Environmental Pollutants and Disease in American Children: Estimates of Morbidity, Mortality, and Costs for Lead Poisoning, Asthma, Cancer, and Developmental Disabilities

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In this study, we aimed to estimate the contribution of environmental pollutants to the incidence, prevalence, mortality, and costs of pediatric disease in American children. We examined four categories of illness: lead poisoning, asthma, cancer, and neurobehavioral disorders. To estimate the proportion of each attributable to toxins in the environment, we used an environmentally attributable fraction (EAF) model. EAFs for lead poisoning, asthma, and cancer were developed by panels of experts through a Delphi process, whereas that for neurobehavioral disorders was based on data from the National Academy of Sciences. We define environmental pollutants as toxic chemicals of human origin in air, food, water, and communities. To develop estimates of costs, we relied on data from the U.S. Environmental Protection Agency, Centers for Disease Control and Prevention, National Center for Health Statistics, the Bureau of Labor Statistics, the Health Care Financing Agency, and the Practice Management Information Corporation. EAFs were judged to be 100% for lead poisoning, 30% for asthma (range, 10–35%), 5% for cancer (range, 2–10%), and 10% for neurobehavioral disorders (range, 5–20%). Total annual costs are estimated to be $54.9 billion (range $48.8–64.8 billion): $43.4 billion for lead poisoning, $2.0 billion for asthma, $0.3 billion for childhood cancer, and $9.2 billion for neurobehavioral disorders. This sum amounts to 2.8 percent of total U.S. health care costs. This estimate is likely low because it considers only four categories of illness, incorporates conservative assumptions, ignores costs of pain and suffering, and does not include late complications for which etiologic associations are poorly quantified. The costs of pediatric environmental disease are high, in contrast with the limited resources directed to research, tracking, and prevention. *Key words:* **asthma, cancer, developmental disabilities, environmental pediatrics, health economics, lead poisoning.** *Environ Health Perspect* **110:721–728 (2002). [Online 31 May 2002]**
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Patterns of illness among children in the United States have changed substantially in the past century (*1*). The classic infectious diseases are much reduced in incidence and are no longer the leading causes of illness and death (*2*). Infant mortality has been lowered, although not equally across American society, and life expectancy increased. Today the most serious diseases confronting children in the United States and in other industrially developed nations are a group of chronic conditions of multifactorial origin that have been termed the "new pediatric morbidity" (*1*). Examples include asthma, for which incidence has more than doubled (*3,4*); childhood cancer, for which reported incidence of certain types has increased significantly (*5,6*); neurodevelopmental and behavioral disorders (*7,8*); and certain congenital defects (*9,10*).

An important unresolved question is the extent to which chemical pollutants in the environment may be contributing to these changing patterns of pediatric disease (*11*). More than 80,000 new synthetic chemical compounds have been developed over the past 50 years, and each year 2,000 to 3,000 new chemicals are brought to the U.S. Environmental Protection Agency (EPA) for review before manufacture. Children are especially at risk of exposure to the 15,000 chemicals produced in quantities greater than 10,000 pounds per year and to the 2,800 produced in quantities greater than 1 million pounds per year. These high-volume chemicals have the greatest potential to be dispersed in air, water, food crops, communities, and homes (*11*). Only 43% of high-volume chemicals have been tested for their potential human toxicity, and only 7% have been studied for their possible effects on development (*12,13*).

Children are more vulnerable than adults to many chemicals (*14*). This susceptibility results from children's disproportionately heavy exposures coupled with the biologic sensitivity that is an inherent characteristic of early growth and development. Injury to developing organ systems can cause lifelong disability.

The burden of disease, disability, and death in American children that may be caused by pollutants in the environment is not known. Previous studies have examined the incidence and prevalence of lead poisoning (*15,16*) and of pediatric asthma (*3,4*) and have calculated the costs associated with these conditions (*17–25*). The costs of learning disabilities and developmental disorders have also been estimated (*26*), and a committee convened by the U.S. National Academy of Sciences has estimated the fraction of neurobehavioral disorders that may be attributable to environmental factors (*27*). No estimates have been developed of the aggregate incidence or prevalence of pediatric environmental disease, and no previous study has assessed the total costs of pediatric disease and disability of environmental origin in the United States.

Knowing the incidence, prevalence, and economic costs of environmental disease and disability in children is important. Experience has shown that accurate information on costs of illness can help focus preventive efforts and can put into perspective arguments that focus exclusively on the costs of preventing pollution (*28,29*). A further rationale for developing data on the costs of pediatric environmental disease is to permit direct comparison with the costs of other categories of illness, an exercise that may be useful in the setting of priorities and in allocation of resources (*30–36*).

We report estimates for the United States of the incidence, prevalence, mortality, and costs of four categories of pediatric illness that may be attributable to chemical

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pollutants in the ambient environment. We chose deliberately not to consider outcomes that are the consequence at least in part of personal or familial choice; therefore we did not include outcomes related to tobacco, alcohol, or drug abuse. We focus on lead poisoning, pediatric asthma, childhood cancer, and neurobehavioral disorders because these conditions are serious, common, and likely related at least in part to chemical pollutants in the environment. Moreover, all of these diseases are potentially preventable through public health efforts and pollution prevention.

Methodology

Overall approach. We used an environmentally attributable fraction (EAF) model as the basis for developing our estimates. This fraction is defined by Smith et al. (*37*) as "the percentage of a particular disease category that would be eliminated if environmental risk factors were reduced to their lowest feasible levels." The EAF is a composite value and is the product of the incidence of a risk factor multiplied by the relative risk of disease associated with that risk factor. Its calculation is a useful tool in developing strategies for resource allocation and prioritization in public health. The EAF model has been used previously to assess the costs of environmental and occupational disease (*28–30*). Most notably it was used by the Institute of Medicine to assess the "fractional contribution" of the environment to causation of illness in the United States (*30*).

Our general model is the following:

$$\text{Costs} = \text{Disease rate} \times \text{EAF} \times \text{Population size} \times \text{Cost per case}$$

In this equation, EAF represents the environmentally attributable fraction. "Cost per case" refers to discounted lifetime expenditures attributable to a particular disease including direct costs of health care, costs of rehabilitation, and lost productivity. The terms "disease rate" and "population size" refer, respectively, to either the incidence or prevalence of each disease as described below and the size of the population at risk.

Environmental toxicants defined. Environmental pollutants are defined in this analysis as chemical substances of human origin in environmental media—air, food, water, soil, the home, and the community. We use this definition because the exposures included within it are potentially preventable through application of the traditional approaches of public health and pollution prevention. We did not include the effects of diet, alcohol, tobacco, other drugs of abuse or other extragenetic factors such as socioeconomic status, although we recognize that all of these factors are components of the environment defined most broadly (*37*).

Disease rates and populations at risk. For lead poisoning, the relevant rate of disease is cumulative incidence up to age 5 because environmental abatement or medical treatment beyond that age will not reverse brain injury or restore lost intelligence in those children who have already been exposed to lead (*38*). For asthma, the relevant rate is current prevalence because environmental abatement can be expected to reduce the existing burden of morbidity (*39*). For childhood cancer, the relevant disease rate is incidence because it cannot be anticipated that environmental cleanup will ameliorate the morbidity of children who now have cancer (*6*). The relevant disease rate for neurobehavioral disorders is incidence (*8*).

For lead poisoning, we took as our population at risk the current cohort of 5-year-old children because the neurologic damage caused by lead is typically noticed when children enter school at about age 5, although undoubtedly it begins much earlier. A new cohort arises, of course, each year, and the total costs of lead poisoning are therefore the costs per birth cohort multiplied by the number of cohorts affected by the disease. Data on the distribution of blood lead levels and of lead poisoning were taken from reports issued by the U.S. Centers for Disease Control and Prevention (CDC) (*15,16*).

For asthma we used the current cohort of 5-year-olds as our population at risk. We selected this population because 80–90% of children with asthma have developed their symptoms by the age of 5 years (*39*). The subsequent course of the disease varies: Most children have only mild, infrequent attacks; some have repeated, severe episodes requiring emergency room visits and hospitalization; some die. Some asthmatic children remain asthmatic as adults; others "outgrow" their illness. To be conservative, our analysis ignores all asthma-related morbidity and expenses that occur after age 18. Data on the prevalence of childhood asthma were taken from the National Health Interview Survey (*40*). Data on the annual number of asthma deaths in children was taken from the CDC (*4*).

For childhood cancer, there is a broad range of age of onset among cases. Therefore, rather than select a single birth cohort for analysis, we based our calculations on the number of incident cases diagnosed among U.S. children per calendar year. Incidence of each type of childhood cancer was determined from the National Cancer Institute's Surveillance Epidemiology and End Results (SEER) database (*5*). Data on the number of deaths from childhood cancer are also taken from the SEER database.

For neurobehavioral disorders, we took as our population at risk the cohort of approximately 4 million children born each year in the United States. An estimated 3–8% (120,000–320,000) of these children have neurobehavioral problems (*7,8*), including approximately 60,500 with mental retardation, autism, and cerebral palsy (*26*). Costs attributable to these disorders were taken from Honeycutt et al. (*26*).

Population counts were taken from the 1990 U.S. Census, as updated to 1997 by the U.S. Census Bureau in the Current Population Survey (*41*).

Estimation of EAF. Data are not available on the fractions of diseases in children that may be caused by toxic exposures in the environment. Therefore, to estimate the proportion of cases of lead poisoning, asthma, and childhood cancer that are potentially attributable to toxic environmental factors, we used a formal decision-making process, the modified Delphi technique (*42,43*).

We initiated this consensus process by selecting three expert panels, one each for lead poisoning, asthma, and childhood cancer. These panels were assembled from among prominent physicians and scientists with established national reputations and extensive records of publication in relation to the diseases under study. Each consisted of three or four persons. All panelists were asked to estimate the EAF on two occasions: before the panel meeting (by mail ballot) and again at the meeting.

To give all experts equal access to the relevant literature, we sent each a description of the goals, objectives, and overall approach of the study along with an extensive collection of reprints of published articles that discussed linkages between the disease in question and toxic environmental exposures. Each panelist was asked to review this literature plus other relevant publications and then to develop an initial best estimate, from 0 to 100%, of the EAF for the disease in which they were expert. Panelists were asked further to indicate an upper and a lower bound of plausibility around their best estimate of EAF. Those initial estimates were mailed to the study team at Mount Sinai and the results tabulated. Areas of disagreement and uncertainty were noted and identified as topics for discussion at the meeting.

Each panel met for one day, and one of the investigators (C.S.) moderated each meeting. Each panel spent the day discussing the estimates of EAF that they had submitted before the meeting. The goal of the meeting was to refine initial estimates through a consensus approach and to reduce the range of uncertainty. At the end of the day, a second vote was taken. Again each panelist was asked to indicate a best estimate of EAF plus upper and lower bounds of plausibility. The arithmetic mean of these

final estimates were used as the basis for our subsequent analyses.

To develop an estimate of the EAF for neurobehavioral disorders, we relied on the recently published findings of an expert committee convened by the U.S. National Academy of Sciences (*27*). The methodology employed by that committee appeared similar to that which we used for estimating EAFs of the other three disease entities.

Disease-Specific Methodologies

Lead poisoning. All cases of lead poisoning were judged by the expert panel to be of environmental origin (*44*). The EAF is therefore 100%, and no range was calculated. The major task before the panel was to develop a model to quantify the full range of toxic effects that may result from early exposure to lead (*44–50*), including cognitive changes; behavioral changes that may produce increased rates of criminality, drug abuse, and incarceration; and cardiovascular disease.

To estimate the costs associated with the cognitive and behavorial consequences of lead poisoning, we relied heavily on an economic forecasting model developed by Schwartz et al. (*24*) and applied this model to current CDC data on prevalence of lead poisoning (*16*). In this model, blood lead levels are assumed on the basis of work by Salkever (*51*) to produce a dose-related decrement in intelligence (IQ score). Those decrements in IQ are, in turn, associated with lower wages and diminished lifetime earning power. The costs of that diminution in earning power were calculated.

We attempted to expand the scope of the Schwartz model by including the costs of adult cardiovascular disease attributable to hypertension resulting from childhood lead exposure. However, a preliminary analysis (*52*) revealed that these costs were probably minor because of the combined effects of a relatively weak correlation between childhood and adult blood pressures, the resulting modest attributable burden of increased cardiovascular disease, and the severe discounting applied to costs that will arise four or more decades after exposure to lead.

Asthma. Asthma is a major cause of morbidity among American children. It is the leading cause of admission of urban children to hospital—over 200,000 hospitalizations annually (*35*). Asthma is also the leading cause of days lost from school—over 10.1 million school days annually (*35*). Asthmatic episodes are the result of complex interactions among genetic predisposition, respiratory infection, climate change, the indoor environment at home and at school, secondhand cigarette smoke, and ambient air pollution (*39,53,54*).

To estimate the fraction of asthma that may be associated with toxic exposures in the environment, a panel of experts in environmental and pulmonary medicine first estimated the proportion of asthma episodes attributable to all extragenetic causes. Then within that broad range, they specifically examined the fraction that could be attributed to toxic exposures of human origin in the environment. Household allergens from pets, insects, and molds were not included within the panel's definition of environment; nor were secondhand cigarette smoke, infections, or climatic factors. Only outdoor, nonbiologic pollutants from sources potentially amenable to abatement, such as vehicular exhaust and emissions from stationary sources, were considered. Using this definition, the panel estimated that 30% of acute exacerbations of childhood asthma (range 10–35%) are environmentally related.

To examine the costs of childhood asthma, we considered the economic impacts that have been shown in previous studies to be associated with emergency room use, hospitalization, and death from the disease (*18–23,53–55*). Those earlier studies used data from various sources including the annual National Hospital Discharge Survey, the 1985 National Ambulatory Medical Care Survey, the annual National Health Interview Survey, the 1980 National Medical Care Utilization and Expenditure Survey, the 1987 National Medical Expenditure Survey, and a managed health care database of medical and pharmacy claims (*56*).

We then updated and extended those earlier economic estimates using more recent data on incidence rates from the NHIS (*40*), price and wage indices from the Bureau of Labor Statistics (*57*), prescription expenditure estimates from the CDC (*58*), and reports on health care costs from the Health Care Financing Agency (*59*).

We obtained data on the number of deaths caused by pediatric asthma from the CDC (*4*) and applied our estimates of EAF to that number. Then to calculate the costs of lost productivity from deaths caused by childhood asthma of environmental origin, we updated estimates of the present value of loss of lifetime earnings and household production for each such premature death, using methods described elsewhere (*60*). Briefly, the present value formula we used is similar to the one used by Rice et al. (*61–63*). We assumed that children who died would have earned what others of the same age and sex would have earned. The present value tables were calculated using average annual earnings for full-time and part-time employees (*64*), labor force participation rates (*63*), estimates of annual home production loss (*65*), and a real discount rate assumed to be 3%.

Cancer. To assess the environmentally attributable fraction of childhood cancer, we convened a panel of experts in pediatric oncology, epidemiology, and environmental medicine. This panel attempted to estimate the fraction of cases of each major category of childhood cancer that may be associated with toxic exposures in the environment.

The panel felt that no more than 10–20% of childhood cancer cases could be attributed solely to genetic predisposition and that extragenetic factors, defined broadly, therefore caused or at least contributed to the genesis of the remaining 80–90%. The panel noted that the specific causes of childhood cancer are largely unknown and that only a small number of chemical substances and physical factors have been directly linked to childhood cancer (*66–70*). Given that scarcity of etiologic information, the panel concluded that insufficient evidence exists to assign a best estimate of the fraction of childhood cancer specifically attributable to toxic chemicals in the environment (*70*). The panel agreed that the correct EAF would prove to be at least 5–10% and less than 80–90%, but could not further refine that broad range. In the face of this uncertainty, we based our computations of the environmentally attributable costs of childhood cancer on three hypothetical EAFs, all at the lower and therefore more conservative end of the range of possibilities: 2, 5, and 10%.

Data on the costs of childhood cancer are not readily available, mostly because over 80% of pediatric cancer patients are participants in randomized clinical trials. No recovery of costs occurs for these trial participants, so the costs of their care must be reconstructed from hospital and other records. To this end, we obtained the medical records of all patients treated under research protocols for pediatric malignancies at The Mount Sinai Medical Center between 1992 and 1997. Summaries of physician services, hospital charges, radiologic services, and laboratory services were abstracted and reviewed. Data on the costs of physician and hospital resources were taken from physician billing rates and hospital charges, adjusted by Health Care Financing Agency cost-to-charge ratios. Costs of laboratory services were estimated from published data on reimbursement from the Practice Management Information Corporation (*71*). Costs of childhood cancer are discounted at an annual rate of 3% based on the time after initial diagnosis at which they occur rather than on age.

We examined two delayed complications of childhood cancer that may occur as long as 30 years after initial diagnosis, and we estimated their costs.

First, we considered the possibility that children who survive cancer are at increased risk for occurrence of a second primary neoplasm. The long-term cumulative risk of second malignancy has been estimated at between 3.3% and 8% and varies according to the type of primary neoplasm and the treatment modalities employed (*72–74*). We relied on the findings of de Vathaire et al. (*75*) for our estimates of risk of second malignancy because *a*) they provided detailed information as to the time interval between first and second neoplasms (thereby facilitating discounting of future costs), and *b*) their cumulative incidence rates fell approximately in the middle of the overall range observed in other studies.

Second, we considered the effects on intelligence of cranial irradiation for treatment of childhood brain cancer. It is known that cranial irradiation is associated with decreased IQ and that the severity of the effect depends on the radiation dose and age at time of treatment (*76*). To estimate the economic impact of this effect among children with brain cancer, we assumed that the average child was irradiated at age 5, had a pre-morbid IQ of 100, and that the resulting decrement in IQ was related to radiation dose. Decrements in intelligence have been associated with diminished life-time earning power (*51*), and we calculated the costs of that diminution.

We obtained information from the National Cancer Institute SEER database on the number of deaths in American children that occur each year from cancer. We applied our estimates of EAF to that number. Then to calculate the costs of premature death from pediatric cancer of environmental origin, we calculated the loss of lifetime earnings for each such death (*56*) and discounted those projected earnings at an annual rate of 3%.

Neurobehavioral disorders. Dyslexia, attention-deficit hyperactivity disorder (ADHD), diminished intelligence, autism, and mental retardation are among the neurobehavioral disorders that affect an estimated 3–8% (120,000–320,000) of the approximately 4 million infants born in the United States each year (*7,8*).

An expert committee convened by the U.S. National Academy of Sciences (NAS) estimated in 2000 that 3% of neurobehavioral disorders in American children are caused directly by toxic environmental exposures and that another 25% are caused by interactions between environmental factors, defined broadly, and genetic susceptibility of individual children (*27*). We considered this the most authoritative published estimate of the EAF for these disorders. We therefore relied on the NAS estimate. Of the total 28% of neurobehavioral disorders thought by the NAS committee to be caused wholly or partly by environmental factors, we estimate that 10% (range 5–20%) are at least partly caused by toxic exposures, not including alcohol, tobacco, or drugs of abuse.

To develop estimates of the costs associated with neurobehavioral disorders of environmental origin, we relied on the work of Honeycutt et al. (*26*) in selecting those figures for which an annual 3% discount rate was used. Because the cost estimates developed by Honeycutt et al. (*26*) pertain only to mental retardation, autism, and cerebral palsy, our cost estimates are limited to those three conditions. Honeycutt et al. (*26*) note that 34% of children with autism and 15% of children with cerebral palsy also suffer from mental retardation. To avoid double-counting children with these two conditions, we counted them only once in our analysis. Because some neurobehavioral dysfunction is caused by lead poisoning, we estimated the fraction of cases attributable to lead poisoning and reduced our estimates of disease burden and costs accordingly.

Results

Lead poisoning. For assessing the incidence, prevalence, and costs of childhood lead poisoning, we used Schwartz et al.'s model (*24*) and applied it to current CDC data on incidence of lead poisoning (*16*).

The mean blood level in the birth cohort of children age 5 years was reported in 1997 to be 2.7 µg/dL (*16*). In that year, the estimated numbers of 5-year-old boys and girls in the United States were 1,960,200 and 1,869,800, respectively. At this age, there is no significant difference between boys and girls in blood lead level. On the basis of Schwartz et al.'s analysis (*24*), we considered each microgram per deciliter of blood lead concentration to be associated with a reduction in IQ of 0.25 points at these levels of lead exposure. Application here of an IQ reduction of 0.25 IQ points/µg/dL assumes implicitly that there is no threshold blood lead level below which cognitive effects are not seen. This assumption appears reasonable, because to date cognitive deficits have been associated with all ranges of blood lead concentration studied, and no evidence of a threshold has been found (*77*).

Salkever (*51*) has calculated that the loss of one IQ point is associated with an overall reduction in lifetime earnings of 2.39%. This corresponds to a loss of 1.61% of earnings potential for an IQ deficit of 0.675 points. Assuming an annual growth in productivity of 1% and applying a 3% discount rate, the present value of lifetime expected earnings is $881,027 for a 5-year-old boy, and $519,631 for a 5-year-old girl (*57*). Thus the present value of economic losses attributable to lead exposure in the birth cohort of current 5-year-olds amounts to $43.4 billion per year (Table 1).

Asthma. Our cost estimates for asthma were developed using the approach of Chestnut et al. (*22*). For components of cost that they do not estimate, we rely on their 1997 updated version of the costs calculated using Weiss et al.'s methodology (*23*). We estimated total medical expenses for asthma among children at $4.6 billion. Nonmedical expenses include lost school days and lost productivity due to premature death. There are 247 deaths each year from childhood asthma (*4*). Indirect costs are estimated to total $2.0 billion (*22*). Total asthma-related expenses are therefore $6.6 billion. Of these, the environmentally attributable fraction is judged to be 30% (range 10–35%). Therefore, we estimate the environmentally attributable annual cost of pediatric asthma to be $2.0 billion (range $0.7–$2.3 billion) (Table 2).

Childhood cancer. We calculated the average annual charges per child with newly incident cancer in 1998 dollars to be $35,900 for physician services, $189,600 for inpatient services, and $20,400 for outpatient services, for a total of $245,900. Laboratory services account for an additional $263,200, bringing the total costs of treatment to $509,000 per case. When lost parental wages are taken into account, based on 5 lost wage days per 7 child hospital days, the total cost rises to $583,000. Assuming the costs of treating a second primary cancer are the same as the first, adding in the present value of those future costs increases the total by 7.46% to $623,000.

Table 1. Estimated costs of pediatric lead poisoning, United States, 1997.

EAF	=	100%	
Main consequence	=	Loss of IQ over lifetime	
Mean blood lead level in 1997 among 5-year-old children	=	2.7 µg/dL	
A blood lead level of 1 µg/dL	=	Mean loss of 0.25 IQ points per child	
Therefore, 2.7 µg/dL	=	Mean loss of 0.675 IQ points per child	
Loss of 1 IQ point	=	Loss of lifetime earnings of 2.39%	
Therefore, loss of 0.675 IQ points	=	Loss of 1.61% of lifetime earnings	
Economic consequences			
For boys: loss of 1.61% × $881,027 (lifetime earnings) × 1,960,200		=	$27.8 billion
For girls: loss of 1.61% × $519,631 (lifetime earnings) × 1,869,800		=	$15.6 billion
Total costs of pediatric lead poisoning		=	$43.4 billion

Finally, cranial irradiation will reduce IQ an average of 2.8 points in each child treated for brain cancer (*76*), corresponding to a loss of lifetime earnings with a present value of $60,471 (*51*). (Because second neoplasms occur later, we ignored the effect of irradiation in these later cancers inasmuch as the effect is substantially reduced as a child grows older.) Thus the total cost per case of childhood cancer is estimated to be $622,579.

The population to which these cost figures are applied is the cohort of incident cancer patients that arises in the United States each year. Among children under age 15, the annual overall incidence of cancer is 133.3 per million (*6*). There were 57.9 million children under 15 years of age in the United States in 1997, according to the Bureau of the Census (*41*). Therefore 7,722 cases of childhood cancer can be anticipated each year among future birth cohorts during their first 15 years of life. The annualized present value of cancer-related costs for children in future birth cohorts under present conditions is therefore $4.8 billion.

The costs of premature loss of life due to primary and secondary cancer in this cohort of children were calculated (*57*) using SEER data from the National Cancer Institute as a basis for computing age-specific mortality rates. These costs totaled $1.8 billion annually.

When we estimate the environmentally attributable fraction of pediatric cancers to be 2, 5, or 10%, the corresponding attributable costs are $132 million, $332 million, or $663 million. (Table 3).

Neurobehavioral disorders. To assess the incidence and costs of neurobehavioral disorders attributable to toxicants in the environment, we combined data on incidence of these conditions from the CDC (*7*) with cost data developed by Honeycutt et al. (*26*). We considered the assessment of the National Academy of Sciences (*27*) that 28% of neurobehavioral disorders are caused partly or entirely by environmental factors, defined broadly. Within that broad estimate, we calculated that 10% of incident cases of mental retardation, autism, and cerebral palsy (range 5–20%) are attributable to exposure to toxicants in the environment.

To avoid double-counting cases from lead exposure, we reasoned that the effect of lead in the population of current U.S. children is to lower IQ by an average of 0.25 points (*24*). Assuming that in both lead-exposed and unexposed populations, IQ has a normal distribution with a standard deviation of 15, and that mental retardation is defined as IQ below 85, we calculated the proportion of mentally retarded persons who would be found in populations with mean IQ of 99.75 (lead exposed) and 100 (unexposed). The difference between these proportions represents the lead-attributable burden of mental retardation. On this basis, we find that 97.5% of mental retardation is not attributable to lead exposure. Therefore, in calculating total costs of neurobehavioral disorders, we include only 97.5% of costs of mental retardation.

Not double-counting children with both mental retardation and either autism or cerebral palsy, we found that mental retardation, autism, and cerebral palsy not attributable to lead generate lifetime costs of $92.0 billion per annual cohort. If the environmentally attributable fraction is 5, 10, or 20%, we arrive at environmentally attributable costs of $4.6 billion, $9.2 billion, or $18.4 billion (Table 4).

Table 2. Estimated costs of pediatric asthma of environmental origin, United States, 1997.

Medical and indirect costs	U.S. dollars
Hospital care	
Inpatient	634 million
Emergency room	323 million
Outpatient	154 million
Physicians' services	
Inpatient	54 million
Outpatient	625 million
Medications	2.81 billion
Subtotal: medical costs	4.6 billion
Indirect Costs	
School days lost	1.78 billion
Premature deaths	193 million
Subtotal: indirect costs	2.0 billion
Total costs of pediatric asthma	6.6 billion
EAF	30% (range 10–35%)
Environmentally attributable costs of pediatric asthma	2.0 billion (range $0.7–2.3 billion)

Table 3. Estimated costs of pediatric cancer of environmental origin, United States, 1997.

Costs	U.S. dollars
Medical costs (per primary case)	
Inpatient care	189,600
Outpatient care	20,400
Laboratory	263,200
Physicians' services	35,900
Subtotal: medical costs	509,000
Indirect morbidity costs (per primary case):	
Lost parental wages	13,500
Loss of IQ	60,500
Subtotal: indirect morbidity costs	74,000
Total morbidity costs per primary case	583,000
Morbidity costs of secondary cases[a]	40,000
Morbidity costs per case for primary and subsequent secondary cancer	623,000
Total annual morbidity costs of childhood cancer[b]	
Medical and indirect morbidity costs	4.8 billion
Costs of premature deaths	1.8 billion
Total morbidity costs	6.6 billion
Costs of environmentally attributable pediatric cancer	332 million (range 132–663 million)

EAF calculated at 2, 5, and 10%.
[a]Present value of costs of second cases, 7.46% of above, excluding effects of radiation on IQ in second cancers. [b]Based on 7,722 new cases of childhood cancer per year.

Table 4. Estimated costs of neurobehavioral disorders of environmental origin, United States, 1997.

Lifetime costs per case of developmental disabilities	Mental retardation	Autism	Cerebral palsy
Physician visits	$17,127	—	$32,844
Prescription drugs	$3,121	—	$3,526
Hospitalization	$26,434	$4,437	$17,335
Assistive devices	$2,725	$116	$2,704
Therapy and rehabilitation	$11,577	$1,685	$14,421
Long-term care	$83,923	$32,846	$4,365
Home and auto modifications	$810	$571	$1,847
Special education services	$64,107	$72,399	$51,182
Home care	$907,742	$1,024,237	$882,932
Productivity losses due to morbidity	$563,869	$472,740	$467,753
Total lifetime costs per case	$1,680,000	$1,609,000	$1,479,000
Annual incident cases	44,190	4,698	11,614
Annual incident cases not attributable to lead	43,085	4,698	11,614
Total costs per annual cohort	$72.4 billion	$7.6 billion	$17.2 billion
Downward adjustment of costs for autism and cerebral palsy to account for co-existing mental retardation	— $72.4 billion	–34% $5.0 billion	–15% $14.6 billion
Total environmentally attributable costs of neurobehavioral disorders	$9.2 billion (range $4.6–18.4 billion)		

EAF estimated at 5, 10, or 20%.

Discussion

This study represents the first comprehensive attempt to estimate the incidence, prevalence, mortality, and costs associated with pediatric disease of toxic environmental origin in the United States. Our analysis of disease rates is based on national data collected by agencies of the federal government. Our estimates of costs are also based largely on national data. Our methodology consists of application of an environmentally attributable proportion model.

We examined four categories of illness in children for which we hypothesize there exists some degree of environmental causation: asthma, lead poisoning, childhood cancer, and certain neurobehavioral disorders. For each disease, we sought to determine the proportion of cases that could be attributed to pollutants in the environment—the environmentally attributable fraction (EAF). We defined this environment as consisting of toxic chemicals of human origin in environmental media. We did not consider outcomes that are caused at least partly by personal or familial choice, such as asthma caused by environmental tobacco smoke or neurobehavioral dysfunction associated with the fetal alcohol syndrome. The EAF in this analysis is therefore the "percentage of a particular disease category that would be eliminated if environmental risk factors were reduced to their lowest possible levels" (*37*).

We estimate that the annual costs of environmentally attributable diseases in American children total $54.9 billion, with a range of plausible estimates from $48.8 to $64.8 million (Table 5). Of this amount, $43.4 billion is due to lead poisoning, $2.0 billion to asthma, $0.3 billion to childhood cancer, and $9.2 billion to neurobehavioral disorders. Total costs to U.S. society are annual costs multiplied by the number of years in which cases of pediatric diseases of environmental origin continue to occur.

Previous efforts to assess the extent and costs of diseases of environmental origin in children have focused principally on lead poisoning and asthma. For lead poisoning, Schwartz et al. (*24*) have developed a model for estimating lifetime costs. They calculated that the societal benefit of reducing mean blood lead levels by 1 μg/dL would be $5.1 billion per year in the United States. Mean blood lead levels have, in fact, declined by more than 10 μg/dL since 1976 (*16*), largely as a consequence of the removal of lead from gasoline. Total cost savings resulting from the removal of lead from gasoline therefore exceed $50 billion each year. Schwartz et al. (*24*) emphasize that in addition to these economic benefits, there are almost certainly large but poorly quantified social benefits that result from reductions in criminality, drug abuse, and incarceration induced by lead (*48,50,78*). These findings underscore the concept that in the information age the wealth of a nation is directly correlated with developmental health and aggregate intelligence (*79*).

For asthma, Weiss et al. (*18*) reported that total costs in 1985 were $4.5 billion across all age groups—nearly 1% of all U.S. health care costs. In children (less than 18 years of age), asthma accounted for $1.2 billion annually: $465 million in direct medical costs plus $825 million in indirect costs, of which the largest component ($726 million) was diminished productivity due to loss of school days. Weiss et al. (*23*) subsequently updated their estimates through 1994 and found that the total costs of childhood asthma had increased to $3.17 billion annually, with direct costs of $1.96 billion and indirect costs of $1.22 billion; lost school productivity again accounted for the bulk of the indirect costs ($0.96 billion).

Further studies of the costs of asthma have been undertaken by Smith et al. (*19*) and by Farquhar et al. (*20*). These studies developed estimates of total costs that were similar to those of Weiss et al. (*23*), ranging from $3.4 to $4.9 billion annually (in 1987 dollars) across all age groups; the differences between those estimates are explained principally by different approaches to calculating the costs of prescription medications (*22*). A 1999 study conducted by the U.S. EPA (*21*) developed estimates of costs by tracking asthma over a lifetime.

To update estimates of the costs of asthma to 1997, a study undertaken by Chestnut et al. (*22*) used asthma occurrence data for 1996–1998 from the National Center for Health Statistics and data on the costs of medical outcomes from Weiss et al. (*18,23*) and Smith et al. (*19*), and they adjusted these costs to 1997 dollars. The principal finding was that annual costs of asthma across all age groups in the United States in 1997 were between $10 and $11 billion—more than double the estimates for the 1980s. Of these total costs, approximately 65% are for direct medical expenses, 20% for indirect morbidity costs, and 15% for mortality costs. Approximately one-third of total costs— $3.3–3.5 billion annually—reflects the costs of asthma in children less than 18 years of age. These data provided the principal input to the analyses undertaken in the present study.

Our estimates of the costs of pediatric asthma are higher than those of previous authors. The bulk of this difference lies in our estimate for drug costs. Weiss et al.'s (*23*) estimate of drug costs is considerably lower than ours. They identified patterns of drug treatment for asthmatics by using data from the National Ambulatory Medical Care Survey (NAMCS). Because the NAMCS is filled out by busy practitioners in the course of regular medical care and has only limited space for listing medications, we believe that the NAMCS underreports drug treatment. We have instead relied on the methodology of Chestnut et al. (*22*). They began with estimates of the number of mild, moderate, and severe asthmatics, and imputed to each asthmatic child a treatment regimen consistent with the asthma treatment guidelines of the National Heart Lung and Blood Institute (*80*). It can be argued that actual practice has yet to catch up with these evidence-based recommendations and that the actual costs of treating asthma are lower than those associated with the NHLBI guidelines because not all clinicians adhere to the guidelines. However, we believe this method comes closer to estimating current prescribing patterns than a model relying on NAMCS. It is, at the least, the pattern toward which asthma treatment is moving.

Another approach to estimating the costs of environmentally related respiratory disease would be to assess the aggregate health benefits that have resulted from reductions in air pollution. Ostro and Chestnut (*54*) have calculated that reduction in fine particulate-matter (< 2.5 μm; $PM_{2.5}$) air pollution in the United States would reduce the costs of asthma and other respiratory diseases across all age groups by between $14 billion and $55 billion annually, with mean estimated annual cost savings of $32 billion. Similarly, the U.S. EPA has estimated the cost savings that resulted from implementation of the Clear Air Act (*81,82*). For 1970–1990, the EPA calculated that the annual monetary benefits of reductions in chronic bronchitis and other respiratory conditions across the entire population of the United States amounted to $3.5.billion (in 1990 dollars), with a range (5th to 95th percentile) of $0.5–$10.7 billion (*81*). If it is assumed that one-third of these costs are associated with respiratory symptoms avoided in children (*21*), then the annual reduction in costs

Table 5. Estimated costs (billions) of pediatric disease of environmental origin, United States, 1997.

Disease	Best estimate	Low estimate	High estimate
Lead poisoning	$43.4	$43.4	$43.4
Asthma	$2.0	$0.7	$2.3
Cancer	$0.3	$0.2	$0.7
Neurobehavioral disorders	$9.2	$4.6	$18.4
Total	$54.9	$48.8	$64.8

attributable to prevention of pediatric respiratory disease from enforcement of the Clean Air Act is $1.2 billion (range, $0.2–3.2 billion). Additional benefits are projected by the EPA to accrue over the years 1990–2010 as a result of implementation of the Clean Air Act Amendments of 1990 (*82*).

Our use of an EAF model is consistent with scholarly work that has used similar models to assess the costs of environmental and occupational diseases (*28–31,83–86*). Thus our work builds on a methodology described in 1981 by the Institute of Medicine of the National Academy of Sciences for assessing the burden and health costs of environmental disease in the United States through assessing the "fractional contribution" of the environment to cause of illness (*30*). It also builds on approaches that have been used to calculate the costs of occupational disease and injury for the State of New York (*29*) and for the United States (*28,86*).

The modified Delphi decision-making process that we employed in this study to estimate EAF for lead poisoning, asthma, and childhood cancer is a structured, formalized approach similar to approaches that have been used extensively over the past five decades to synthesize the opinions of experts and thus to achieve consensus in complex problems in medicine and public health (*42,43*). Since 1977, the U.S. National Institutes of Health have convened over 40 consensus panels to resolve issues relating to the safety and efficacy of new medical technologies. Similarly, researchers at the Rand Corporation have found consensus approaches very useful for assessing the appropriateness of diagnostic and therapeutic interventions against heart disease, colon cancer, and stroke (*43,87*). The CDC used a formal consensus technique to judge the appropriativeness of various treatments of isoniazid-resistant tuberculosis infection (*88*). Consensus approaches represent an efficient way to synthesize opinion in complex and rapidly developing areas of medicine and public health before developing definitive data. The Delphi process is necessarily speculative and the outcomes depend on the underlying assumption and beliefs of the consensus panel. Therefore, our panels were comprised of nationally recognized experts and all of our results are bracketed by a range of uncertainty.

Our estimates of disease burden and costs are conservative. Most important, they are low because we considered only four categories of childhood illness and only certain categories of neurobehavioral dysfunction. Additionally, in the case of neurobehavioral dysfunction, we avoided double-counting costs for children with coexisting conditions such as autism, mental retardation, or lead poisoning, although we recognize that the costs of caring for such children are certainly greater than the costs of caring for children with only one such disorder.

We were hampered in our modeling by the lack of etiologic research quantifying the possible contribution of environmental factors to the causation of many pediatric diseases, and also by the lack of knowledge of the possibly toxic effects of most chemicals to which American children may be exposed (*12,13*). In future years, as more etiologic research is undertaken and as better information becomes available on possible associations between environmental exposures and additional pediatric diseases, the model can be expanded. Our estimates are low additionally because we did not consider late complications of toxic exposures that could not reliably be attributed to exposures sustained during childhood. Thus, we did not examine the possible late cardiovascular consequences of childhood lead poisoning (*52*), nor did we consider the costs of adult asthma that might be the direct consequence and/or continuation of asthma that began in childhood. Finally, our estimates are low because we did not attempt to estimate the costs of the pain, the deterioration in quality of life, or the emotional suffering in families, friends, or affected children that are the consequences of childhood illness.

In summary, diseases of toxic environmental origin make an important and insufficiently recognized contribution to total health care costs among children in the United States. The costs of these diseases currently amount to $54.9 billion annually, approximately 2.8% of the total annual cost of illness in the United States (*89*). By comparison, the annual health care costs attributable to motor vehicle accidents are $80.6 billion, and those due to stroke are $51.5 billion (*89*). The annual costs of military weapons research are $35 billion, and the costs of veterans' benefits are $39 billion (*90*). The costs of pediatric disease of environmental origin are large compared with the relatively meager amount of money spent on all research related to children, which in 1995 was only about $2 billion—a sum less than 3% of the total research enterprise of the federal government (*32*).

The costs due to pediatric disease of environmental origin will likely become yet greater in the years ahead if children's exposures to inadequately tested chemicals are permitted to continue. Increased investment is required in tracking and surveillance (*91*), in basic studies of disease mechanisms, and in prevention-oriented epidemiologic research (*92*). Most important, increased investment is needed to prevent pollution.

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