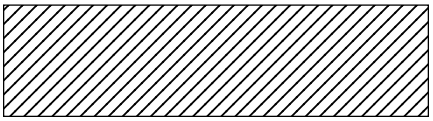

COSTS AND BENEFITS OF A UNIVERSAL SCREENING PROGRAM FOR ELEVATED BLOOD LEAD LEVELS IN 1-YEAR-OLD-CHILDREN

Peter A. Briss, M.D.[1], Thomas D. Matte, M.D., M.P.H.,[1] Joel Schwartz, Ph.D.,[2], Lisa S. Rosenblum, M.D., M.P.H.,[1] Sue Binder, M.D.[1]

Abstract

Background. In 1991, the Centers for Disease Control recommended screening all children for elevated blood lead levels, that is blood lead levels of at least 10 micrograms per deciliter, except in communities where large numbers or percentages of children have been screened and found not to have lead poisoning. We have quantitatively compared the economic costs and benefits of universal screening to help refine guidance on screening and to define information gaps in evaluating the effectiveness, cost-effectiveness, and economic benefits of blood lead screening.

Methods. We used mathematical simulations of a blood lead level screening program to estimate the costs and benefits of universal screening as the prevalence of elevated blood lead levels varied. To do this, we estimated 1) the distribution of elevated blood lead levels in 1-year-old children, 2) the accuracy of blood lead screening tests, 3) the costs of screening for and intervening to reduce elevated blood lead levels, 4) the effectiveness of interventions to reduce blood lead levels, 5) the relationship of elevated blood lead levels to adverse health outcomes, and 6) the economic costs of lead-related adverse health effects.

Results. As the observed prevalence of elevated blood lead levels increased, the cost, effectiveness, and economic benefits of universal screening increased. When more than 14% of children had elevated blood lead levels, the economic benefits of universal screening exceeded the costs. When less than 14% of children had elevated blood lead levels, the costs of universal screening exceeded the benefits. The simulations were reasonably robust to changes in most assumptions; changing most assumptions within broad ranges resulted in relatively modest changes in the threshold prevalence at which benefits of screening exceeded the costs within a range of 11% to 17%. This threshold prevalence was, however, very sensitive to the estimated effectiveness of educating families of children with elevated blood lead levels about ways to reduce lead exposures and, to a lesser extent, to the estimated costs and effectiveness of environmental interventions for reducing children's blood lead levels.

Discussion. In mathematical simulations of a blood lead screening program, universal screening for elevated blood lead levels produced economic benefits exceeding program costs in communities where at least 11% to 17% of children had elevated blood lead levels. In communities with lower prevalences of elevated blood lead levels, universal screening may be inefficient or ineffective in improving children's health and development; in lower prevalence communities, other strategies such as more targeted screening, reducing lead exposure sources in the environment, and educating families about lead hazards and ways to avoid them may be preferable to testing every young child for an elevated blood lead level. Additional studies to better evaluate the effectiveness and cost-effectiveness of interventions to reduce children's blood lead levels, especially relatively low blood lead levels, are needed.

[1] *National Center for Environmental Health, Centers for Disease Control and Prevention (CDC), Atlanta, Georgia;*
[2] *Harvard University School of Public Health*

Introduction

Despite considerable progress in controlling lead exposure in the United States, 9% of American children have elevated blood lead levels (BLLs), that is, BLLs of at least 10 micrograms per deciliter (μg/dL). Some of these children have higher BLLs.[1] Very high BLLs are associated with a variety of severe health effects; subtle problems with learning and behavior have been reported among children with BLLs at least as low as 10 μg/dL.[2] Screening children for elevated BLLs to trigger interventions to reduce lead exposure is one of many tools for preventing or controlling childhood lead poisoning.

In 1991, the Centers for Disease Control (CDC) recommended screening all children for elevated BLLs, except in communities where large numbers or percentages of children have been screened and found not to have lead poisoning.[3] In some communities, the resultant increase in screening helped to identify large numbers of children with elevated BLLs who needed individual management to reduce their BLLs.[4,5] However, average BLLs U.S. children have declined,[1] and some communities have identified relatively small numbers of children with elevated BLLs, a finding that has prompted considerable concern about whether universal screening for elevated BLLs provides benefits that outweigh its risks and costs.[6,7]

A quantitative comparison of the costs and benefits of universal screening for elevated BLLs (universal screening) at varying prevalences of elevated BLLs may now be useful for two reasons. First, it can serve as a basis for guidance about screening in populations with different prevalences of elevated BLLs. Second, it may help to define areas where research is needed into the effectiveness and cost-effectiveness of BLL screening.

Methods

Structure of the simulations

We used mathematical simulations of a BLL screening program to compare the estimated economic costs and benefits of performing universal screening for elevated BLLs compared with performing no screening in hypothetical populations of 10,000 1-year-old children with different prevalences of elevated BLLs. For each population, we estimated the following (Figure 1):

1. A distribution of "true" BLLs among the children.
2. The BLLs observed among children in a screening program.
3. The costs of screening, follow-up, and interventions to reduce children's BLLs.
4. The effectiveness of interventions triggered at age one to reduce children's BLLs at age 2.
5. The health and economic benefits that might result later in life as a result of reducing children's BLLs at age 2.

Data and assumptions

We obtained data for the simulations by reviewing published and unpublished studies and by consulting with experts in lead poisoning prevention, epidemiology, pediatrics, public health, and economics. When necessary, we contacted authors of published studies for additional data that do not appear in the published reports. We chose a single best estimate and a range of uncertainty for every assumption.

Economic assumptions

The analysis was done from a societal perspective (i.e., we attempted to include all costs and benefits of screening without regard to who would pay the costs or receive the benefits). We adjusted economic costs and benefits to 1992 dollars using the Consumer Price Index for all items (CPI) or the medical CPI and also adjusted wages to 1992 dollars using the

estimated annual hourly earnings growth for the nonfarm sector.[8] We discounted economic costs and benefits occurring in the future at 5% per year.

Distribution of BLLs in the population and performance of screening tests

Information about the distribution of BLLs in the population and the performance of BLL screening tests are summarized in Table 1. We defined distributions of true BLLs in children and changed the prevalence of elevated BLLs by changing the geometric mean of the distribution.

BLLs measured in a screening program can be either falsely high or falsely low compared with true blood lead levels because laboratory measurement of BLLs is not perfectly accurate or precise. We accounted for errors and biases in blood lead measurement from three sources: biases due to blood-sampling techniques, imprecision in laboratory measurement of BLLs, and changes in children's BLLs with time.

We assumed that screening blood samples were obtained by fingerstick and that confirmatory and follow-up samples were obtained by venipuncture. Because BLLs obtained by fingerstick may be contaminated by lead on the child's skin, we assumed that the laboratories overestimated "true" BLLs by an average of 1μ g/dL.[9,10] We assumed that specimens obtained by venipuncture did not have a systematic bias.

We estimated the variability in children's BLLs from imprecision in laboratory testing and variability in children's BLLs with time by using data from research studies in which children's BLLs were repeatedly measured. These studies allowed us to estimate the geometric standard deviation (GSD) of each log-transformed BLL (the within-individual GSD). We used this value to randomly simulate screening, confirmatory, and follow-up BLLs that would be observed in a screening program in which the observed BLL = $e^{[\ln(\text{"true" BLL at age one})+(\ln(\text{within individual GSD}))*\text{random term}]}$ and the random term was normally distributed with a mean of zero and variance of one.

This method allows us to account for blood lead testing results that are either higher than the true BLLs (false positive) or lower than the true BLLs (false negative). False positive results generate costs out of proportion to benefits, and false negative results may result in a failure to obtain some of the benefits that would otherwise have been expected from the screening program.

The observed GSD (antilog of the standard deviation on the log scale) in the simulated screening test results was 1.9—higher than the range of 1.67-1.79 reported in several recent studies of children living near lead smelters.[11] We chose this value because children living near smelters probably have less than typical variability in BLLs since all such children share a single large source of lead exposure. In contrast, we selected values so that the "observed" GSD in our simulations was less than the 2.12 recently measured in a probability sample of U.S. children in the Third National Health and Nutrition Examination Survey (NHANES III)[1] **(and CDC, unpublished data, date ?)** because the national estimate includes variability among communities that is not relevant in any single community.

Costs of Screening and Interventions

The cost estimates used in this analysis and the ranges for sensitivity analyses are shown in Table 2.

Screening and follow-up services

A visit to a physician and a blood sample for anemia screening are recommended for 1-year-old children whether or not BLL testing is done.[12] For children whose observed BLLs are not elevated, no additional follow-up care is recommended, and the laboratory cost of a blood lead test represents the entire cost of screening.

For children with elevated BLLs, additional blood lead testing is recommended. We assumed that children with screening BLLs of at least 10 μg/dL would require one confirmatory and one follow-up BLL test and that children with BLLs of at least 20 μg/dL would require a confirmatory and two follow-up tests. The cost of each recommended confirmatory and follow-up test included the costs of a visit to a pediatrician, a venipuncture, and a BLL test.

We assumed that children with elevated BLLs received education about lead poisoning and environmental and medical management.[3] Children were assigned these services on the basis of confirmatory BLL results.

Families of children with confirmed elevated BLLs were assumed to receive education about lead poisoning and ways to prevent it. Available studies that estimate the effectiveness of education in reducing BLLs involved home visits by study personnel. Therefore, we assumed that home visits would occur and assigned costs and benefits accordingly.

In our simulations, children with confirmed BLLs of at least 20 μg/dL or two consecutive BLLs exceeding 15 μg/dL received environmental assessments and interventions (environmental management) in addition to education. The environmental management on which benefits were based in our simulations involved house cleaning and spot-paint repair.[13] We evaluated changing the cost and effectiveness of these interventions in sensitivity analyses.

In our simulations, children with BLLs of at least 40 μg/dL but less than 70 μg/dL received outpatient medical treatment with the oral lead-chelating drug succimer, as well as education and environmental management. Children with confirmed BLLs of at least 70 μg/dL received in- hospital treatment with intravenous edetate disodium calcium (EDTA). Chelation therapy is sometimes used for children with BLLs as low as 20 μg/dL,[14,15] so we evaluated changing BLL ranges for which chelation would be used in sensitivity analyses.

We assumed that half of the children who received chelation therapy with EDTA required two courses, that one-quarter of the children required three courses,[16] and that the average number of chelation treatments with succimer was similar to that required with EDTA. We assumed that all repeat courses of chelation therapy used succimer. Thus, each child requiring EDTA received an average of one course of EDTA and 0.75 courses of succimer, whereas each child receiving succimer received an average 1.75 courses.

Side effects of chelation therapy are generally minor and rare.[3] We did not assign costs associated with treating these side effects.

Direct nonmedical costs

We estimated that both clinic visits and environmental interventions required 2 hours of one parent's time and that a home education visit required 1 hour of one parent's time. We did not assign a time cost for chelation therapy because we are unaware of available data allowing us to estimate this cost and because few children undergo chelation therapy. Thus, this cost would have little effect on the simulations. We estimated the cost of parents' time on the basis of the U.S. mean daily wage.

Benefits of screening

The objective of BLL screening is to identify children with elevated BLLs so that educational, environmental, and medical therapy can lower their BLLs and improve their health outcomes. For this analysis, we estimated the health and economic benefits of screening by estimating 1) the number of children with elevated BLLs who would not have been identified without screening, 2) the reductions in BLLs that could be achieved by educational, environmental, and

medical interventions, and 3) the health and economic benefits of reducing BLLs. We have attempted to place an economic value on the following benefits of reduced BLLs: improved learning and behavior, lower special education costs, benefits of identifying and fixing lead hazards in housing.[17]

Expected BLLs in the absence of screening
BLLs in children typically increase from age 1 to age 2.[18] To predict these expected increases, we used data from the Cincinnati cohort study in which the ratio of children's geometric mean (GM) BLLs at age 2 to those at age 1 stratified by housing type ranged from 1.16 to 1.29[18] (S. Clark, University of Cincinnati School of Medicine, Department of Environmental Health, personal communication, 1994). We chose 1.19 as our base estimate of this value.

Individual children have BLL increases with age that vary around this average. We estimated 1) each child's expected BLL at age 2 as a function of the "true" BLL at age 1, 2) the average increase in children's BLLs from age 1 to age 2, and the within-individual standard deviation of children's BLLs at age 2 using this equation: $e^{[\ln(\text{"true" BLL at age one})+1.19+(\ln(\text{within-individual GSD}))*\text{random term}]}$.

We estimated the within-individual standard deviation as 1.33 on the basis of changes in children's BLLs from age 1 to age 2 in the Cincinnati cohort study[18] (P. Succop, University of Cincinnati School of Medicine, Department of Environmental Health, personal communication, 1994). The random term was normally-distributed with a mean of zero and a variance of 1. We applied changes in BLLs attributable to interventions to the expected BLL at age 2.

Effectiveness of interventions in reducing BLLs
Estimates of the effectiveness of interventions in reducing children's BLLs are summarized in Table 3.

Education
Our "base-case" estimate of education's effectiveness in reducing BLLs came from Milwaukee Health Department program data. These data were collected from children whose initial BLLs ranged from 20 to 24 μg/dL, and most follow-up blood lead data were collected from 3-12 months after the initial BLL. After adjusting for season, researchers found that children whose parents received education about lead poisoning prevention had follow-up BLLs that were 0.87 times the BLLs of children whose parents did not receive education. This estimate varied little with the increasing time interval between the initial and follow-up BLL test.[19]

We assumed that this reduction in exposure would apply to all children who received educational visits and had true BLLs of at least 20 μg/dL. We assumed that children who had true BLLs of less than 20 μg/dL had no change in BLLs after their parents had received educational information about preventing lead poisoning.

An alternative estimate of the effectiveness of education in reducing children's BLLs came from a study done in a community located near an Illinois lead smelter.[20] In this study, families of children with elevated BLLs received intensive education. Children whose families had the intervention had average follow-up BLLs of 0.64 times their initial BLLs[20] (and R. Kimbrough, The Institute for Evaluating Health Risks, Washington, D.C., personal communication, 1995). This study did not incorporate a control group and probably overestimated the effectiveness of education for at least two reasons: first, it did not account for regression to the mean (i.e., it did not account for the tendency of subjects with extreme values of a test to have scores closer to the mean on

retesting). Second, it did not account for the effect of aging of the children on BLLs (i.e., it did not account for the fact that older children have lower average BLLs than younger children). For these reasons this study represents a ceiling estimate of education's potential effectiveness. We used this estimate in a sensitivity analysis for children with true BLLs of at least 10 μg/dL. For a lower-bound estimate of the effectiveness of education, we assumed education had no effect on BLLs.

Environmental management

We used data from a study in St. Louis, Missouri, to estimate the effect of environmental management on BLLs.[13] One year after house cleaning and spot-paint repair, children in the intervention group whose initial BLLs ranged from 25 μg/dL to < 35 μg/dL had BLLs that were 0.99 times those in the control group. Children whose initial BLLs were at least 35μg/dL had BLLs of 0.79 times those among children in the control group. In base-case analyses, because of the limited effectiveness of this intervention for children with lower initial BLLs, we did not assume that this environmental intervention reduced BLLs for children with true BLLs < 25 μg/dL.

We did not find other controlled studies measuring the effect of environmental interventions on children's BLLs although several such studies are in progress. We expect that more extensive interventions would result in greater reductions in children's BLLs but would be more expensive. We tested the effect of increasing the costs and the effectiveness of environmental management in sensitivity analyses.

Chelation therapy

The goal of chelation therapy is to permanently reduce a child's BLL to < 25 μg/dL.[14,21] In our simulations, we assumed that the combination of chelation therapy, environmental management, and education could reduce the BLLs of children receiving chelation therapy to 20 μg/dL by age 2. We did not evaluate the effects of chelation independently from the effects of other interventions because chelation therapy should always be done in conjunction with education and environmental management.[3]

Health benefits of reducing BLLs

We have used the established inverse relationship between children's BLLs and their full-scale IQ to estimate the adverse health effects of elevated BLLs because this relationship between BLL and IQ is consistently reported in most studies and has been well quantified by meta-analyses. For a base-case analysis, we used the results of a recent meta-analysis that showed that a 1 μg/dL increase in BLL at age 2 results in a loss of 0.257 points of IQ at school age.[22] In sensitivity analyses, we present the results of using another recent meta-analysis that has estimated that a 1 μg/dL increase in BLL at age 2 results in a loss of 0.185 points of IQ at school age,[23] and we also show the results of varying the range of assumptions more widely.

Economic benefits of reducing BLLs

Estimates of the economic benefits of reducing BLLs have been published previously.[16,17] Estimates of economic benefits of reduced lead exposure used in this analysis include three main categories: 1) improvements in lifetime earnings attributable to reductions in lead-induced problems with intelligence or behavior, 2) reduction in lead-related special-education costs, and 3) economic benefits of identifying and fixing dangerous housing so that other people are not exposed to lead. A complete review of this topic is beyond the scope of this discussion, but these valuation methods have been discussed in detail.[17]

Lifetime earnings

In this analysis we used reductions in lifetime earnings as a proxy for the economic costs of continuing lead exposure for children. It has

been suggested that lead exposure may reduce lifetime earnings by three pathways.[16,17] First, increased BLLs cause declines in IQ,[22,23] and reduced IQ is associated with lower wages and earnings.[17] Next, even after adjusting for lead's direct effect on IQ, researchers suggested that children with elevated BLLs may progress less far in school.[17] This reduced scholastic achievement is assumed to be mediated by the non-IQ effects of lead on development, such as reduced attention or worsened behavior. Reduced final grade achieved also directly reduces wages and may also reduce lifetime participation in the work force; both of these factors can also reduce lifetime earnings.[17] Estimates of the size of these effects are presented in Table 4. Combining these effects, we estimate that a 1μg/dL reduction in a child's BLL at age 2 compared with the BLL that would otherwise have occurred, would result in an average $1169 increase in lifetime earnings discounted to the present.

Reductions in special education costs
The cost of 3 years of special education for one child was estimated to be $18,780.[17] Assuming that 20% of children prevented from exceeding a BLL of 25 μg/dL will avoid special education that they otherwise would have required[17] and discounting special-education costs to 4 years in the future (i.e., when the child begins school), we estimate a benefit of $3090 in special-education costs saved per child who is prevented from having a BLL $\geq$ 25 μg/dL.

Primary prevention benefits
As with some other prevention activities, such as screening for sexually transmitted diseases, BLL screening may benefit people other than the person who is screened. This benefit occurs if BLL screening leads to identifying and remediating environmental lead sources, thus preventing future exposure of other people.

A previous analysis has estimated the primary prevention benefits of reducing lead in housing stock (i.e., the benefits of reducing lead exposure associated with housing that accrue to future inhabitants of a home).[16,] We have updated that model to make it consistent with current average BLLs on the basis of data from NHANES III and have assumed that the duration of the environmental management methods similar to those used in this study that involve house cleaning and spot-paint repair, is for 1 year rather than for the life of the house. We estimate a primary prevention benefit of this level of environmental management that is $745 per house that has undergone such an intervention.

Sensitivity analyses
We performed sensitivity analyses in which we varied each of our assumptions (including assumptions about distribution of BLLs in the population, performance of screening tests, effectiveness of interventions, costs, and benefits) one at a time within broad ranges.

Statistical testing
The primary purpose of this analysis was to estimate the prevalence of elevated BLLs at which the economic benefits of screening exceeded the economic costs (i.e., the prevalence at which the ratio of benefits to costs exceeds 1). After developing the final simulation, we performed replicate analyses with different random numbers to evaluate the sensitivity of the simulation to sampling error. At benefit/cost ratios near 1, the coefficient of variation (ratio of the standard deviation to the mean) of the benefit/cost ratio is approximately 5%. Thus, our estimates are relatively insensitive to sampling error, and we do not present additional measures of statistical variability.

Results
Table 5 shows estimates of the cost, effectiveness, and economic benefit of a universal screening program compared with the costs to society of having no program.

As the observed prevalence of elevated BLLs increases, both costs and benefits of universal screening increase. At low prevalences of elevated BLLs, the costs exceed the benefits. At higher prevalences, the benefits of universal screening exceed the costs. The benefits of universal screening first exceed the costs at a prevalence of 14%.

Sensitivity analyses

Results of sensitivity analyses are shown in Table 6. Changing most assumptions within broad ranges resulted in changes in the threshold prevalence at which benefits exceeded costs within a relatively narrow range of 11% to 17%. However, the simulations are very sensitive to estimates of education's effectiveness in reducing BLLs. The range of estimated educational effectiveness in reducing BLLs that we tested resulted in threshold prevalences from as low as 1% to as high as 25%. The simulations are also moderately sensitive to 1) estimates of the variability of lead exposure in the population (as measured by the population GSD), 2) biases in capillary sampling, 3) high-cost laboratory tests, 4) the cost and effectiveness of environmental management, 5) the size of the effect of lead exposure on IQ and scholastic achievement, 6) estimates of lifetime earnings, and 7) the primary prevention benefits of reducing lead in housing.

Discussion

Childhood lead poisoning is a major preventable environmental health problem in the United States. However, childhood lead exposure is not equally distributed in the U.S. population and the appropriateness of different strategies for reducing lead exposure will differ among communities. The available tools for addressing childhood lead poisoning include reducing lead hazards in housing, reducing other sources and pathways of lead exposure, screening young children for elevated BLLs, performing surveillance for elevated BLLs, and educating families about lead hazards in the environment and how to avoid them.

This analysis compares the costs versus the benefits of screening all 1-year-old children for elevated BLLs to the costs versus the benefits of screening no children. The analysis is useful for estimating the threshold prevalence at which universal screening is likely to provide benefits out of proportion to its harms and costs. In communities where universal screening seems ineffective or inefficient for preventing childhood lead poisoning, the effectiveness and cost effectiveness of targeted screening strategies and other childhood lead poisoning prevention approaches should be explored.

Ideally, decisions about BLL screening could be based on direct information that compares the advantages and disadvantages of screening in populations of children. However, no well-designed clinical trials have evaluated the effectiveness of screening to improve children's learning or behavior over the long term. Well-designed trials to test the long-term effectiveness of screening to improve children's learning or behavior would be difficult or impossible to perform today because of substantial practical and ethical difficulties.

Despite the limitations of currently available data, screening children in high-prevalence communities seems desirable. Observational studies of BLL screening in communities with high exposures to lead have generally shown reduced lead exposure when screening programs start; some of these studies have shown declining rates of symptomatic lead poisoning, case fatality, or lead-poisoning mortality.[24-27] Educational, environmental, and medical interventions that can be triggered by screening can reduce children's BLLs.[15,20,28] On the other hand, screening all 1-year-old children in low-prevalence communities does not seem efficient, effective, or desirable.[7,29] Thus, we have used

mathematical simulations of a BLL screening program to estimate the threshold prevalence of elevated BLLs at which the benefits of a universal screening program might exceed the costs.

The simulations suggested that, in communities where at least 14% (range 11% to 17%) of 1-year-old children have elevated BLLs, universal screening for elevated BLLs may provide societal economic benefits exceeding the costs of the program as well as providing health benefits for children. The national average prevalence of elevated BLLs among 1- and 2-year-old non-Hispanic Black children is 22%.[1] The national average prevalence among 1- to 5-year-old children who are poor is 16% and among children who live in large central cities is 21%.[1]

Many local studies in both urban[30-33] and rural[34,35] areas have recently reported high prevalences of elevated BLLs in all children or in subgroups of children. These prevalences of elevated BLLs are not exactly comparable to prevalence estimates in our simulations because the children in the studies are not limited to 1-year-olds. Nonetheless, these data suggest that there continue to be many U.S. populations in which testing every child's BLL at 1 year of age may provide benefits out of proportion to the costs of a screening program.

These simulations do not result in a bright line that clearly separates communities where universal screening is indicated from those where it is not. This fact is due to limitations in the data available for this analysis, to limitations in local data that would be available for decision making (i.e., a perfect estimate of prevalence of elevated BLLs in 1-year-old children will never be available), and to the fact that policy decisions are never made on the basis of a single piece of information. Nonetheless, the results of this analysis are increasingly robust as prevalence varies from 14% in either direction.

The national average prevalence of elevated BLLs in children who are poor, black, and live in urban areas is 36%.[1] None of our sensitivity analyses showed the costs of universal screening to exceed the benefits at this prevalence, except for assuming a substantial increase in the cost of environmental management without any increase in effectiveness, primary prevention benefit, or the real estate value of the home.

Conversely, only two sensitivity analyses, one assuming substantial increases in the effectiveness of environmental interventions without any increase in cost, and the other a probable overestimate of education's effectiveness in reducing BLLs,[20] result in the benefits of universal screening exceeding the costs at a prevalence of 4%, the U.S. average for children who are not poor.[1] Thus, the results of this analysis will be useful for making decisions about screening, especially in communities where prevalences of elevated BLLs are not close to the threshold.

Although the simulations are robust to changes in many assumptions, changing some assumptions substantially alters the results. Some variables that make universal screening less cost-beneficial can be avoided by the people performing the screening. For example, as the bias in capillary screening tests increases, universal screening is less cost-beneficial. Several studies have now demonstrated that careful technique can avoid substantial bias in capillary sampling.[9,10] Some assumptions to which the simulations are sensitive have already been reasonably well quantified. The established inverse relationship between BLL and IQ[22,23] is an example.

Other assumptions to which the simulations are sensitive demonstrate a need for better information; this is particularly true of

assumptions about the effectiveness of interventions to reduce BLLs. Many available studies of educational and environmental interventions for reducing children's BLLs did not incorporate a control group and could have overestimated the effectiveness of interventions by failing to account for changes in BLLs due to the aging of children or regression to the mean.

With the exception of a ceiling estimate of education's effectiveness in reducing BLLs,[20] our analysis used data from studies that incorporated control groups to avoid this problem. Next, much of the available information showing that interventions reduce BLLs in children came from studies where children had BLLs that were higher than are typical among children screened today. Because interventions may be more effective in reducing the BLLs of children who have higher levels than in reducing BLLs of children with lower BLLs,[15,36,37] we have not extrapolated the results of studies performed in children with higher BLLs to children whose BLLs are lower. For this reason, we assumed in base-case analyses that interventions do not reduce BLLs of less than 20 g/dL; we tested the effect of this assumption in sensitivity analyses. This assumption makes moot the continuing debates about the clinical significance of small declines in IQ related to BLLs < 20 μg/dL[22] and about whether interventions to reduce BLLs < 20 μg/dL are effective.[29]

However, if there are benefits associated with identifying individual children with smaller elevations in BLL, this analysis will have underestimated the benefits of universal screening. Although we have attempted to cope with the limitations of the available data, additional controlled studies of interventions to lower children's BLLs, especially at modestly elevated BLLs, are needed.

The results of the simulations are very sensitive to the estimated effectiveness of education in reducing BLLs because education is recommended for the parents of children with lower BLLs, and thus to the parents of many more children, than are other interventions.[3] There are conceptual reasons to believe that education could reduce BLLs by reducing exposure to lead sources, reducing exposure to lead-contaminated dust, or improving children's nutrition;[3] however, we were able to find only two studies evaluating the effectiveness of education in reducing children's BLLs.[19,20] One of these is uncontrolled.[20]

Obviously, studies that better define the effectiveness of education in reducing BLLs are needed in order to allow continuing refinement of strategies to prevent and control childhood lead poisoning.

Better studies of environmental management to reduce lead hazards in housing are also needed. The observational study used in this analysis[14] is the only available controlled study that tests the effectiveness of environmental management in reducing children's elevated BLLs. It is limited, however, because follow-up rates were low and because the environmental interventions did not conform to current guidelines.[38] More extensive environmental management results in greater and more sustained reductions in lead-contaminated dust than do less extensive interventions.[39] However, more extensive interventions are also more costly. Sensitivity analyses suggest that better environmental management methods would provide more benefit to lead-exposed children, but this larger benefit would be balanced, at least in part, by these methods' greater cost.

This analysis used methods of economically valuing reductions in lead exposure using a technique called a human capital approach; it valued reductions in BLL on the basis of improvements in lifetime earnings that might result from the lower BLLs. In general, however, people are often willing to pay more than the

cost of an illness to avoid having it entirely.[40] This potential limitation of our approach is unlikely to have substantial effect on the results at low prevalences where few people are exposed to lead and where the effectiveness of interventions to lower BLLs or improve outcomes is questionable. It may, however, result in underestimates of the benefits of screening children in communities where risk for lead exposure is higher.

We could not measure some of the noneconomic costs of screening. These include, for example, the discomfort to the child that is associated with obtaining blood samples and the potential labeling or stigmatization of some children with modest BLL elevations. These costs are likely to be small but relatively more important as the prevalence of elevated BLLs declines. Such costs seem unlikely to change substantially the results of our simulations except to further reduce the ratio of benefits to costs.

Some potential benefits of screening also could not be quantified. These fall into two general categories: 1) benefits of reducing the health or developmental consequences of lead exposure other than reduced IQ and impaired school performance; and 2) additional economic benefits of identifying and fixing dangerous housing, including improving home values and increasing energy efficiency. Especially for communities with high prevalences of elevated BLLs in children, where large numbers of children might benefit from reductions in BLLs and where large numbers of dangerous homes might be identified and fixed, our benefit calculations may be conservative. As the prevalence of elevated BLLs declines and fewer affected children and hazardous homes are identified, this underestimate will become smaller.

The analysis assumes that all children receive appropriate and timely management to lower their elevated BLLs. However, some children undoubtedly do not receive appropriate management. This lack of appropriate management has relatively little effect on estimates of the threshold prevalence at which benefits of screening exceed costs because such lack has the effect of reducing the total benefit of the program and its cost. In contrast, if appropriate interventions are delayed, benefits of screening are likely to be reduced out of proportion to costs. Although mismanagement of children with elevated BLLs may have relatively modest effects on this analysis, it has significant consequences for children and should be eliminated.

Finally, the reversibility of the adverse effects of lead exposure is open to question. The epidemiologic studies which have shown that IQ declines as BLLs increase have generally focused either on a child's BLL at age 2 or on some measure of average BLL during the preschool years as a measure of exposure to lead.[23] Screening at age 1 has been recommended[3] because early screening and interventions could reduce BLLs that would occur later compared with the BLLs that otherwise would have occurred. Thus, questions about the reversibility of lead's adverse effects may in part be mitigated by screening young children. Nonetheless, to the extent that screening is expected to reduce lead exposure that has already occurred, this analysis may have overestimated the benefits of screening. The primary prevention of lead poisoning—reducing lead hazards in the environment before children are exposed—has been successful in reducing children's exposures to lead[41] and is not subject to questions about reversibility. For this and other reasons, primary prevention of lead poisoning is preferable to screening for elevated BLLs and treating lead-poisoned children.

Acknowledgments

We thank Drs. Ken Falter, Steven Teutsch, Anne Haddix, Dana Flanders, and Henry Falk for their many helpful comments on drafts of

this manuscript.

References

1. Brody DJ, Pirkle JL, Kramer RA, et. al. Blood lead levels in the US population: Phase 1 of the Third National Health and Nutrition Examination Survey (NHANES III, 1988 to 1991). JAMA 1994;272:277-83.
2. National Research Council. Measuring lead exposure in infants, children, and other sensitive populations. Washington, DC: National Academy Press, 1993.
3. Centers for Disease Control. Preventing lead poisoning in young children: a statement by the Centers for Disease Control. Atlanta, GA: U.S. Department of Health and Human Services, 1991.
4. California Department of Health Services. Childhood lead poisoning in California —an update. California Morbidity 1994;June 3:(21/22).
5. Schlenker TL, Johnson Fritz C, Murphy A, Shepeard S. Feasibility and effectiveness of screening for childhood lead poisoning in private medical practice. Arch Pediatr Adolesc Med 1994;148:761-64.
6. Gellart GA, Wagner GA, Maxwell RM, Moore D, Foster L. Lead poisoning among low-income children in Orange County, California: a need for regionally differentiated policy. JAMA 1993;270:69-71.
7. Robin LF, Beller M, Middaugh JP. Childhood lead screening in Alaska: results of survey of blood lead levels among Medicaid-eligible children. State of Alaska, Department of Health and Social Services, 1994.
8. Bureau of Labor Statistics. Employment and earnings: annual supplement. U.S. Department of Commerce; 1992.
9. Schlenker TL, Johnson FC, Mark D, et al. Screening for pediatric lead poisoning: comparability of simultaneously drawn capillary and venous blood samples. JAMA 1994;271:1346-48.
10. Schonfeld DJ, Cullen MR, Rainey PM, et. al. Screening for lead poisoning in an urban pediatric clinic using samples obtained by fingerstick. Pediatrics 1994;94:174-79.
11. Marcus AH. Use of site-specific data in models for lead risk assessment and risk management. Fundam Appl Toxicol 1992;18:10-16.
12. American Academy of Pediatrics Committee on Psychosocial Aspects of Child and Family Health, 1985-1988. Guidelines for health supervision II. Elk Grove Village, IL: American Academy of Pediatrics, 1988.
13. Staes C, Matte T, Copley CG, Flanders D, Binder S. Retrospective study of the impact of lead-based paint hazard remediation on children's blood lead levels, St. Louis. Am J Epidemiol 1994; 139:1016-26.
14. Mortensen ME, Walson P. Chelation therapy for childhood lead poisoning: the changing scene in the 1990s. Clin Pediatr 1993;32:284-91.
15. Glotzer DE, Bauchner H. Management of childhood lead poisoning: a survey. Pediatrics 1992;89:614-8.
16. Schwartz J. Benefits of preventing lead exposure in the United States and costs and benefits of lead-based paint abatement. In: Strategic plan for the elimination of childhood lead poisoning. Atlanta, GA: Centers for Disease Control, 1991.
17. Schwartz J. Societal benefits of reducing lead exposure. Environ Res 1994; 66:105-24.
18. Clark CS, Bornschein RL, Succop P, Que Hee SS, Hammond PB, Peace B. Condition and type of housing as an indicator of potential environmental lead exposure and pediatric blood lead levels. Environ Res 1985;38:46-53.
19. U.S. Environmental Protection Agency. Effect of In-home Educational Interventions on Children's Blood Lead Levels in Milwaukee. Washington, D.C. Environmental Protection Agency, 1996.
20. Kimbrough RD, LeVois M, Webb DR. Management of children with slightly elevated blood lead levels. Pediatrics 1994;93:188-91
21. Piomelli S, Rosen JF, Chisolm JJ, Graef JW. Management of childhood lead poisoning. J Pediatr 1984;105:523-32.
22. Schwartz J. Low-level lead exposure and children's IQ: a meta-analysis and search for a threshold. Environ Res 1994;66:105-24.
23. Pocock SJ, Smith M, Baghurst P. Environmental lead and children's intelligence: a systematic review of the epidemiological evidence. BMJ 1994;309:1189-97.
24. Sachs HD, Blanksma LA, Murray EF, O'Connell MJ. Ambulatory treatment of lead poisoning: report of 1,155 cases. Pediatrics 1970;46:389-96.

Pediatr 1994;33:536-41.

25. Sachs HK. Effect of a screening program on changing patterns of lead poisoning. Environ Health Perspect 1974;41-5.
26. Browder A, Joselow M, Louria DB, et al. Evaluation of screening programs for childhood lead poisoning by analysis of hospital admissions. Am J Public Health 1974;64:914-5.
27. Whitlock NH, Reigart JR, Priester LE. Lead poisoning in South Carolina. J S C Med Assoc 1977;73:378-80.
28. Chisolm JJ Jr. Evaluation of the potential role of chelation therapy in treatment of low to moderate lead exposures. Environ Health Perspect 1990;89:67-74.
29. Harvey B. Should blood lead screening recommendations be revised? Pediatrics 1994;93:201-4.
30. Casey R, Wiley C, Rutstein R, Pinto-Martin J. Prevalence of lead poisoning in an urban cohort of infants with high socioeconomic status. Clin Pediatr 1994;480-4.
31. Schaffer SJ, Szilagyi PG, Weitzman M. Lead poisoning risk determination in an urban population: use of a standardized questionnaire. Pediatrics 1994;93:159-63.
32. Blatt SD, Weinberger HL. Prevalence of lead exposure in a clinic using 1991 Centers for Disease Control and Prevention recommendations. Am J Dis Child 993;147:761-3.
33. Wiley JF, Bell LM, Rosenblum LS, Nussbaum J, Tobin R, Henretig FM. Lead poisoning: low rates of screening and high prevalence among children seen in inner-city emergency departments. J Pediatr 1995;126:392-5.
34. Norman EH, Bordley C, Hertz-Picciotto I, Newton DA. Rural-urban blood lead differences in North Carolina children. Pediatrics 1994;94:59-64.
35. Paulozzi LJ, Shapp J, Drawbaugh RE, Carney JK. Prevalence of lead poisoning among two-year-old children in Vermont. Pediatrics 1995;96:78-81.
36. Charney E, Kessler B, Farfel M, et al. Childhood lead poisoning: a controlled trial of the effect of dust-control measures on blood lead levels. N Engl J Med 1983;309:1089-93.
37. Swindell SL, Charney E, Brown MJ, Delaney J. Home abatement and blood lead changes in children with class III lead poisoning. Clin
38. U.S. Department of Housing and Urban Development. Guidelines for the evaluation and control of lead-based paint hazards in housing. Washington, DC: U.S. Department of Housing and Urban Development, 1995.
39. Farfel MR, Chisolm JJ, Rohde CA. The long-term effectiveness of residential lead paint abatement. Environ Res 1994;66:217-21.
40. Landefeld JS, Seskin EP. The economic value of life: linking theory to practice. Am J Public Health 1982;72:555-66.
41. Pirkle JL, Brody DJ, Gunter EW, et. al. The decline in blood lead levels in the United States: the National Health and Nutrition Examination Surveys (NHANES). JAMA 1994;272:284-91.
42. Glotzer DE, Bauchner H, Freedberg KA, Palfrey S. Screening for childhood lead poisoning: a cost minimization analysis. Am J Public Health 1994;84:110-12.
43. Crane M. What your colleagues are charging. Medical Economics 1991; October 7, 124-42.
44. U.S. Department of Housing and Urban Development. Lead-based paint: interim guidelines for hazard identification and abatement in public and Indian housing. Washington, DC: U.S. Department of Housing and Urban Development, 1990.

Figure 1. Structure of the simulations for estimating the costs and benefits of universal screening for elevated blood lead levels (BLLs) in children.

Table 1. Population distribution of lead exposure and lead screening test performance used in an analysis of the costs and benefits of universal BLL screening.

Parameter	Estimate	Range for sensitivity analyses	Reference or rationale
Prevalence of elevated blood lead levels (BLLs)	0-50%	N/A*	Approximately consistent with the range of prevalences currently seen among children in U.S. communities.
Observed population geometric standard deviation (GSD)	1.9		See text
		1.7 to 2.12	Based on Marcus[11] National estimate based on children aged 1-5 in NHANES III† [1]
Average bias‡ of a capillary sample for blood lead	1 μg/dL		Matte[11] Schlenker et al[9] Schonfeld et al[10]
		0-2 μg/dL	Estimated
GSD of a single BLL measurement	1.27	1.17-1.43	Based on data from the Cincinnati cohort study[18]
Ratio of children's BLLs at age 2 compared with age 1	1.19	1.16-1.29	Clark et al[18]

*Not Applicable
†The Third National Health and Nutrition Examination Survey.
‡The observed value exceeds the true value by an average of 1 μg/dL.

Table 2. Cost estimates for an analysis of the costs and benefits of universal screening for elevated blood lead levels (BLLs) in children.

Parameter	Cost	Range for sensitivity analyses	Reference or rationale
Cost of a venipuncture	$7.01*		Glotzer et al[42]
		$3-$15	Estimated
Cost of a laboratory test for blood lead	$18.68*	$5.84-$87.58	Glotzer et al[42]
Cost of a provider visit for follow-up of an elevated BLL	$27.92*		Crane[43]
		$20-$50	Estimated
Direct non-medical cost of a provider visit for follow-up of an elevated BLL	$24.91†		Two hours of a parent's time at the U.S. mean daily wage
		$0-$50	Estimated
Cost of an educational visit	$51.51‡		Enterprise Foundation, 1991
		$0-$100	Estimated
Direct non-medical cost of an educational visit	$12.46†		One hour of a parent's time at the U.S. mean daily wage.
		$0-$25	Estimated
Cost of an environmental assessment	$109.75‡		Schwartz[16]
		$385‡	HUD[44] §
Direct non-medical cost of an environmental assessment	$24.91†		Two hours of a parent's time at the U.S. mean daily wage
		$0-$50	Estimated
Cost of an environmental intervention	$515‡	$515-$15,452	EnterpriseFoundation,1991§
Cost of a course of succimer	$1429†		Estimated
		$1000-	Estimated
		$4711†	Estimated inpatient cost
Cost of a course of EDTA	$4711†		Schwartz[16]
		$1000-$8000	Estimated

*Updated to 1992 dollars with the Medical Consumer Price Index (CPI).
†Updated to 1992 dollars using estimated growth in hourly wages from the Bureau of Labor Statistics.
‡Updated to 1992 dollars with the CPI.
§No lower estimate was selected for this variable.

Table 3. Effectiveness of interventions in reducing children's blood lead levels (BLLs).

Type of intervention	Ratio of children's BLLs 1 year after an intervention to those that would have occurred without the intervention	Range for sensitivity analyses	BLL Range*	Reference or rationale
Educational	1		< 20 μg/dL	U.S. Environmental Protection Agency[19]
	0.87		≥ 20 μg/dL	
		1	< 10 μg/dL	Kimbrough et al[20]†
		0.64	≥10 μg/dL	
		1		Assumes no effect of education for a lower-bound estimate
Environmental	1		< 25 μg/dL	
	0.99		≥ 25 μg/dL and	Staes et al[13]
	< 35 μg/dL			
	0.79		≥ 35 μg/dL	
		0.95-0.70	Children with confirmed BLLs of at least 20 μg/dL or persistently ≥ 15 μg/dL	Estimated§
Medical (Chelation Therapy)	20 μg/dL		Initial BLLs ≥40 μg/dL	Estimated
		15-25 μg/dL	Initial BLLs ≥40 μg/dL	Estimated
			20 μg/dL	Initial BLLs
			≥ 25 μg/dL	Estimated

*The range of true BLLs at age 1for which the effectiveness estimates were applied.
†See text for discussion.
§No estimate of lesser effectiveness was selected for this variable.

Table 4. Assumptions used to estimate the economic benefits of reducing lead exposure in children.

Parameter	Value	Range for sensitivity analyses	Reference or rationale
Reduction in IQ associated with a BLL increase of 1 μg/dL	.257 points		Schwartz[22]
		0.1-0.5	Estimated
Reduction in wages associated with each point of IQ loss	0.5%		Schwartz[17]
		0.2%	Schwartz[17]
		0.75%	Schwartz[17]
Reduction in final grade attained for each increase in lead exposure sufficient to reduce IQ by one point	0.131		Schwartz[17]
		0-0.2	Estimated‡
Reduction in wages for each one-grade reduction in final grade attained.	6%		Schwartz[17]
		4.8%-	Schwartz[17]
		8.8%	Schwartz[17]
Increased risk of failure to graduate from high school associated with an increased BLL sufficient to reduce IQ by one point	4.5%		Schwartz[17]
		0.00	Estimated‡
Reduction in workforce participation associated with failure to graduate from high school	10.5%		Schwartz[17]
		0-	Estimated
		20%	Schwartz[17]
Average lifetime earnings of a 1-year-old child discounted to the present	$266,843*		Schwartz[17]
		$200,000-	Estimated
		$500,000	
Average reduction in special education costs per child who is prevented from having BLLs exceeding 25 µg/dL.	$3090†		Schwartz[17]
		$0-$6180	Estimated
Primary prevention benefits of reducing lead in housing/per house treated.	$745		Schwartz[17]§
		$0-$2000	Estimated

*Updated to 1992 dollars using estimated growth in hourly wages from the Bureau of Labor Statistics.
†i.e., the cost of 3 years of special education discounted to the present, multiplied by the estimated 20% excess in the number of children with BLLs exceeding 25 µg/dL who will require special education.
‡No upper estimate was chosen for this variable because larger estimates can result in risks exceeding 100% at very high BLLs.
§This model has been updated for consistency with the rest of the current simulation. See text.

Table 5. Costs and benefits of universal screening for childhood lead exposure in a cohort of 10,000 children as prevalence of elevated BLLs varies for the base-case model.

Observed prevalence of elevated BLLs* (%)	Cost of the screening program†	Economic benefit of the screening program†	Ratio of benefits to costs‡
2	$230,000	$19,000	.08
5	$306,000	$69,000	.22
10	$460,000	$328,000	.71
14	$603,000	$637,000	1.05
20	$839,000	$1,236,000	1.47
25	$1,071,000	$2,002,000	1.87
30	$1,308,000	$2,919,000	2.23
40	$1,898,000	$5,693,000	3.00
50	$2,706,000	$10,328,000	3.82

*10 µg/dL, rounded to the nearest whole number.
†per 10,000 children, rounded to the nearest $1000.
‡Calculated on the basis of cost and benefit estimates that have not been rounded. The ratio may differ slightly from one calculated on the basis of rounded data from the table.

Table 6. Sensitivity of the simulations to changing assumptions for a cost-benefit analysis of universal screening for elevated BLLs in children.* Results show the threshold at which benefits first exceed costs as assumptions are changed.

Assumption	Threshold prevalence of elevated BLLs† at which benefits first exceed costs (%)
Base model	**14**
Observed population geometric standard deviation	
= 1.7	30
= 2.12	7
Average bias of a capillary blood sample	10
= 0 µg/dL	
= 2 µg/dL	19
Cost of laboratory testing for blood lead	
= $5.84	9
= $50	22
= $87.58	27
Cost of an environmental intervention	
= $1545	19‡§
= $3502	36‡¶
= $7211	64‡**
= $15,452	89‡††
Ratio of children's BLLs after educational interventions compared to those that would have occurred without interventions.	
Based on Kimbrough et al[20]	1
Assuming that education has no effect	25

Table 6 (continued)

Assumptions	Threshold prevalence of elevated BLLs† at which benefits first exceed costs (%)
Ratio of children's BLLs after environmental interventions compared with those BLLs that would have occurred without an intervention	
= 0.90	9††§§
= 0.80	6††¶¶
= 0.70	4††***
Assume that chelation therapy is given to all children with initial BLLs of 25 µg/dL and that chelation reduces their BLLs to 20 µg/dL after 1 year	10
Reduction in IQ per 1 µg/dL increase in BLL	
= 0.1	24
= .185[23]	17
= 0.5	9
Reduction in final grade attained for each increase in lead exposure sufficient to reduce IQ by one point	
= 0	21
= 0.2	12
Average lifetime earnings of a 1-year-old child discounted to the present	
= $200,000	16
= $500,000	9
Primary prevention benefit of reducing lead in housing	
= $0	17
= $2000	10

*Results are presented if changes in assumptions within the ranges presented in Tables 2-5 changed the threshold at which benefits first exceed costs by more than ±3% compared with the base model result of 14%. Changing the following variables resulted in changes of 3% compared with the base model: within-individual GSD; changes in children's BLLs from age 1 to age 2; direct medical and nonmedical costs of venipunctures, provider visits, educational interventions, environmental assessments, and courses of succimer or EDTA; risk of failure to graduate from high school because of increases in lead exposure; reductions in wages associated with IQ loss or final grade attained; or special education costs associated with lead exposure.
† 10 µg/dL.
‡These estimates overestimate the prevalence at which benefits would exceed costs because they assume no additional health or economic benefits of more expensive interventions.
§These additional costs could be offset (i.e., benefits would exceed costs at a prevalence of 14%) if the ratio of BLLs after the intervention to those that would otherwise have occurred was 0.96 for all children who had environmental interventions.
¶These additional costs could be offset (i.e., benefits would exceed costs at a prevalence of 14%) if the ratio of BLLs after the intervention to those that would otherwise have occurred was 0.88 for all children who had environmental interventions.
** These additional costs could be offset (i.e., benefits would exceed costs at a prevalence of 14%) if the ratio of BLLs after the intervention to those that would otherwise have occurred was 0.74 for all children who had environmental interventions.
††These additional costs could be offset (i.e., benefits would exceed costs at a prevalence of 14%) if the ratio of BLLs after the intervention to those that would otherwise have occurred was 0.40 for all children who had environmental interventions.
‡‡These estimates of prevalence at which benefits would exceed costs are probably too low because they are based on the assumption that more effective interventions could be done for no additional cost.
§§This additional benefit would be offset (i.e., benefits would exceed costs at a prevalence of 14%) if an intervention this effective cost at least $3218.
¶¶This additional benefit would be offset (i.e., benefits would exceed costs at a prevalence of 14%) if an intervention this effective cost at least $5468.
***This additional benefit would be offset (i.e., benefits would exceed costs at a prevalence of 14%) if an intervention this effective cost at least $8286.