ARTICLE

The Social Costs of Childhood Lead Exposure in the Post–Lead Regulation Era

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Objective: To estimate the benefits that might be realized if all children in the United States had a blood lead level of less than 1 μg/dL.

Design: Data were obtained from published and electronic sources. A Markov model was used to project lifetime earnings, reduced crime costs, improvements in health, and reduced welfare costs using 2 scenarios: (1) maintaining the status quo and (2) reducing the blood lead level of all children to less than 1 μg/dL.

Participants: The cohort of US children between birth and age 6 years in 2008, with economic and health outcomes projected for 65 years.

Interventions: Increased primary prevention efforts aimed at reducing lead exposure among children and pregnant women.

Main Outcome Measures: Societal costs and quality-adjusted life years (QALYs) gained.

Results: Reducing blood lead levels to less than 1 μg/dL among all US children between birth and age 6 years would reduce crime and increase on-time high school graduation rates later in life. The net societal benefits arising from these improvements in high school graduation rates and reductions in crime would amount to $50 000 (SD, $14 000) per child annually at a discount rate of 3%. This would result in overall savings of approximately $1.2 trillion (SD, $341 billion) and produce an additional 4.8 million QALYs (SD, 2 million QALYs) for US society as a whole.

Conclusion: More aggressive programs aimed at reducing childhood lead exposure may produce large social benefits.

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During the critical developmental period between birth and age 6 years, lead exposure may reduce cognitive ability, as measured by the IQ test, and executive control.[1-5] As a result, children who have been exposed to lead tend to perform below their potential in school. This way, lower educational attainment reduces an individual's earnings and increases welfare dependency.[6] Lower educational attainment and lead-induced neurobehavioral changes have been shown to increase criminal behavior and incarceration rates.[7-16] These social deprivations may, in turn, adversely affect health and longevity.[17-20]

In the past, children were primarily exposed to lead via inhalation of the combustion products of leaded gasoline and ingestion of lead-containing paint.[2,8] Before regulations required removing lead from these products, geometric mean blood concentrations of lead reached 15 μg/dL among children between birth and age 6 years in the late 1970s (to convert to micromoles per liter, multiply by 0.0483).[8,21] Today, blood lead levels in children are at historic lows.[8,11] Nevertheless, many children continue to be exposed to lead through old housing stock, soil contamination, traditional medications, or lead-based industry near human habitats.[8] Because little has been done to address these ongoing sources of lead exposure, the mean blood levels of lead appear to have reached an asymptote at around 2 μg/dL.[21]

The present study examines the social benefits of policy changes sufficient to reduce childhood lead exposures such that no child between birth and age 6 years has a blood lead level of 1 μg/dL or more. This threshold was picked because complete elimination of childhood lead exposure may be unrealistic and because exposure at this level appears to produce minimal reductions in measures of cognitive performance.[5,22-24]

METHODS

OVERVIEW AND DEFINITIONS

Lead plausibly produces a wide variety of direct and indirect social effects. These include effects on medical costs, schooling costs (eg, special education or grade retention), teen pregnancy, low-birth-weight infants, child abuse,

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crime, earnings, welfare utilization, and adult health.[2,14] However, teen pregnancy, low-birth-weight infants, intergenerational transmission of poverty, child abuse, and nonviolent criminal activity were not included in this analysis because the evidence base linking lead to these social costs was weaker and because the analysis produced a large net benefit without the inclusion of such costs.

The remaining costs (**Figure**) were included as inputs to a Markov chain model. The Markov model estimates year-to-year changes in costs during the lifetime of a cohort of children between birth and age 6 years who were exposed to lead at the current rate of exposure and a cohort of children between birth and age 6 years who were unexposed (defined here as a blood lead level of <1 μg/dL). The model calculates annual changes in earnings, welfare utilization, and crime. It also accounts for health and mortality differences between the cohorts. All costs are presented in constant 2008 dollars. Costs and quality-adjusted life years (QALYs) are discounted at a rate of 3% in accordance with the recommendations of the Panel on Cost-Effectiveness in Health and Medicine.[25]

Model inputs were selected using a "levels of evidence" approach,[26] with inputs derived from randomized controlled trials given the highest priority, instrumental variable analyses second, and prospective studies with comprehensive and appropriate controls third. Studies exploiting spatial and temporal variations in exposures were used as supporting evidence for the other study designs. The proportion of children between birth and age 6 years within each blood lead level stratum was obtained using the combined results of the 1999-2006 National Health and Nutrition Examination Surveys,[27] which includes a nationally representative sample of the noninstitutionalized civilian population of the United States.

IQ

The inverse association between childhood lead exposure and IQ is curvilinear, with a steep, falling slope between 1 μg/dL and 10 μg/dL followed by a significantly less steep linear decline thereafter.[22] The social costs associated with the effect of childhood lead poisoning on educational attainment were therefore estimated by separating blood lead levels into 3 strata: less than 1.0 μg/dL, 1 to 10 μg/dL, and more than 10 μg/dL.

The studies used to estimate IQ values control for household socioeconomic status, maternal IQ, and the Home Observation for Measurement of the Environment (HOME) score. Children with a blood lead level of less than 1 μg/dL were assumed to function at their full potential. Children with a blood lead level from 1 to 10 μg/dL were assigned a 7-point reduction in IQ.[22] This value was obtained from a single, prospective study of 172 children with low levels of exposure that examined the nonlinear effects of blood lead level concentrations on IQ. This result is similar in magnitude to that from a pooled estimate using international data from 1333 children.[24]

For childhood blood lead levels of more than 10 μg/dL, 2 reviews found a slope between −0.19[23] and −0.32.[28] This latter estimate includes studies of children with lower blood lead levels and is therefore biased by the steeper lead-IQ association among children with low-level (≤10 μg/dL) exposure. Therefore, to define the slope of the relationship for childhood blood lead levels higher than 10 μg/dL, the −0.19 value was used.

EARNINGS

Previous estimates of the impact of childhood lead exposure on earnings were based on the effect of IQ on earnings and high school graduation rates.[9,13,14] However, the literature on the direct effect of IQ on earnings is less rigorous than that of educational attainment on earnings.[29,30] Therefore, the present study estimates changes in earnings based solely on changes in high school graduation rates (Figure).

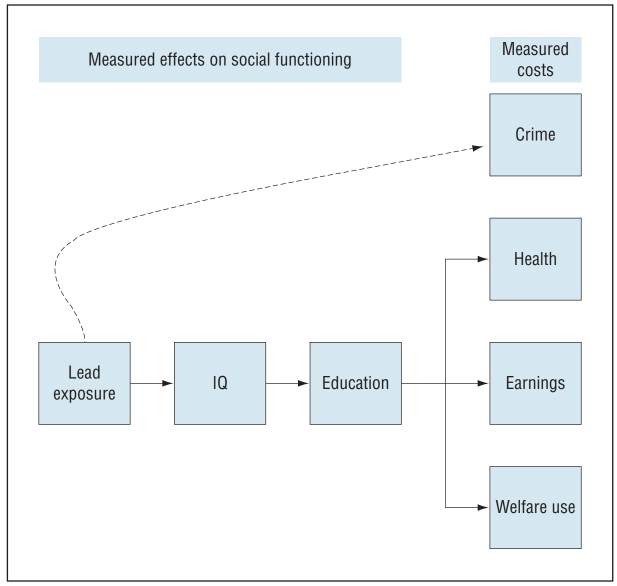

Figure. The model linking childhood lead exposure to social costs. Solid lines represent pathways mediated via educational attainment; dashed pathway, the direct effects of childhood lead exposure on crime.

The economics literature contains estimates of the effect of educational attainment on earnings derived from randomized controlled trials, instrumental variable analyses, and twin studies.[6,30-33] These studies find a 10% to 17% increase in earnings associated with a year of schooling.[30] The present analysis relied on a recent and extensive review of the economics literature coupled with a recent analysis of Current Population Survey data to derive the earnings increases associated with producing 1 additional high school graduate.[34]

Many childhood lead exposures occur among children from families with lower socioeconomic status.[2] These children face a wide range of social obstacles unrelated to lead exposure that may limit a child's full earning potential. Notably, such children are much less likely to ultimately attend top-tier colleges. Therefore, in the base-case analysis, earnings conservatively include those of students who complete high school, but exclude those of students who go on to complete college.

CRIME COSTS

Criminal activity was the sole social cost associated with childhood lead exposure that was not based on high school graduation.[7] The relationship between childhood lead exposure and adult criminal activity is curvilinear throughout the range of exposures. Therefore, it was necessary to use narrower strata in this analysis (5 to <10, 10 to <15, 15 to <20, 20 to <25, and ≥25 μg/dL) than those used to estimate other social costs.

Evidence of a link between educational attainment and criminal activity is available from randomized controlled trials of educational interventions, among other study designs.[6,35,36] There is also evidence for a direct effect of childhood lead exposure on crime arising from the neurobiology literature, which shows that childhood lead exposure leads to behavioral problems[2,11,12,16]; spatial and temporal data using variation in exposure as a measure, which shows that at least 56% of the variation in crime rates can be explained by childhood lead exposure[11,37]; and prospective follow-up data with the same covariates used in the lead-IQ analysis (eg, maternal IQ, socioeconomic status, and the HOME score), which show a 7% to 40% increase in arrests per 5 μg/dL increase in blood lead level, depending on the measure of childhood lead exposure used.

The latter prospective study was used to estimate crime costs in the present analysis. In that prospective study, the most appropriate measure of childhood lead exposure—the mean blood lead level between birth and age 6 years—is statistically significant for violent criminal activity but not for other types of crime. Therefore, only the effect of lead on violent crime is included in the present analysis.

Approximately 73% to 92% of violent crimes occur when perpetrators are aged 18 to 40 years, with a spike at ages 18 to 25 years. Uniform Crime Reports data were used to adjust for variations in violent crime rates across different ages.[38] The cost per crime was obtained from a review of the academic literature.[39]

Crime costs were calculated as follows. First, arrest ratios by mean childhood blood lead levels were obtained.[7] Second, reported crimes were conservatively assumed to be equal to the number of crimes committed. Third, because future crime costs are calculated among children born today, it was necessary to use projected crime rate data to 2027.[37] Fourth, the marginal change in costs of each of the 4 types of violent crime (murder, rape, assault, and robbery) at each stratum of childhood lead exposure was calculated as follows: $CR \times RR - CR$, where CR is the adjusted rate of crime expected in 2027 and RR is the risk ratio for increased criminal activity at each of the lead-specific blood levels used in the study. These excess rates were then multiplied by the crime-specific cost. Because the risk ratios were not broken down by the specific type of violent crime, it was assumed that all 4 crime types were equally influenced by childhood lead exposure.

WELFARE COSTS

Welfare programs in the United States are means-tested. Welfare utilization is therefore inversely related to earnings. To the extent that educational attainment affects earnings, we would expect declines in welfare utilization with increasing educational attainment. A recent comprehensive review of predicted changes in welfare utilization by educational attainment was used to estimate changes in the use of Temporary Assistance to Needy Families, food stamps, and housing assistance.[40] These costs are essentially transferred from one segment of the population (the taxpayer) to another (the recipient). Because money is transferred rather than spent, it is only appropriate to count the administrative cost associated with this transaction when viewing costs from the perspective of society as a whole.[25] The costs of administering these programs was obtained from the Congressional Budget Office.[41]

HEALTH BENEFITS

The health benefits of additional educational attainment are well documented[42-44] and may arise from having a quality job that provides health insurance, enhanced social networks, decreased behavioral risk factors, nepotistic connections, improved decision-making, and higher income.[20]

Instrumental variable analyses of the education-mortality relationship may produce larger effect size estimates than regression, suggesting that the regression-based estimates in the present study are conservative.[42,43] To enhance modeling of quality-adjusted life expectancy, this analysis uses regression-based estimates of morbidity (QALYs) and mortality. One QALY is equivalent to a year of life in perfect health.[25]

Mortality models were constructed using data from the 1997-2000 National Health Interview Surveys linked to mortality data via the National Death Index, with follow-up through the end of 2002 (the most recent follow-up year that is publicly available).[45,46] Health-related quality of life (HRQL) models were constructed using the EuroQol EQ-5D from the 2000-2002 Medical Expenditure Panel Surveys.[47] The EQ-5D is QALY-compatible and captures the respondents' mobility, self-care, usual activities, pain/discomfort, and anxiety/depression.[48] To derive the age-specific mortality risks and mean HRQL scores, US high school graduates were used as a standard population. This allows removal of possible confounding owing to between-group differences in covariate distributions. Two sets of estimated regression coefficients were applied to each member of this standard population, and predictions were averaged to derive risk-factor specific estimates of age-specific mortality rates and HRQL scores.

Regression analyses were conducted using Stata statistical software, version 10.0 (Statacorp, College Station, Texas), adjusting for the complex survey designs of the National Health Interview Survey and the Medical Expenditure Panel Survey. All regression models adjusted for age, log age (to address nonlinear age effects), sex, region of the country (Northeast, South, Midwest, and West), and survey year (as a series of dummy variables).

Mortality regression coefficients were estimated by a multiplicative hazards parametric regression model of age-at-event failure time data, specified as a log-linear model using Poisson regression.[49,50] To better estimate the effect of time-varying age on the baseline hazard, this model used person years as the unit of analysis, with each person contributing an observation for each full or partial year of follow-up.

MARKOV MODEL

A Markov model was used to compare life expectancy, HRQL scores, direct medical costs, special education costs, earnings, crime costs, and welfare costs during the lifetime of the 24 million children between birth and age 6 years in the United States. In the model, mortality effects, salary benefits, crime costs, and welfare costs begin to accrue only after age 18 years. Therefore, although the cost of the intervention is presented in today's dollars, future benefits are not realized until age 18 onward. They are therefore continuously discounted for 15 years before they begin to accrue. Model inputs are listed in **Table 1**.

The model contains 2 arms: reduction of childhood blood lead levels to less than 1 μg/dL and the status quo (current practice). The only variations between the less than 1 μg/dL and status quo arms are that high school graduation rates differ and crime costs are only incurred in the status quo arm of the model. The core model is described in more detail elsewhere.[53]

Monte Carlo simulation, based on values in Table 1, was used to generate confidence intervals around the estimates with 10 000 samples and 100 random walks per trial.[25] The model was constructed using DATApro 2008 (TreeAge Software, Williamstown, Massachusetts). Standard deviations are presented in parentheses.

RESULTS

Of the 24 million children between birth and age 6 years in the United States, 17 million have blood lead levels of 1 μg/dL or higher (Table 1).[27] If current trends continue, we would expect 68% of these children to ultimately graduate from high school on time. This rate would increase to 91% if none of these children had a blood lead level higher than 1 μg/dL. Each of these additional high school graduates could reasonably be expected to realize earnings at least $11 500 higher per year than if they had not graduated from high school and would use $691 less per year in administrative overhead for welfare programs. These additional high school graduates would also have a lower risk of annual mortality and an improved HRQL. Finally, lower exposures to lead in childhood would reduce the mean per person social cost of crime in the United States by $399 per year.

These annual monetary benefits would add up to $50 000 ($14 000) in savings during the average person's lifetime at a 3% discount rate (**Table 2**). The health benefits would add up to 0.2 QALYs (0.08 QALYs) during the average person's lifetime at a 3% discount rate. Reducing blood lead levels among the entire cohort of 24 million children between birth and age 6 years would save society $1.2 trillion ($341 billion) and produce an additional 4.8 million QALYs (2 million QALYs).

Because these projected benefits are not realized until the children reach age 18, they are highly dependent on the discount rate. Undiscounted benefits reach $145 000 ($40 000) and 1.15 QALYs gained (0.45 QALYs) per person. When discounted at 5%, projected benefits fall to $27 000 ($6000) and 0.07 QALYs (0.007 QALYs) gained per person.

The only other source of error in the model with as much influence as the discount rate was the projected effect of childhood lead exposure on high school graduation rates. Under the assumption that the impact of lead on high school graduation is half of the best estimate in the literature (on-time graduation rates increased from 68% to 80% rather than 91%), the lifetime returns fall to approximately $30 000. At this level of high school graduation, the average number of QALYs gained per person falls to 0.1.

Table 1. Parameters Used as Markov Chain Model Inputs[a]

	Baseline	Low	High
No. of US children between birth and age 6 y[51]			
All	24 354 685	. . .	. . .
Lead level >1 μg/dL[27]	16 665 911	. . .	. . .
Lead levels for children between birth and age 6 y, %[27]			
<1 μg/dL	12.8	. . .	. . .
1-10 μg/dL	85.4	. . .	. . .
>10 μg/dL	1.7	. . .	. . .
On-time high school graduation rate, %[52]			
<1 μg/dL	91	88	93
1-10 μg/dL	68	68	68
>10 μg/dL	65	65	65
Benefits per additional high school graduate, $			
Income[34]	11 511	4620	18 401
Social services[40]	691	458	924
Health-related quality of life[b]			
High school dropouts	0.80	0.79	0.82
High school graduates	0.84	0.83	0.84
Crime benefits of lead level <1 μg/dL, $[c]	399	399	1700
Relative mortality risk[d]	0.83	0.78	0.90

Abbreviation: ellipses, not applicable.

SI conversion factor: To convert lead to micromoles per liter, multiply by 0.0483.

[a]The baseline values are the most likely. The low and high values were used in 1-way and Monte Carlo sensitivity analyses.

[b]Based on the EuroQol EQ-5D from the 2000-2002 Medical Expenditure Panel Surveys and scaled 0 to 1, with 0 equal to a state of death and 1 equal to a state of perfect health. These figures represent the mean of age-specific EQ-5D scores between ages 18 and 90 years in 1-year intervals.

[c]The baseline value was the lowest value encountered in the literature and is thus set equal to the low value. The high value is based on a randomized controlled trial of an educational intervention that also included a parental educational component. This high value was used in a 1-way sensitivity analysis but not in the Monte Carlo simulation.

[d]This figure represents the ratio of the mean age-specific mortality rates for high school dropouts and graduates. The Markov model used age-specific rates in 1-y intervals.

COMMENT

Although mean blood lead levels in children today are a fraction of what they were 2 decades ago, childhood lead exposure remains a significant social problem. If every child's blood lead level was reduced to less than 1 μg/dL, a single cohort of newborns to 6-year-olds would conservatively contribute more than a trillion additional dollars to US society during their lifetimes. As additional children are born into a world with a lower baseline lead exposure, the benefits would multiply. It is likely that achieving this blood lead level would cost a tiny fraction of the projected savings.

Still, any examination of the benefits of reducing childhood lead exposures is inherently limited by the available

Table 2. Lifetime Monetary Contributions and QALYs[a]

Strategy	Lifetime Societal Contribution, $	Incremental Contribution (SD), $	Lifetime QALYs	Incremental Effectiveness (SD), QALYs
		Discount Rate 0%		
Status quo	897 641	. . .	49.16	. . .
Lead level <1 μg/dL	1 042 494	145 000 (40 000)	50.31	1.15 (0.45)
		Discount Rate 3%		
Status quo	315 242	. . .	15.35	. . .
Lead level <1 μg/dL	365 572	50 000 (14 000)	15.55	0.20 (0.09)
		Discount Rate 5%		
Status quo	171 869	. . .	8.30	. . .
Lead level <1 μg/dL	199 158	27 000 (6000)	8.37	0.07 (0.007)

Abbreviations: ellipses, not applicable; QALYs, quality-adjusted life years.

SI conversion factor: To convert lead to micromoles per liter, multiply by 0.0483.

[a]Status quo indicates present-day children between birth and age 6 years, and lead level of <1 μg/dL indicates children born into a world in which no child's blood lead level is 1 μg/dL or higher.

data. First, although all model inputs were supported by data from randomized controlled trials and instrumental variable analyses, the literature supporting these relationships is still not well developed. For instance, existing randomized trials of educational interventions were small or few, and some included additional intervention components, biasing the study estimates downward.[6,19,32,54] Likewise, instrumental variable analyses are highly dependent on the quality of the instrument.[33,42,55]

These study designs also limit the specificity of the analysis. For instance, it is often difficult to obtain the accurate age-specific estimates that are needed to model changes in social costs during the lifetime of the 2 cohorts of interest. To improve the specificity of the estimates, regression analyses were used where the estimates from randomized controlled trials and instrumental variable analysis produced estimates that were equal to or greater than those produced by regression. This ensures that costs are better tabulated across different age groups.

This analysis also renders more conservative estimates of modeled benefits, which were based on a number of conservative assumptions, low estimates, and excluded costs. For instance, other estimates of the impact of childhood lead exposure on earnings are higher than those used here.[9,14,56] The same is true for the relationship between high school graduation and mortality[42,43] or crime rates.[37,39] By presenting estimates of the minimal benefits of reducing childhood lead exposure, the present study minimizes the potential costly error of diverting constrained resources from important social investments to a less cost-effective alternative.

The weakest link in the analytical model is the impact of childhood lead exposure or IQ on high school graduation rates. Much of the literature on this relationship is based on simple correlation without adequate controls. Estimates are complicated by the observation that educational attainment is positively correlated with IQ. The one value used in the present study was derived from the relationship between educational attainment and dentine lead levels with adequate controls.[14] Although input relies on a single estimate in the literature, the social costs were still considerable, amounting to roughly $30 000 per child or $731 billion per cohort nationwide, even when the effect size was halved.

Finally, this study does not include suggestions for reducing environmental lead hazards. Some sources of exposure, such as tainted alternative medicine remedies, should be relatively inexpensive to address.[56] Others, such as exposure to contaminated soil, could be significantly more expensive. It will be challenging to correctly identify the remaining sources of exposure that can be addressed at an acceptable cost. A panel of experts is needed to help develop a priority list of potential points of intervention. What is clear from this study is that the public health battle against childhood lead exposure is not yet over.

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The machine does not isolate man from the great problems of nature but plunges him more deeply into them.

—Antoine de Saint-Exupéry, *Wind, Sand, and Stars*, 1939