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Estimated burden of blood lead levels $\geqslant 5\,\mu g/dl$ in 1999–2002 and declines from 1988 to 1994

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Abstract

In light of recent data suggesting adverse health effects at blood lead levels (PbB) $<10\,\mu g/dl$, lowering the current definition of elevated blood lead ($\geqslant 10\,\mu g/dl$) has been recommended. To ascertain the population level impact of such a change, we calculated the prevalence of PbB $\geqslant 5\,\mu g/dl$ in 1–21-year-old population in the United States. Furthermore, we characterized changes in PbB between 1988–1994 and 1999–2002.

We analyzed data from the National Health and Nutrition Examination Survey (NHANES) III ($n = 10{,}755$) and NHANES 1999–2002 ($n = 8013$).

In 1999–2002, about 91.7% of study children had detectable levels of lead in the blood. Among them, 7.3%, 2.8%, and 1.0% children and adolescents aged 1–5, 6–11, and 12–21 years, respectively, had PbB between 5 and 9.9 μg/dl. This number translates to approximately 2.4 million individuals. Between 1988–1994 and 1999–2002, the geometric mean PbB declined from 2.88 to 1.94 μg/dl in children 1–5 years, 1.80 to 1.36 μg/dl in children 6–11 years, and 1.24–1.02 μg/dl in children and adolescents 12–21 years of age. Also, the prevalence of PbB $\geqslant 5\,\mu g/dl$ declined from 25.7% to 8.8%, 12.8% to 3.0%, and 7.5% to 1.2% in these age groups, respectively.

A substantial proportion of children may be at risk for adverse health effects from lead exposure below 10 μg/dl and a large number of children will be classified as having elevated PbB if 5 μg/dl is considered the threshold. Significant public health resources will have to be mobilized for intervention, screening, and case management of these children.
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1. Introduction

According to data from 1999 to 2002 National Health and Nutrition Examination Survey (NHANES), the prevalence of elevated blood lead (EBL; $\geqslant 10\,\mu g/dl$) among children 1–5 years of age is 1.6%; a substantial decline from 77.8% in 1976–1980 [Centers for Disease Control and Prevention (CDC, 2005)]. Despite the overall reduction in blood lead levels (PbB) in the US population, a large number of children (approximately 310,000) 1–5 years of age remain at risk of harmful environmental lead exposure (CDC, 2005). Given the widespread presence and detrimental effects of lead, lowering its exposure in childhood is an important public health objective and a priority of *Healthy People* 2010 [US Department of Health and Human Services (DHHS), 2000; US Department of Housing and Urban Development (HUD), 2000].

In 1991, the Centers for Disease Control and Prevention (CDC) set the threshold for defining EBL in children at 10 μg/dl (CDC, 1991). However, there is no clinical threshold of lead below which it can be considered 'safe'

Abbreviations: CDC, Centers for Disease Control and Prevention; CI, confidence interval; EBL, elevated blood lead levels; NHANES, National Health and Nutrition Examination Survey; PbB, blood lead levels.

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for human health (CDC, 2002). Canfield et al. (2003) found significant declines in children's IQ scores associated with PbB, even among children whose lifetime peak PbB were below the threshold of 10 μg/dl. Similar findings were reported from a prospective study in Boston (Bellinger et al., 1992; Bellinger and Needleman, 2003). A recent international pooled analysis of seven cohort studies reported that an increase in PbB from 2.4 to 10 μg/dl was associated with a 3.9 point decrement in IQ (Lanphear et al., 2005). In a study among Mexico City metropolitan area children, researchers found inverse associations between PbB <10 μg/dl at 24 months and concurrent mental and psychomotor development indexes (Tellez-Rojo et al., 2006). Based on these findings, reconsideration of the acceptable threshold of PbB has been recommended (Lanphear et al., 2000, 2005; Tellez-Rojo et al., 2006; Landrigan, 2000; Needleman and Landrigan, 2004).

The adverse effects of PbB below 10 μg/dl are also present in older children. Children between the ages of 4–15 years with PbB above 2.0 μg/dl had a 4.1-fold increased risk of ADHD compared with children with PbB <2.0 μg/dl (Braun et al., 2006). Analysis of data from a large prospective clinical trial of intervention for lead poisoning suggests neurological toxicity of lead persists beyond the pre-school age (Chen et al., 2005). Also, neurocognitive deficits were associated with PbB lower than 5 μg/dl in children 6–16 years old in NHANES III (Lanphear et al., 2000).

Since EBL is currently defined as PbB ⩾10 μg/dl, many children, currently defined as 'not elevated', may have harmful PbB. To better understand the burden of lead exposure under 10 μg/dl, we sought to determine the prevalence and distribution of PbB ⩾5 μg/dl among children and adolescents 1–21 years of age in the United States using data from NHANES 1999–2002. The 5 μg/dl cut off was chosen based on the fact that all past revisions and decrements of EBL definitions were a multiple of five points (Bernard and McGeehin, 2003). Additionally, we characterized the change in PbB from 1988–1994 through 1999–2002.

2. Methods

2.1. Participant selection

This study utilized data from NHANES 1999–2002 and NHANES III (1988–1994). These surveys include a representative sample of civilian, non-institutionalized US population and were conducted by the National Center for Health Statistics of the CDC. To provide stable sub-group estimates, non-Hispanic blacks, Mexican Americans, low income persons, adolescents 12–19 years were over-sampled in each NHANES [National Center for Health Statistics (NCHS, 1996a, 2005)].

The current study included children and adolescents 1–21 years of age from NHANES 1999–2002 ($N = 9525$). Females who were pregnant at the time of the physical examination were excluded ($n = 97$). A total of 1415 (16.3%) individuals were missing blood lead values and were excluded from all analyses. Implication of missing blood lead values on study results has been addressed in the discussion section. Data were available for 8013 participants after all exclusions. Similar inclusion and exclusion criteria resulted in 10,755 individuals in the final dataset from NHANES III.

2.2. Data collection

NHANES survey components included a household interview followed by a medical evaluation and laboratory testing. Of relevance to the current study, information on participants' race, sex, health insurance status, home ownership, total household income, and housing age were collected during the home interview. For the household interview, proxy respondents, when available, were used for children under 16 years of age (NCHS, 1996a, 2005). Age at the time of the medical evaluation was used for all analyses; this variable was missing for eight participants in NHANES 1999–2002 and was replaced by age at the time of the interview. During the visit to the mobile examination clinic, blood samples were drawn following standardized protocol (NCHS, 1996a, 2005).

2.3. Measurement of blood lead

Blood samples were shipped on dry ice to the NHANES laboratory at the National Centers for Environmental Health at the CDC in Atlanta, GA. Blood lead was measured using whole blood and graphite furnace atomic absorption spectroscopy [National Center for Environmental Health (NCEH, 2001); NCHS, 1996b]. In NHANES 1999–2002, the detection limit for blood lead was 0.6 μg/dl and the lowest value assigned to persons with undetectable PbB was 0.2 μg/dl ($n = 106$) (NCEH, 2001). The lowest detectable PbB for NHANES III was 1.0 μg/dl and the values below detection levels were assigned 0.7 μg/dl ($n = 1090$) (NCHS, 1996b). For purposes of comparability, all PbB below the detection limit values in NHANES III were recoded to 0.2 μg/dl. This change will result in a conservative estimate (i.e., an under-estimate) of the decline in PbB between 1988–1994 and 1999–2002. However, this approach permitted an unbiased assessment of PbB for 1999–2002. Recoding PbB below the detection limit to 0.2 μg/dl did not substantially alter any of the results.

2.4. Statistical analyses

For NHANES 1999–2002, demographic and socio–economic characteristics of participants included in the current study were calculated by age groups. These characteristics include sex, race-ethnicity, home ownership, health insurance status, income levels, and housing age. Also, the age-specific prevalence of PbB ⩾5 μg/dl and geometric mean PbB with 95% confidence intervals (CI) were calculated for these population subgroups. Chi-square and *t*-tests were used to assess the significance of differences in the prevalence of PbB ⩾5 μg/dl and geometric mean PbB, respectively, across population subgroups. Least squares and maximum likelihood were used to determine the trend in PbB and prevalence of PbB ⩾5 μg/dl, respectively, across income levels and housing age. The geometric mean and prevalence of PbB ⩾5 and PbB ⩾10 μg/dl were calculated by age grouping (1–5, 6–11, and 12–21 years) for NHANES III and NHANES 1999–2002, separately. *t*-Tests were used to determine the significance of changes in geometric mean PbB between 1988–1994 and 1999–2002. Chi-square tests were used to assess the changes in prevalence of PbB ⩾5 and PbB ⩾10 μg/dl between these two periods.

SAS software (Version 9.0, SAS Institute Inc., Cary, NC) was used for data management and SUDAAN (Release 9.0, Research Triangle Institute, Research Triangle Park, NC) for data analysis. All analyses took into account the complex survey design and study weights utilized in NHANES (NCHS, 1996a, 2005).

3. Results

3.1. Results from NHANES 1999–2002 population

The distributions of socio-demographic characteristics were similar in each age group in NHANES 1999–2002 (Table 1). The study population was almost equally represented by males and females and the majority of the population was non-Hispanic white. In all age groups, most of the participants were home owners and had health insurance; approximately one third of the population had an annual household income of less than $25,000 and almost half resided in houses built before 1978.

Children 1–5 years of age had higher geometric mean PbB compared with children 6–11 and 12–21 years of age (Table 2). For each age group, non-Hispanic blacks had a higher geometric mean PbB than non-Hispanic whites. Also, in the oldest age group, Mexican Americans had significantly higher PbB than non-Hispanic whites. Participants who were not home owners and did not have health insurance had significantly higher PbB compared with their counterparts who were home owners and had health insurance, respectively. In each age group, we found that PbB increased significantly with progressively lower income and increasing housing age (p-trend <0.05).

The prevalence of PbB $\geqslant 5\,\mu g/dl$ was lower at older age (Table 3); children 1–5 years of age had the highest prevalence of PbB $\geqslant 5\,\mu g/dl$ (8.8%) compared with children 6–11 years (3.0%) and 12–21 years (1.2%) of age (p-trend <0.05). In each age group, participants with lower household income were more likely to have PbB $\geqslant 5\,\mu g/dl$. In the two younger age groups, non-Hispanic blacks, participants who were not home owners, and residents of older housing (pre-1950) had a higher prevalence compared with non-Hispanic whites, home owners, and residents of housing built recently (1978 and after). In the oldest age group, a higher prevalence of PbB $\geqslant 5\,\mu g/dl$ was present among males, and participants without health insurance compared with females and participants with health insurance, respectively.

Table 1
Characteristics of the NHANES 1999–2002 study population by age groups ($N = 8013$)

Variable	1–5 years ($n = 1600$) %	6–11 years ($n = 1946$) %	12–21 years ($n = 4467$) %
Sex, male	52.3	52.6	51.4
Race			
Non-Hispanic White	57.2	59.7	60.7
Non-Hispanic Black	15.4	16.1	14.6
Mexican American and other Hispanic	23.9	20.7	19.0
Other races, and multiracial	3.5	3.5	5.7
Home ownership			
Owner	55.9	60.2	64.6
Renter or other arrangements	44.1	39.8	35.4
Health insurance			
Yes	88.8	84.7	81.3
No	11.2	15.3	18.7
Annual household income			
<$25,000	35.6	31.7	31.4
$25,000 to <$45,000	24.4	21.3	20.5
$ 45,000 to <$75,000	22.2	21.9	22.5
⩾$75,000	17.9	25.1	25.5
Year residence built			
Before 1950	20.4	20.3	20.9
From 1950 to 1978	28.2	26.0	33.1
1978 and after	51.4	53.7	46.0

Overall, 91.7% of the study children had detectable levels of lead in their blood (Fig. 1). A majority of them (68.4%) had PbB between 0.6 and 1.9 μg/dl; 20.1% had PbB between 2.0 and 4.9 μg/dl. The prevalence of PbB between 5.0 and 9.9 μg/dl was 7.3%, 2.8%, and 1.0% in 1–5, 6–11, and 12–21 years of age group, respectively, and 2.8% in the overall study population (Fig. 1).

3.2. Declines in PbB from 1988–1994 through 1999–2002

For each age group studied, a significant decline (each $p<0.05$) in the geometric mean PbB (Fig. 2) and the prevalence of PbB $\geqslant 5\,\mu g/dl$ (Fig. 3) occurred between 1988–1994 and 1999–2002. Specifically, 25.7%, 12.8%, 7.5% children and adolescents 1–5, 6–11, and 12–21 years of age had PbB $\geqslant 5\,\mu g/dl$ in 1988–1994 compared with 8.8%, 3.0%, and 1.2% in 1999–2002, respectively. The prevalence of PbB $\geqslant 10\,\mu g/dl$ also decreased significantly (each $p<0.05$) in all age groups between these two time periods (data not shown).

4. Discussion

Several studies have reported a non-linear relationship between children's PbB and intellectual development suggesting adverse effects of PbB at levels $<10\,\mu g/dl$ (Canfield et al., 2003; Lanphear et al., 2005; Tellez-Rojo et al., 2006; Kordas et al., 2006). An inverse relationship between IQ scores and PbB $<10\,\mu g/dl$ after adjusting for potential confounders, maternal IQ, and home environment has been reported (Fulton et al., 1987; Schwartz, 1994). A significant decline in children's cognitive functions was observed even when their lifetime peak PbB was below 10 μg/dl (Canfield et al., 2003; Lanphear et al., 2005). Studies have also found adverse lead-induced health effects in children older than 5 years at levels lower than 10 μg/dl (CDC, 2002; Lanphear et al., 2000; Chen et al., 2005; Kordas et al., 2006). In our study, around 7.3%, 2.8%, 1.0% children in the 1–5, 6–11, and 12–21 years age group had PbB between 5.0 and 9.9 μg/dl, respectively. Since the current threshold of an EBL is 10 μg/dl, an additional 7.3% of children 1–5 years old (approximately 1,360,623 children) may be affected by environmental lead exposure than currently estimated, if 5 μg/dl is considered the

Table 2
Geometric mean (95% CI) blood lead by population characteristics and age groups in 1999–2002

Variable	Geometric mean PbB (95% CI) (μg/dl)		
	1–5 years	6–11 years	12–21 years
Overall	1.94(1.79, 2.10)***	1.36(1.29,1.45)	1.02(0.98,2.06)
Sex			
Male	1.95(1.81,2.11)	1.45(1.34, 1.57)*	1.26(1.21, 1.31)**
Female	1.94(1.75, 2.13)	1.27(1.18, 1.37)	0.82(0.79, 0.85)
Race			
Non-Hispanic white	1.79(1.59, 2.01)	1.24(1.13, 1.37)	0.95(0.90, 1.01)
Non-Hispanic black	2.80(2.54, 3.09)**	1.97(1.75, 2.22)**	1.23(1.16, 1.31)**
Mexican American and other Hispanic	1.87(1.70, 2.07)	1.33(1.21, 1.47)	1.13(1.07, 1.21)**
Other races, and multiracial	2.02(1.62, 2.50)	1.37(1.05, 1.81)	0.97(0.85, 1.11)
Home ownership			
Owner	1.70(1.54, 1.87)	1.22(1.13, 1.32)	0.96(0.92, 1.00)
Renter or other arrangements	2.29(2.12, 2.48)**	1.60(1.51, 1.70)**	1.14(1.05, 1.23)**
Health insurance			
Yes	1.89(1.75, 2.05)	1.32(1.25, 1.40)	0.97(0.93, 1.01)
No	2.38(2.08, 2.74)*	1.61(1.37, 1.87)*	1.27(1.20, 1.35)**
Annual household income			
<$25,000	2.45(2.32, 2.61)***	1.77(1.63, 1.91)***	1.22(1.15, 1.30)***
$25,000 to <$45,000	1.91(1.67, 2.20)	1.36(1.24, 1.50)	1.04(0.96, 1.13)
$ 45,000 to <$75,000	1.64(1.47, 1.85)	1.13(1.04, 1.22)	0.95(0.91, 0.99)
⩾$75,000	1.32(1.20, 1.46)	1.03(0.93, 1.14)	0.83(0.78, 0.88)
Year residence built			
Before 1950	2.73(2.39, 3.15)***	1.45(1.31, 1.60)***	1.15(1.06, 1.24)***
From 1950 to 1978	1.83(1.70, 1.99)	1.25(1.15, 1.35)	0.96(0.87, 1.06)
1978 and after	1.48(1.34, 1.63)	1.15(1.04, 1.27)	0.90(0.85, 0.96)

*p-Value <0.05.
**p-Value <0.001.
***p-Value for trend <0.05.

threshold of concern. Although PbB decreased with age, 2.8% and 1.0% (approximately 1,062,063 children, total) of children and adolescents 6–11 and 12–21 years, respectively, had PbB between 5 and 10 μg/dl in 1999–2002. In total, approximately 2.4 million US children and adolescents aged 1–21 years may be affected by adverse lead exposure. However, it should be noted that there is no 'safe' clinical threshold of PbB (CDC, 2002). Therefore, using PbB ⩾5 μg/dl as a cut-off point provides a conservative estimate of the burden of harmful lead exposure.

As a result of ongoing prevention efforts, PbB as well as prevalence of EBL (⩾10 μg/dl) in the US has declined substantially (CDC, 2005). A significant decrease in both the geometric mean PbB and the prevalence of PbB ⩾5 μg/dl across all age groups were observed when we compared data from 1999–2002 to data from 1988–1994. This reveals that the declining trend in the US population continues even at PbB<10 μg/dl in children and adolescents in the US population.

While substantial declines in blood lead levels have occurred in recent decades, it is important to place the reduction in blood lead into historical context; current PbB remain orders of magnitude higher than in pre-industrial human societies (0.016 μg/dl) (Flegal and Smith, 1992; Bellinger, 2004). The population mean PbB has been estimated to be between 1^{51} and 2^{52} orders of magnitude higher than the natural background PbB in humans (Bellinger, 2004). In our study population, 91.7% of participants had detectable levels (⩾0.6 μg/dl) of blood lead (Fig. 1) with large proportions (68.4% and 20.1%, respectively) between 0.6–1.9 μg/dl and 2.0–4.9 μg/dl. This burden of PbB below 10 μg/dl is significant from a public health perspective since, admittedly, population PbB remains a concern for health professionals even at low levels and despite the lack of effective interventions at these levels (Bernard, 2003).

Among those 1–5 years of age, non-Hispanic blacks, children with low household income, who were not home owners, and children residing in older housing (pre-1950) had a higher burden of PbB ⩾5 μg/dl. These findings are consistent with data from NHANES III (Bernard and McGeehin, 2003). It is not surprising to find that socio-demographic risk factors for PbB ⩾5 μg/dl are the same as the risk factors for EBL (⩾10 μg/dl) (Bernard and McGeehin, 2003; Bernard, 2003). The higher risk of these subpopulations for increased PbB highlights the need for targeted prevention efforts. Population subgroups that were found to be at highest risk for PbB ⩾5 μg/dl in the 1–5 years age group continue to be at risk through 11 years of age. However, among older children and adolescents (i.e., between ages 12–21 years of age), males, those with low income level, and without health insurance were found to be at highest risk for PbB ⩾5 μg/dl. This indicates that the at-risk population may be different for children and adolescents 12–21years of age compared with their younger counterparts. However, the finding that females 12 years of age or older had significantly lower prevalence than males warrants further research as to the etiology of such difference.

Table 3
Prevalence of blood lead ⩾5 μg/dl by population characteristics and age groups in 1999–2002

Variable	PbB ⩾5 μg/dl (%)		
	1–5 years	6–11 years	12–21 years
Overall	8.8***	3.0	1.2
Sex			
Male	9.3	3.3	2.0*
Female	8.2	2.7	0.3
Race			
Non-Hispanic white	7.3	2.1	1.1
Non-Hispanic black	18.5*	7.6*	1.2
Mexican American and other hispanic	6.7	1.6	1.9
Other races, and multiracial	5.0	6.2	0.0
Home ownership			
Owner	6.6	1.8	0.6
Renter or other arrangements	11.3*	4.9*	2.3
Health insurance			
Yes	8.2	2.7	0.9
No	12.6	4.9	2.5*
Annual household income			
<$25,000	12.8***	5.9***	2.6***
$25,000 to <$45,000	8.6	1.7	0.7
$ 45,000 to <$75,000	4.5	1.8	0.4
⩾$75,000	2.4	0.6	0.2
Year residence built			
Before 1950	19.1***	3.4***	1.7
From 1950 to 1978	5.4	2.3	0.9
1978 and after	2.1	0.6	0.5

*p-Value <0.05.
**p-Value <0.001.
***p-Value for trend <0.05.

A limitation of this study lies in the high proportion of children who were missing blood lead values. For a large number of children in NHANES 1999–2002 (16.3%), PbB values were missing. Among children 1–5 years of age, non-Hispanic white, home owners, children with high income levels, and with health insurance and among those 6–11 years of age, home owners, and children with health insurance had higher percentage of missing PbB values. Since these population subgroups had a lower prevalence of PbB ⩾5 μg/dl, we may have overestimated the prevalence of PbB ⩾5 μg/dl for the 1–5 and 6–11 years age groups. No significant differences were present among those with and without missing PbB values for the 12–21-year-old age group (data not shown).

More than once in the past, evidence from scientific research studies has led to the revision and subsequent lowering of the toxicity threshold of PbB (Lanphear et al., 2000; Bernard and McGeehin, 2003; Bernard, 2003; Bellinger and Bellinger, 2006; Bellinger, 1995). Evidence of adverse health effects below the current defined threshold of EBL (10 μg/dl) have resulted in recommendations for lowering or revision of the definition (Lanphear et al., 2005; Tellez-Rojo et al., 2006; Landrigan, 2000; Lanphear et al., 2000; Needleman and Landrigan, 2004). The CDC advisory Committee on Childhood Lead Poisoning Prevention is reported to be currently reviewing the health effects of lead under 10 μg/dl (Brown and Meehan, 2004; Bernard, 2003). Should the CDC revise current screening practices and the threshold for EBL, our study findings,

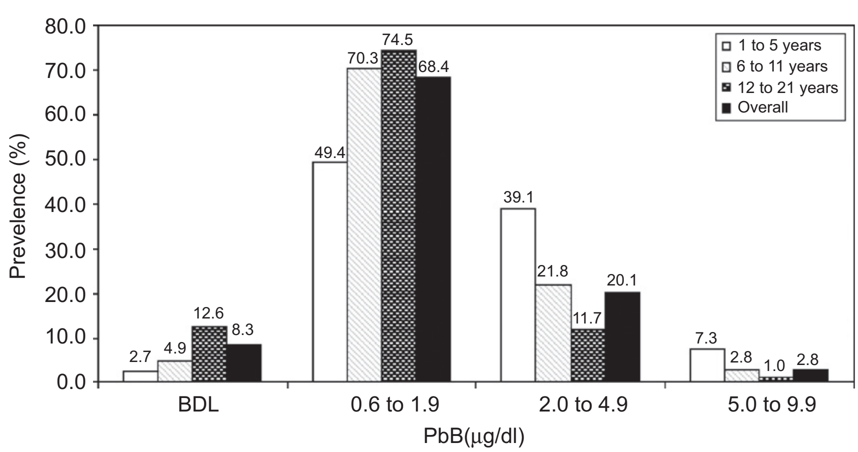

Fig. 1. Blood lead levels below 10 μg/dl among 1–21 years old US population 1999–2002.

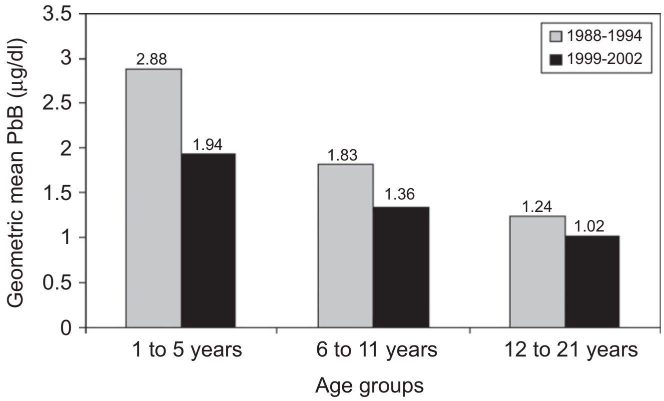

Fig. 2. Geometric mean PbB in 1988–1994 and 1999–2002.

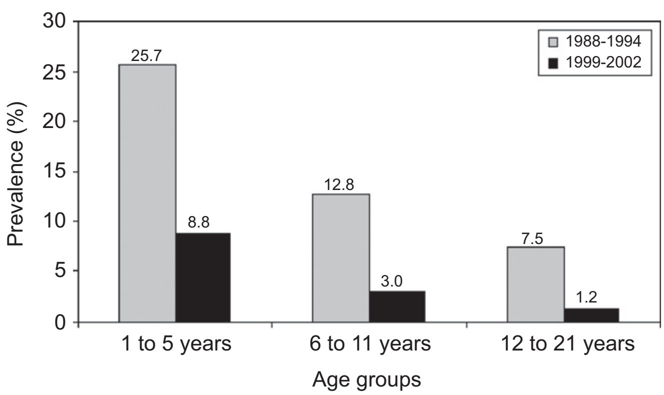

Fig. 3. Prevalence of PbB $\geqslant 5\,\mu g/dl$ in 1988–1994 and 1999–2002.

based on a representative sample of the US population, indicate that a large number of children will be classified as having elevated PbB and significant public health resources will have to be mobilized for intervention, screening, and case management of these children.

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