.20 (1.12, 1.29)	1.07 (0.99, 1.16)	0.96 (0.90, 1.01)	0.88 (0.83, 0.93)
Non-Hispanic Asian	0.91 (0.85, 0.98)	0.90 (0.82, 0.98)	1.06 (0.96, 1.16)	0.95 (0.86, 1.06)	0.99 (0.89, 1.10)	1.01 (0.92, 1.12)	0.93 (0.85, 1.02)	0.91 (0.85, 0.98)	1.03 (0.93, 1.15)	1.01 (0.91, 1.12)	0.87 (0.80, 0.95)	0.91 (0.84, 0.98)
Non-Hispanic black	1.07 (1.02, 1.12)	1.02 (0.96, 1.10)	1.09 (1.01, 1.18)	1.06 (0.96, 1.17)	1.05 (0.95, 1.16)	0.99 (0.91, 1.08)	1.08 (1.01, 1.17)	1.08 (1.03, 1.14)	1.21 (1.11, 1.33)	1.17 (1.08, 1.28)	0.99 (0.93, 1.05)	1.03 (0.98, 1.08)
Other[c]	1.21 (1.11, 1.31)	1.27 (1.17, 1.39)	1.12 (1.08, 1.21)	1.03 (0.97, 1.10)	1.03 (0.96, 1.10)	1.09 (1.01, 1.18)	1.19 (1.09, 1.30)	1.27 (1.18, 1.37)	1.05 (0.97, 1.12)	1.12 (1.02, 1.22)	1.13 (1.05, 1.23)	1.25 (1.16, 1.35)
Maternal educational attainment												
≥College	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
<High school	0.84 (0.80, 0.88)	0.77 (0.73, 0.82)	0.78 (0.73, 0.84)	1.02 (0.93, 1.13)	1.05 (0.96, 1.15)	0.81 (0.76, 0.87)	0.78 (0.74, 0.83)	0.80 (0.77, 0.84)	0.97 (0.91, 1.05)	0.77 (0.73, 0.82)	0.90 (0.85, 0.95)	0.71 (0.68, 0.75)
High school/ some college	0.99 (0.96, 1.04)	1.06 (1.03, 1.11)	1.12 (1.08, 1.17)	1.18 (1.14, .123)	1.14 (1.10, 1.19)	1.14 (1.09, 1.18)	1.12 (1.08, 1.16)	0.97 (0.93, 1.01)	1.34 (1.29, 1.39)	1.18 (1.13, 1.22)	1.01 (0.97, 1.05)	0.87 (0.83, 0.90)
Other[d]	0.60 (0.52, 0.70)	0.66 (0.53, 0.84)	0.54 (0.42, 0.70)	0.61 (0.46, 0.81)	0.73 (0.55, 0.99)	0.65 (0.50, 0.85)	0.55 (0.43, 0.69)	0.58 (0.50, 0.67)	0.63 (0.47, 0.84)	0.77 (0.59, 0.99)	0.60 (0.49, 0.74)	0.51 (0.44, 0.60)
Payment source for delivery												
Private insurance	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Medicaid	1.01 (0.97, 1.05)	1.23 (1.19, 1.28)	1.37 (1.32, 1.43)	1.47 (1.39, 1.55)	1.41 (1.34, 1.49)	1.37 (1.31, 1.43)	1.31 (1.26, 1.36)	0.99 (0.96, 1.03)	1.68 (1.61, 1.76)	1.37 (1.32, 1.43)	1.14 (1.09, 1.18)	0.91 (0.88, 0.95)
Self-payment	0.61 (0.55, 0.68)	0.22 (0.19, 0.24)	0.20 (0.18, 0.23)	0.33 (0.28, 0.38)	0.29 (0.25, 0.33)	0.22 (0.19, 0.24)	0.20 (0.18, 0.22)	0.56 (0.51, 0.62)	0.23 (0.20, 0.26)	0.16 (0.14, 0.18)	0.57 (0.50, 0.65)	0.56 (0.50, 0.63)
Other[e]	0.99 (0.92, 1.06)	0.99 (0.92, 1.07)	1.02 (0.95, 1.11)	0.97 (0.89, 1.06)	0.96 (0.87, 1.04)	1.02 (0.94, 1.10)	1.01 (0.94, 1.09)	0.98 (0.92, 1.05)	1.11 (1.03, 1.21)	1.05 (0.97, 1.14)	1.05 (0.97, 1.13)	0.83 (0.77, 0.89)
WIC enrollment												
No	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Yes	1.53 (1.48, 1.59)	1.85 (1.79, 1.92)	1.90 (1.82, 1.97)	1.96 (1.86, 2.07)	1.91 (1.81, 2.00)	1.98 (1.90, 2.06)	1.90 (1.83, 1.98)	1.50 (1.45, 1.55)	2.25 (2.16, 2.35)	2.05 (1.67, 2.13)	1.65 (1.58, 1.71)	1.41 (1.36, 1.46)
Unknown	1.03 (0.93, 1.15)	1.20 (1.06, 1.35	0.93 (0.83, 1.05)	1.02 (0.92, 1.14)	0.95 (0.85, 1.07)	1.05 (0.94, 1.18)	1.19 (1.06, 1.34)	0.99 (0.89, 1.09)	1.05 (0.94, 1.17)	1.19 (1.06, 1.34)	0.93 (0.83, 1.04)	0.99 (0.89, 1.09)
Maternal smoking												
No	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Yes	0.90 (0.86, 0.93)	1.11 (1.07, 1.16)	1.23 (1.18, 1.29)	1.19 (1.12, 1.26)	1.19 (1.12, 1.26)	1.23 (1.17, 1.29)	1.14 (1.09, 1.19)	0.89 (0.85, 0.92)	1.37 (1.30, 1.44)	1.22 (1.17, 1.28)	1.02 (0.97, 1.06)	0.83 (0.80, 0.87)
Unknown	0.84 (0.75, 0.94)	0.90 (0.75, 1.07)	0.90 (0.76, 1.07)	1.02 (0.86, 1.23)	1.01 (0.84, 1.23)	0.98 (0.82, 1.16)	0.87 (0.73, 1.05)	0.83 (0.75, 0.92)	0.95 (0.81, 1.12)	1.14 (0.96, 1.36)	0.85 (0.73, 0.99)	0.79 (0.70, 0.89)
Maternal infection												
No	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Yes	1.01 (0.96, 1.07)	1.13 (1.05, 1.22)	1.22 (1.13, 1.32)	1.17 (1.06, 1.28)	1.19 (1.08, 1.30)	1.25 (1.15, 1.35)	1.16 (1.08, 1.25)	0.99 (0.94, 1.04)	1.32 (1.22, 1.44)	1.19 (1.10, 1.28)	1.02 (0.96, 1.09)	1.02 (0.96, 1.08)

[a]Adjusted odds ratio.
[b]95% confidence interval.
[c]Other race includes all other races, unknown or missing race.
[d]Other maternal educational attainment includes unknown or missing maternal educational attainment.
[e]Other principal source of payment for delivery includes unknown or missing principal source of payment for delivery.

Table 5. Adjusted Odds Ratios (95% Confidence Intervals) for Associations between Maternal and Infant Demographics and Having a Confirmed EBLL Among Children Under 2 Years of Age, by Quartiles of Each Neighborhood Characteristics, 2015−2016 Pennsylvania Birth Cohort.

	Quartiles of household income				Quartiles of poverty				Quartiles of old housing			
	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
Race												
Non-Hispanic white	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00				
Hispanic	0.82[a] (0.7, 0.96)[b]	0.73 (0.54, 0.98)	1.17 (0.86, 1.57)	0.94 (0.59, 1.50)	1.46 (1.01, 2.15)	0.62 (0.39, 0.96)	0.81 (0.60, 1.11)	0.83 (0.71, 0.96)				
Non-Hispanic Asian	1.06 (0.85, 1.32)	1.15 (0.80, 1.65)	1.33 (0.89, 2.00)	1.64 (0.98, 2.73)	2.55 (1.67, 3.89)	0.90 (0.54, 1.50)	0.98 (0.65, 1.48)	1.09 (0.88, 1.36)				
Non-Hispanic black	1.25 (1.10, 1.43)	0.75 (0.57, 0.98)	0.95 (0.68, 1.33)	1.32 (0.83, 2.10)	1.35 (0.88, 2.09)	0.66 (0.43, 1.02)	1.04 (0.81, 1.35)	1.21 (1.06, 1.38)				
Other[c]	0.75 (0.57, 0.98)	0.82 (0.57, 1.19)	1.24 (0.87, 1.76)	1.12 (0.75, 1.66)	1.32 (0.89, 1.96)	0.78 (0.50, 1.23)	1.23 (0.89, 1.72)	0.73 (0.56, 0.94)				
Payment source for delivery												
Private insurance					1.00	1.00	1.00	1.00				
Medicaid					1.51 (1.17, 1.94)	1.15 (0.94, 1.41)	1.13 (0.95, 1.34)	1.31 (1.17, 1.48)				
Self-payment					2.84 (1.43, 5.66)	1.26 (0.62, 2.59)	2.98 (1.98, 4.48)	1.62 (1.18, 2.20)				
Other[d]					1.12 (0.66, 1.90)	0.78 (0.48, 1.26)	0.65 (0.42, 1.00)	1.29 (1.05, 1.58)				
WIC enrollment												
No									1.00	1.00	1.00	1.00
Yes									0.83 (0.66, 1.04)	0.91 (0.75, 1.10)	1.11 (0.96, 1.29)	0.80 (0.72, 0.89)
Unknown									1.50 (0.83, 2.72)	1.04 (0.56, 1.92)	0.97 (0.57, 1.65)	0.64 (0.44, 0.93)
Maternal smoking												
No									1.00	1.00	1.00	1.00
Yes									1.34 (1.05, 1.71)	1.00 (0.81, 1.25)	1.25 (1.07, 1.47)	0.90 (0.79, 1.04)
Unknown									0.80 (0.25, 2.45)	1.20 (0.56, 2.57)	1.57 (0.97, 2.53)	1.04 (0.74, 1.46)

Abbreviation: EBLL, elevated blood lead level.
[a]Adjusted odds ratio.
[b]95% confidence interval.
[c]Other race includes all other races, unknown or missing race.
[d]Other principal source of payment for delivery includes unknown or missing principal source of payment for delivery.

lowest educational attainment, whose payment source for delivery was Medicaid, who enrolled in WIC, and who lived in more deprived neighborhoods. The above-mentioned results were consistent with previous findings.[9-11,15-16]

To the best of our knowledge, this is the first population-based study using GLMMs to investigate independent and interaction effects of selected maternal and infant demographics and neighborhood characteristics on the likelihood of receipt of lead testing and of having EBLLs. We found that being non-Hispanic black, having mothers with higher educational attainment, paying for delivery by Medicaid, enrolling in WIC, and living in neighborhoods with higher burdens of old housing were associated with higher odds of receipt of lead testing. Being non-Hispanic black, having mothers with lower educational attainment, paying for delivery by Medicaid or self-payment, and living in the poorest and the oldest neighborhoods were significant risk factors for EBLLs. These results are consistent with findings from previous studies.[9-11,15-17,25,26] Besides these well-known risk factors, being non-Hispanic Asian and paying for delivery by self-payment were associated with undertesting of lead and having EBLLs. Parental linguistic and cultural barriers may affect Asian children's ability to gain access to appropriate and timely health care services. Children without Medicaid or private insurance may have difficulties finding a primary care provider due to the out of pocket costs.

Furthermore, we found that the odds of receipt of lead testing and of having confirmed EBLLs related to disparities in some maternal and infant demographics vary by different levels of neighborhood characteristics. Being Hispanic, having mothers with high school/some college educational level, paying for delivery by Medicaid, and enrolling in WIC were associated with a higher likelihood of receipt of testing in the least deprived neighborhoods, but these positive relationships diminished and even reversed in more deprived neighborhoods.

Additionally, non-Hispanic black children had higher odds of having EBLLs in the most economically disadvantaged neighborhoods compared to non-Hispanic white children, but this significant racial gap was nonexistent in less economically disadvantaged neighborhoods. Our results here are different from findings from the previous study conducted by Moody et al. in the Detroit metropolitan area.[13] Their findings showed that the black-white racial gap in blood lead levels was the narrowest for children living in the neighborhoods of the lowest socioeconomic position (SEP), and the gap exacerbated with increasing levels of neighborhood SEP. It is important to note that the outcomes of interest, classification of neighborhood characteristics, and data analysis methods were different in the 2 studies. More studies are needed to address whether the racial differences seen regarding the risk of having EBLLs exacerbates or narrows with increasing levels of neighborhood socioeconomic characteristics.

This study had several limitations. First, the underreporting of blood lead test results by health care service providers, unmatched blood lead test records, and children born to Pennsylvania resident mothers and moved out of state before the receipt of lead testing may have contributed to the underestimate of the screening rate. Secondly, the inherent limitations of accuracy errors in deterministic linkage would introduce bias into analyses, even though we conducted manual validation reviews on matching data to minimize these errors. Finally, because Pennsylvania does not have a statewide universal lead screening mandate for children, it is important to note that the results presented in this study should be interpreted with knowledge of local childhood lead screening related policies. This limits the generalizability of our findings to other areas of the country.

In summary, certain maternal and infant demographics and neighborhood socioeconomic characteristics are significantly associated with undertesting of childhood blood lead and with higher risk of having EBLLs. Therefore, proactive and effective lead screening to identify potentially exposed children is essential. Our findings can not only be used to guide targeted efforts in planning prevention programs but also guide health provider decisions on priorities regarding which children should receive a follow-up test within the recommended time period and treatment if necessary.

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