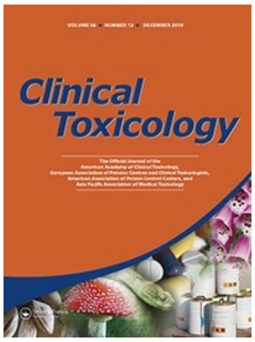

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CLINICAL RESEARCH

Analysis of blood lead levels of young children in Flint, Michigan before and during the 18-month switch to Flint River water

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ABSTRACT

Background: The toxicity of lead, like any xenobiotic, is directly linked to the duration of exposure and toxin concentration in the body. The elevation in blood lead levels (BLLs) in young Flint, Michigan children noted in time-periods before, and during the 18-month exposure to Flint River water (FRW) from 25 April 2014 to 15 October 2015 is well-known internationally. The length of time BLLs were elevated is unknown, yet key in understanding the potential health impact of the event. The objective of this study was to evaluate whether BLLs in Flint children were increased during the entire 18-month FRW exposure compared to similar earlier time periods.

Methods: We conducted a retrospective study analyzing BLLs from Flint children aged 5 years and under. The geometric mean (GM) BLLs and percentages of BLLs $\geq$5.0 µg/dL in Period I: 25 April 2006 to 15 October 2007 (earliest timeframe available for study) and Period II: 25 April 2012 to 15 October 2013 (timeframe immediately before the water switch), were compared to Period III, 25 April 2014 to 15 October 2015 (FRW exposure).

Results: There were 5663 BLLs available for study. GM $\pm$ SE BLLs decreased from 2.19 $\pm$ 0.03 µg/dL in Period I to 1.47 $\pm$ 0.02 µg/dL in Period II [95% CI, 0.64, 0.79]; $p<.001$ and *decreased further* to 1.32 $\pm$ 0.02 µg/dL during the FRW Period III [95% CI, 0.79, 0.95]; $p<.001$. The percentage of BLLs $\geq$5.0 µg/dL decreased from Period I (10.6%) to Period II (3.3%) [95% CI, 5.7, 8.8]; $p<.001$ and from Period I to Period III (3.9%) [95% CI, 5.0, 8.2]; $p=.002$. The 0.6% increase from Period II to Period III was not statistically significant [95% CI, $-$1.9, 0.57]; $p=.30$.

Conclusion: Analyses of GM and percentages $\geq$5.0 µg/dL of BLLs do not support the occurrence of a global increase in BLLs in young children of Flint during the entire 18-month period of FRW exposure.

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Introduction

There is no known safe blood lead concentration in children. Lead is a neurotoxin that can cause chronic medical and behavioral health problems in children [1–4] and is arguably the most prevalent pediatric toxin of environmental origin in the United States [5]. Mean lifetime BLLs as low as 1.0–10.0 µg/dL are inversely associated with children's IQ scores [1,2]. Epidemiologic studies have demonstrated that environmental lead exposure is also associated with aggressive behavior in children [4,5].

Flint, Michigan is a typical "post-industrial" community with a socioeconomic profile of a city at higher risk for childhood lead exposure from multiple sources. This has been true for decades prior to the drinking water switch from the Detroit Water Authority (DWA) to FRW that occurred from 25 April 2014 to 15 October 2015. The water source switch resulted in a higher percentage of households having tap water that exceeded allowable water lead concentration of 15 parts per billion, as outlined by the Lead and Copper rule of the Environmental Protection Agency [6–8]. Previous reports showed transient increases in the frequency percentage of BLLs of young children with BLLs above the current Centers for Disease Control and Prevention (CDC) reference value of 5.0 µg/dL [9–11]. An initial investigation compared percentages of childhood BLLs above the CDC reference value for 8.5-month periods of time before (2013) and during FRW exposure (2015) [9]. An investigation by Kennedy et al analyzed BLLs above the CDC reference value during four periods, including periods after issuance of a water advisory, and after the switch back to DWA from FRW [10]. Most recently, an investigation of BLLs in young children in Flint annually over a decade noted an increase in GM BLLs of 0.11 µg/dL from 2014 to 2015, with a subsequent decrease in 2016 [11]. However, the water switch was not confined to 8.5 months, nor a single calendar year, but rather took place over a period of 18 months [10]. In this investigation, we compare BLLs during the FRW change to two prior 18-month time-periods in order to place BLL changes, and the potential

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health impact on children during the FRW switch period, into an accurate historical and clinical context.

This study analyzes the 18-month period of the FRW switch in its entirety. We set out to: (1) study BLLs of children before and during the FRW change, (2) geocode household addresses of Flint children tested to analyze any potential changes in geographical clusters as defined by city wards (and thus determine potential areas of higher risk). This is the first study comparing geometric mean BLLs, and percentages of Flint children with BLLs ≥5.0 μg/dL during the entire 18-month FRW switch period to identical prior 18-month time-periods in Flint.

Methods

Study design

This is a retrospective cohort study of BLLs from a population sample of children aged 5 years and under, residing in Flint during the three 18-month timeframes from 2006 to 2015. Hurley Medical Center (HMC) contains the regional children's hospital and is the primary source of pediatric BLL analysis in Flint. The investigation further examines the HMC database utilized by Gómez et al [11]. Primary care doctors affiliated with this institution provide clinical services for the majority of Medicaid-enrolled children in the region. BLLs associated with home addresses were obtained through the Epic EMR (Epic Systems Corporation, Verona, Wisconsin) or through legacy databases available for query at HMC.

All blood lead samples in the databases had a subject's address geocoded within the Flint boundary for all 18-month periods examined. If a subject had more than a single lead level obtained during any given period studied, only the highest value was retained for analysis. The data utilized in this study were reviewed, cleaned of incomplete or inaccurate data, and de-duplicated. Each subject was assigned a unique identifier linking the subject to pertinent demographics such as date of birth, home address, gender and Medicaid status. BLLs were measured in Warde Medical Laboratory, Ann Arbor, Michigan, by atomic absorption spectrophotometry with electrothermal atomizer methodology (Zeeman Model AA280Z; Agilent technologies, Santa Clara, California) using a graphite tube atomizer (Model GTA120). The detection limit of the method used was 0.5 μg/dL. We conservatively assigned a value of 0.4 μg/dL to children sampled and found to have undetectable BLLs.

In HMC databases, 24 April 2006–15 October 2007 is the earliest 18-month period available for analysis. We controlled for BLL seasonal variability by selecting the same monthly timeframes in all 18-month cohorts; blood lead concentrations and the prevalence of lead poisoning are known to be higher in warmer months than in colder months of the year [12,13]. The relationship between seasons and children's BLLs has been recently reviewed [13]. The increase in BLLs during warmer months is mainly attributed to the combined effect of increased lead exposure (windows open, paint chips on the window sill, pica behaviors with lead-impregnated soil outdoors), and changes in lead kinetics in part attributed to vitamin D [13]. The study was approved by the Institutional Review Board of the medical center (HMC) where the data were obtained.

Outcome measures

18-Month analysis of mean BLLs in Flint before and during the FRW switch

The switch to FRW exposure occurred on 25 April 2014, and the switch back to the DWA drinking water occurred on 15 October 2015. We evaluated: (1) GM BLLs and (2) changes in the percentage of BLLs ≥5.0 μg/dL in children aged 5 years and younger obtained during three 18-month periods; two earlier periods were selected to match the dates of the FRW exposure to control for seasonal variability of BLLs [12,13]. Period I: 25 April 2006 to 15 October 2007 (earliest time period before the FRW switch), and Period II: 25 April 2012 to 15 October 2013 (timeframe closest to the FRW switch) were compared to Period III: 25 April 2014 to 15 October 2015 (dates of the FRW switch).

Ward-specific analysis of GM BLLs in Flint before and during the FRW change

Addresses of Flint children were geocoded to allow for regional analysis. The city of Flint is comprised of nine voting wards with distinct demographics, median income, poverty rate, and community assets [14,15]. Ward-specific analysis was conducted to determine potential changes on a ward by ward basis during the three periods. These geographical data were analyzed for the same dates and cohorts described.

Statistical analysis of BLLs

A measure of central tendency is a single value that describes the way in which a group of data cluster around a central value. It is a way to describe the center of a data set. There are three measures of central tendency: the mean, the median, and the mode. We retrospectively compared central tendencies of the BLL data from each time period utilizing geometric means (GM). The CDC uses GM data to analyze population exposure to environmental toxins in blood [16]. GMs are used specifically to provide a better estimate of central tendency for data that are distributed with a long tail at the upper end of the distribution [17]. For the present study, GMs were calculated utilizing approaches described previously by the CDC for the National Health and Nutrition Examination Survey (NHANES) [18]. Consistent with prior approaches [17], 95% confidence intervals for the GMs were computed by first applying the delta method to estimate the standard error of a computed GM, and then adding and subtracting the product of a Student's *t*-statistic (with degrees of freedom equal to the sample size minus 1 and 0.025 of the distribution larger than the value of the statistic) and the standard error of the estimate. The GMs from different periods were formally compared by: (1) computing an estimate of their difference, along with a delta method estimate of the standard error of the difference (allowing for clustering of repeated measures on the same child across any two time periods [288 children had two measures in the data set]), (2)

Table 1. Demographic summary for the three time periods studied.

Flint study demographics	Period I 25 April 2006–15 October 2007	Period II 25 April 2012–15 October 2013	Period III 25 April 2014–15 October 2015
Number of children (*N*)	2095	1834	1734
Race/ ethnicity %			
African American	NA	72	73
White or other	NA	28	27
Mean age in years	2.3	2.2	2.2
Male %	53	51	51
Medicaid Insurance %	NA	94	91

NA: Data not available. Details form HMC legacy databases other than age, *N*, and gender are not available prior to 2012.

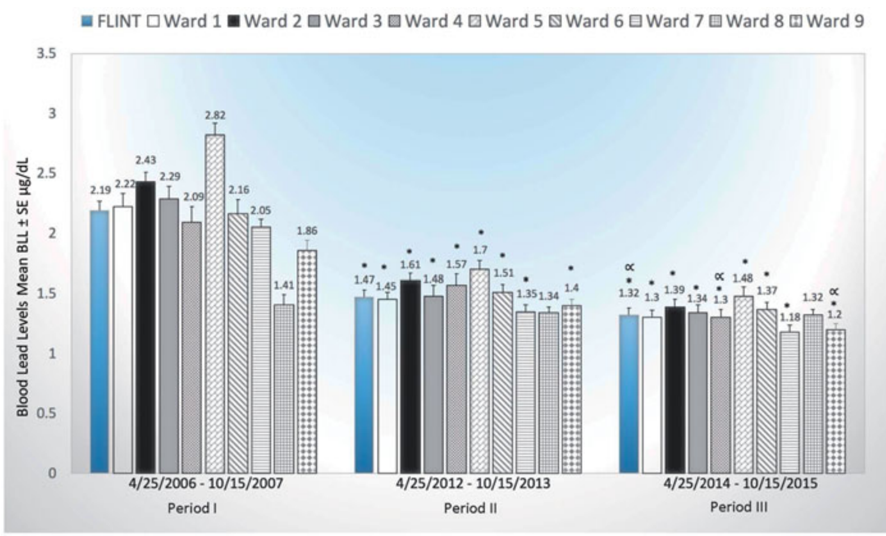

Figure 1. BLL geometric mean ± SE µg/dL for all of Flint (blue bar) and the breakdown of Wards 1 through 9 during three defined 18-month time periods. *: Bonferroni-adjusted significance for Period I v. Period II & III; ∝: Bonferroni-adjusted significance Period II v. Period III. The Flint geometric mean BLL declined in children during the Flint water switch.

forming a test statistic defined by the estimated difference divided by its standard error, and (3) forming a 95% confidence interval for the difference. The null hypothesis that the difference in GMs for any two periods was zero was tested formally by comparing the test statistic to a standard normal distribution to compute a two-sided *p*-value. A Bonferroni adjustment was applied to all *p*-values to account for the multiple pairwise period comparisons performed, either overall for Flint, or for a given ward in Flint. All calculations were facilitated by the Stata software (Version 14.2).

Percentages of BLLs equal to or greater than the CDC reference value of 5.0 µg/dL were compared across time periods using a similar approach, applied to a binary indicator of whether a given BLL value was greater than or equal to 5.0 µg/dL.

Results

Demographics

During the three described 18-month periods, 5663 BLLs of children in Flint, Michigan were analyzed: 2095 in Period I, 1834 in Period II, and 1734 in Period III. The population studied had a mean age of 2.2 years, with 52% of the samples from males (Table 1). Further demographic information regarding race, ethnicity or Medicaid status was not available prior to the introduction of the Epic® EMR in 2012. Medicaid insurance status collection through the Epic® EMR began in 2013. During Periods II and III, over 90% of children were insured through Medicaid (Table 1). Federal regulations mandate that Medicaid-enrolled children be tested for lead exposure at the age of one and two years, or at three to five years of age if not previously tested [1].

Comparison of GM BLLs during the three 18 month periods:

GM BLLs of children aged 5 years and younger residing within Flint boundaries during the three periods studied are shown in Figure 1. There was a 32.9% decrease in GM BLLs ± SE from Period I to Period II: from 2.19 ± 0.03 µg/dL to 1.47 ± 0.02 µg/dL [95% CI, 0.64, 0.79]; $p<.001$. GM BLLs decreased another 10.2% from Period II to Period III (during the FRW switch) from 1.47 ± 0.02 µg/dL to 1.32 ± 0.02 µg/dL respectively [95% CI, 0.10, 0.22]; $p<.001$. Total BLL ranges for the three periods are <0.5 – 94.3 µg/dL, <0.5 – 33.1 µg/dL, and <0.5 – 37.8 µg/dL respectively.

The decrease in GM BLLs from Period I to Period II and Period III is also found at the voting ward level with GM BLLs decreasing significantly in all Flint wards with the exception of Ward 8 (Figure I and Table 2). In comparing Period II to Period III, GM BLLs decreased significantly in Wards 4 and 9 while decreases in other wards did not reach significance.

Table 2. (A) Flint percentage ≥5.0 μg/dL of the three 18-month periods. (B) Geometric mean ± SE μg/dL for the Flint boundary, and detailed breakdown wards 1–9.

	Period I % ≥5 μg/dL (N)	Period II % ≥5 μg/dL (N)	Period III % ≥5 μg/dL (N)	Period I v. II *p*-value 95% CI	Period I v. III *p*-value 95% CI	Period II v. III *p*-value 95% CI
A. Percentage ≥5.0 μg/dL (N)	10.6%	3.3%	3.9%	$p < .001$*	$p = .002$*	$p = .30$
	(2095)	(1834)	(1734)	[5.7, 8.8]	[5.0, 8.2]	[−1.9, 0.57]
B. Geometric mean	Period I μg/dL ± SE (N)	Period II μg/dL ± SE (N)	Period III μg/dL ± SE (N)	Period I v. II *p*-value 95% CI	PERIOD I v. III *p*-value 95% CI	PERIOD II v. III *p*-value 95% CI
Flint total (Wards 1-9)	2.19 ± 0.03 (2095)	1.47 ± 0.02 (1834)	1.32 ± 0.02 (1734)	$p < .001$* [0.64, 0.79]	$p < .001$* [0.79, 0.95]	$p < .001$∝ [0.10, 0.22]
Ward 1	2.22 ± 0.11 (301)	1.45 ± 0.06 (207)	1.30 ± 0.06 (193)	$p < .001$* [0.58, 0.97]	$p < .001$* [0.73, 1.13]	$p = .07$ [−0.01,0.32]
Ward 2	2.43 ± 0.11 (281)	1.61 ± 0.06 (198)	1.39 ± 0.06 (172)	$p < .001$* [0.68, 1.17]	$p < .001$* [0.80, 1.28]	$p = .21$ [−0.06, 0.29]
Ward 3	2.29 ± 0.08 (336)	1.48 ± 0.06 (237)	1.34 ± 0.06 (245)	$p < .001$* [0.61, 1.00]	$p < .001$* [0.75, 1.14]	$p = .07$ [−0.01,0.30]
Ward 4	2.09 ± 0.10 (168)	1.57 ± 0.09 (144)	1.30 ± 0.07 (134)	$p < .001$ [0.26, 0.78]	$p < .001$* [0.26, 0.78]	$p = .02$ ∝ [0.04, 0.50]
Ward 5	2.82 ± 0.13 (266)	1.70 ± 0.09 (194)	1.48 ± 0.08 (205)	$p < .001$* [0.81, 1.42]	$p < .001$* [1.03, 1.64]	$p = .07$ [−0.02, 0.46]
Ward 6	2.10 ± 0.10 (225)	1.51 ± 0.07 (213)	1.37 ± 0.08 (165)	$p < .001$* [0.42, 0.88]	$p < .001$* [0.55, 1.04]	$p = .16$ [−0.05, 0.34]
Ward 7	2.05 ± 0.12 (134)	1.35 ± 0.07 (151)	1.18 ± 0.06 (159)	$p < .001$* [0.43, 0.98]	$p < .001$* [0.60, 1.00]	$p = .08$ [−0.02, 0.36]
Ward 8	1.41 ± 0.07 (134)	1.34 ± 0.06 (202)	1.32 ± 0.06 (187)	$p = .45$ [−0.10, 0.23]	$p = .35$ [−0.09, 0.27]	$p = .80$ [−0.15, 0.19]
Ward 9	1.86 ± 0.08 (250)	1.40 ± 0.05 (288)	1.20 ± 0.05 (274)	$p < .001$* [0.27, 0.64]	$p < .001$* [0.48, 0.83]	$p = .004$ ∝ [0.06, 0.33]

*: Bonferroni-adjusted significance for period I v. Period II & III. ∝: Bonferroni-adjusted significance for period II v. Period III. Flint geometric mean BLLs were significantly lower during the Flint water switch.

Ward 8 GM BLLs remained stable throughout all 18-month periods.

Comparison of percentages equal to and above the CDC reference range of 5μg/dL

BLL percentages equal to and/or exceeding the CDC reference level of 5.0 μg/dL for the three periods are shown in Table 2. The percent of BLLs ≥5.0 μg/dL decreased from Period I (10.6%) to Period II (3.3%) [95% CI, 5.7, 8.8]; $p<.001$ and from Period I to Period III (3.9%); [95% CI, 5.0, 8.2]; $p=.002$. The 0.6% increase noted from Period II (just prior to the FRW change) to Period III (during FRW change) was not statistically significant [95% CI, -1.9, 0.57]; $p=.30$.

The first 8.5 months of years before and during the FRW switch

Using the same data source that was used in the initial post-water switch study of the percentage of BLLs ≥5.0 μg/dL in Flint children, we examined percentages ≥5.0 μg/dL and GM BLLs during the first 8.5-month periods of 2013 and 2015 [9]. In our analysis, percentages above 5.0 ≥ μg/dL increased from 2.26% in the first 8.5 months of 2013 ($N = 840$) to 4.50% in 2015 ($N = 823$); similar to the changes above the CDC reference range reported in the initial paper (2.40%–4.90%) [9]. During the same 8.5-month periods, GM BLLs decreased from 1.35 ± 0.02 μg/dL, to 1.26 ± 0.03 μg/dL in young children [95% CI, −0.19, −0.10]; $p=.04$.

The percentage of BLLs ≥5.0 μg/dL and GM BLLs were also examined during the first 8.5 months of 2012 and compared to 2015. The 2012 percentage was 4.5% ($N = 982$); to the same percentage of 4.5% as in the first 8.5 months of 2015. However, GM BLLs decreased from 1.63 ± 0.03 μg/dL in 2012 to 1.26 ± 0.03 μg/dL in 2015; [95% CI, −0.34, −0.025]; $p=.027$.

Discussion

Contrary to previous investigations focused on examining defined samples of time during the FRW switch, we found that GM BLLs in young Flint children actually *decreased* during the 18-month water switch period compared to identical previous time-periods when controlling for length of time, seasons and months. Similar to national trends, the community of Flint as a whole had consecutive decreases in GM BLLs from Periods I through III. In this study, we demonstrate a substantial decline of 39.7% in GM BLLs and a 63.2% decrease in percentages ≥5.0 μg/dL from the earliest 18-month time period beginning in 2006 to the 18-month time-period of the FRW change. There was a 0.6% non-statistically significant increase from Period II to III in the percentage of children with BLL ≥5.0 μg/dL.

The toxicity of lead, like any xenobiotic, is directly linked to the duration of exposure and toxin concentration in the body. We focused this analysis on the entire 18-month FRW exposure as opposed to other studies [9–11] as there is no discernible or plausible scientific reason to evaluate shorter selected time periods of exposure when evaluating the potential health impact of BLLs in young children during the FRW switch. The examination of the three identical 18-month time frames and the study of *both* GM BLLs and frequency

Table 3. A profile of the demographics of the nine wards located in the City of Flint. These data were compiled from a publication by Rosencrants et al [15].

	Population (approximate)	Ethnicity	Median income	Poverty rate%	College degree	Sub-standard housing
A. City of Flint	100,000	55% African-American, 39% White, 3% Hispanic, 3 % other	$25,000	36.0%	18.6%	12.0%
B. Profiles by ward						
Ward 1	10,069	92% African-American, 3% White, 2% Hispanic	$22,000	41.0%	16.1%	18.0%
Ward 2	10,396	91% African-American, 4% White, 1.5% Hispanic	$25,000	38.0%	17.7%	21.0%
Ward 3	9,700	66% African-American, 28% White, 4% Hispanic	$24,000	50.0%	11.0%	26.0%
Ward 4	11,900	18% African-American, 75% White, 8% Hispanic	$30,555	37.0%	15.1%	9.0%
Ward 5	9,800	56% African-American, 33% White, 3% Hispanic	$23,000	42.0%	15.0%	22.0%
Ward 6	10,847	62% African-American, 33% White, 3% Hispanic	$26,000	43.0%	25.1%	7.0%
Ward 7	11,912	53% African-American, 42% White, 5% Hispanic	$26,000	35.0%	36.5%	5.0%
Ward 8	13,302	33% African-American, 61% White, 3% Hispanic	$32,300	37.0%	24.1%	4.0%
Ward 9	12,065	37% African-American, 57% White, 3% Hispanic	$29,300	39.0%	20.3%	4.0%

percentiles $\geq$5.0 μg/dL reveals comprehensively and accurately the historical pattern of changes in BLLs of Flint children and their relationship to the FRW exposure.

This study indicates that the restriction of studying only percentile changes above the CDC reference value of 5.0 μg/dL may provide an incomplete understanding of BLL changes in a population. Although we found similar percentile changes above the CDC reference range as previously reported during the first 8.5-month periods of 2013 and 2015 [9], GM BLLs *decreased* 7% in young children during this period. This demonstrates the importance of reporting actual BLLs instead of depending only on changes in percentages $\geq$5.0 μg/dL to fully assess the impact of lead exposure in a community.

In addition to reporting actual BLLs instead of simply relying on measuring percentile changes above the CDC reference range of 5.0 μg/dL, *the selection of periods* to be studied can significantly affect a comparative analysis. For example, during the first 8.5 months of PRE-water switch year 2012 data were available for analysis in addition to 2013. The frequency percentage above the CDC reference value during the first 8.5 months of 2012 and 2015 was static at 4.5% for both years, however, the GM BLLs in Flint significantly *decreased 22*% during this period.

We elected to study the 18-month exposure period in its entirety as well as providing the results of *both* the percentage above the CDC reference range and GM BLLs across three 18-month periods to provide a complete and transparent analysis for public health practitioners and clinicians to place the FRW switch in an historical and clinical context. Furthermore, virtually all longitudinal investigations examining the impact of the neurological effects of low-level lead exposure have used BLLs for study [1,2]. Not a single study utilized CDC reference value percentage changes (% $\geq$5.0 μg/dL) to determine neurological impacts in young children [1,2].

The goal of this investigation was not to analyze the many possible sources of lead exposure of children in Flint. There are various sources of lead that likely contributed to lead exposure, especially the sub-standard housing in a post-industrial city such as Flint. However, Period I & II BLLs were significantly higher prior to the FRW switch and were likely a result of well-established sources of lead exposure such as peeling leaded paint, leaded dust on the floor and window sills, and lead-impregnated soil in and around children's domiciles. The continued decrease in BLLs during the FRW exposure suggests that these other sources were an important, and likely the main source of lead exposure inclusive of Period III. Lead in paint, lead in dusts and soils, and lead in drinking water constitute the more important source of lead exposure today. In that group, leaded paint ranks first in importance for young children, followed closely by lead in dusts and soils, and then by tap-water lead [19]. Public health efforts to reduce exposure to leaded paint continue in the Flint community.

A known risk of lead exposure in children includes demographic challenges such as economic disadvantages and dilapidated housing. The switch to FRW changed the source of water to all nine wards contained within the Flint City boundary. A detailed ward by ward analysis (Figure 1, Table

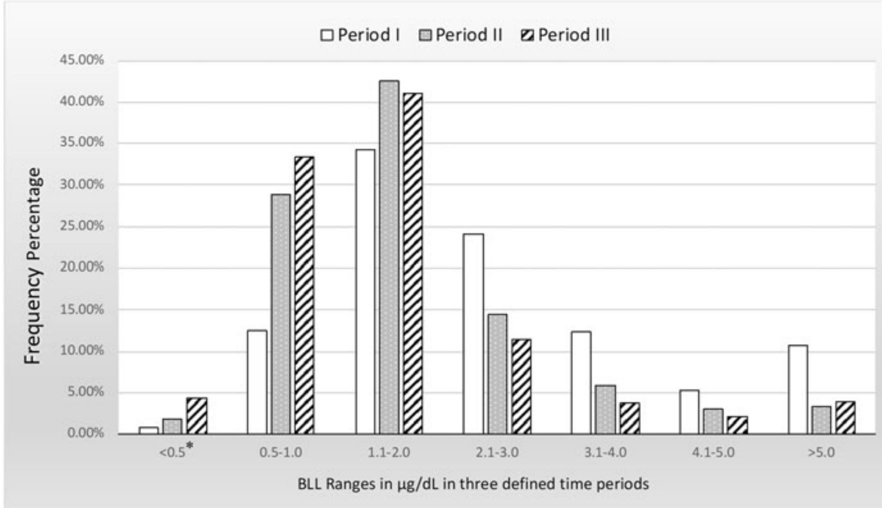

Figure 2. Frequency percentages of BLLs of Flint children within the Flint boundary line in the three defined time intervals. Total BLL ranges for the three periods are <0.5 - 94.3 µg/dL, <0.5 - 33.1 µg/dL, and <0.5 - 37.8 µg/dL respectively. *: Below the limits of detection by atomic absorption.

2) of Flint was done because of known differences in demographics, median income, education and community assets among these sub-communities (15, Table 3). Although each Flint ward contains unique demographics, there was not a single increase in GM BLLs over time in any of the nine Flint wards studied.

We suggest that Flint residents may have been protected through avoidance of using Flint River water either in food preparation or direct consumption. The avoidance of drinking of FRW by the citizenry may in part explain the higher frequency percentage of undetectable BLLs in children noted in Period III (Figure 2) , in addition to ongoing efforts by state and county public health services in reducing the lead burden in the community. Lead itself cannot be seen, tasted, or smelled in drinking water [20,21]. The only way to verify the concentration of lead in water is through direct laboratory testing. The disagreeable appearance and odor of the water during the crisis in Flint was not from lead, but rather from other contaminants such as rust, and divalent metals such as calcium and magnesium that are known to alter the taste of water and affect properties of water characterized as hardness or softness [20,21]. Nevertheless, these minerals are non-toxic despite the poor quality of the taste of water they impact. As a result, depending on a building's service line or water infrastructure, the drinking water may have had perfectly acceptable smell and taste; yet had elevated levels of lead, placing children at higher risk. However disagreeable water may have given a significant portion of Flint citizenry, ample reason and warning to avoid consumption. Furthermore, there was an issuance of a water advisory on 2 January 2015 cautioning the Flint community regarding potential health issues associated with the consumption of the FRW [10] which undoubtedly resulted in further avoidance of FRW by Flint citizens.

Evidence for a water avoidance phenomenon may be found in the statistics from the City of Flint's financial reports, which document the decline in total water consumption in fiscal years 2013–2015 [22]. The centum cubic feet (CCF) of residential water consumption dropped from 2013 through 2015 as follows: 2013 = 9,470,315 CCF, 2014 = 8,114,852 CCF and 2015 = 2,857,898 CCF. This is an overall decline of 69.8% of residential water consumption in Flint from 2013 to 2015 [22]. The average consumption per user declined from 290 CCF in 2013 to 97 CCF in FRW year 2015; a remarkable 66.6% decrease in user water usage [22]. The decline in water consumption decreased lead exposure from water but not from the major sources of lead exposure; such as leaded paint dust, chips or contaminated soil.

No report of lead exposure in children in socially and economically depressed communities comes without significant emotionally charged responses from public health and medical organizations, citizenry, and (in Flint's case) local and national media news outlets which continue to this day [23]. For a community struck with hardship and the recipient of negative news for over 3 years regarding the exposure to the FRW, this investigation reveals that GM BLLs actually *decreased* during the 18-month FRW switch compared to both matched 18-month time-periods examined prior to the water switch. The data does not support the concept of a global BLL increase to merit the stigma nor the opprobrium of a generation of children with permanent intellectual deficits. These findings suggest that when considering the decrease of BLLs in Flint children during the exposure to FRW, public health efforts to reduce lead exposure have been largely effective in the community.

Limitations

We note a decline in the number of BLLs sampled from Periods I to III which may reflect the overall and ongoing decline in the population of Flint from over 107,000 in 2006 to 99,802 in 2015 (Table 1) [24]. Although HMC affiliated clinics and physicians are the primary source of care of high risk lead exposed Flint children, our data does not account for every Flint child's BLL. Based on CDC data, we estimate that our investigation and others [9,11] accounts for approximately half of BLLs in Flint children during 2006–2016 [10]. Few children aged less than one-year were tested, and no child tested was young enough to be formula dependent. Therefore, changes in BLLs in the very young from water used in formula preparation during 2014–2015 FRW switch cannot be determined. We have no data to determine the source or the combination of sources that are responsible for elevated levels in some Flint children.

Conclusions

The exposure of young children to FRW from 25 April 2014 to 15 October 2015 in Flint coincided with a decrease in BLLs of young children when compared to prior time-periods controlling for time-length studied, months and seasons. Over the three 18-month time-periods studied, GM BLLs decreased 39.7% and the percentage of children with BLLs above the CDC reference value decreased 63.2%; this occurred across all 9 wards in the community. Analyses of GM BLLs and percentages $\geq 5.0\,\mu g/dL$ do not support the common perception of an occurrence of a global increase in BLLs occurring during the 18-month FRW change in the young children of Flint. Additionally, national, state and local BLLs have historically been down-trending for years. Although the environmental hazard of the FRW switch was significant, it did not result in globally increased BLLs nor percentages above the CDC reference value during the entire 18-month FRW switch. These findings suggest that public health efforts to reduce BLLs of Flint children have been effective. Nevertheless, public health officials, legislators and clinicians should continue efforts and allocate resources to further decrease environmental lead exposure of all children in the nation.

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