Assessing the Health Benefits of Air Pollution Reduction for Children

Eva Y. Wong, Julia Gohlke, William C. Griffith, Scott Farrow, and Elaine M. Faustman

1Institute for Risk Analysis and Risk Communication, Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, Washington, USA; 2Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylvania, USA; 3U.S. General Accounting Office, Washington, DC

Benefit–cost analyses of environmental regulations are increasingly mandated in the United States. Evaluations of criteria air pollutants have focused on benefits and costs associated with adverse health effects. Children are significantly affected by the health benefits of improved air quality, yet key environmental health policy analyses have not previously focused specifically on children’s effects. In this article we present a “meta-analysis” approach to child-specific health impacts derived from the U.S. Clean Air Act (CAA). On the basis of data from existing studies, reductions in criteria air pollutants predicted to occur by 2010 because of CAA regulations are estimated to produce the following impacts: 200 fewer expected cases of postneonatal mortality; 10,000 fewer asthma hospitalizations in children 1–16 years old, with estimated benefits ranging from $20 million to $46 million (1990 U.S.$); 40,000 fewer emergency department visits in children 1–16 years old, with estimated benefits ranging from $1.3 million to $5.8 million; 20 million school absences avoided by children 6–11 years old, with estimated benefits of $0.7–1.8 billion; and 10,000 fewer infants of low birth weight, with estimated benefits of $230 million. Inclusion of limited child-specific data on hospitalizations, emergency department visits, school absences, and low birth weight could be expected to add $1–2 billion (1990 U.S.$) to the $8 billion in health benefits currently estimated to result from decreased morbidity, and $600 million to the $100 billion estimated to result from decreased mortality. These estimates highlight the need for increased consideration of children’s health effects. Key needs for environmental health policy analyses include improved information for children’s health effects, additional life-stage-specific information, and improved health economics information specific for children.

Key words: air pollution, benefit, children, morbidity, mortality, risk assessment. Environ Health Perspect 112:226–232 (2004). doi:10.1289/ehp.6299 available via http://dx.doi.org/[(Online 14 October 2003)

Ambient air pollution has been associated with a multitude of health effects, including mortality, respiratory and cardiovascular hospitalizations, changes in lung function, asthma attacks, and days lost from work (Bates 1995a; Pope 1996, 2000; Samet et al. 2000a, 2000b; Segala 1999). These studies have been performed in multiple cities around the United States and internationally using various designs and statistical methods.

Attempts have been made to consider the public health impacts of the criteria air pollutants [particulate matter (PM), ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, and lead]. The U.S. Clean Air Act (CAA) Amendments of 1990 (1990) included the provision (section 812) that the U.S. Environmental Protection Agency (U.S. EPA) perform periodic analyses of the benefits and costs of the CAA. A retrospective analysis of the benefits and costs from 1970 to 1990 compared the costs of implementation of the CAA and its regulations with the health and welfare effects avoided (benefits) because of decreases in criteria air pollutant concentrations and found that benefits outweighed costs between 11 and 95 times (U.S. EPA 1997). A prospective analysis examining the benefits and costs of criteria air pollutant reductions (excluding lead) from 1990 to 2010 found that benefits would outweigh costs by 4 to 1 in 2010 (U.S. EPA 1999a).

In retrospective and prospective analyses, the U.S. EPA attempted to analyze the effects of the criteria air pollutants on 20 health endpoints. Although some children’s health effects were considered, these data were not comprehensive and were typically aggregated with estimates of impacts in adults. Lave and Selskin (1970) included infant mortality rates in their analysis of mortality attributable to air pollution in the 1960s. International and regional analyses have also been recently conducted but do not highlight child-specific impacts (Cifuentes et al. 2001; Hall et al. 1992; Murray and Lopez 1997).

In the United States, federal impetus has increased to include benefit–cost analyses when promulgating significant pieces of regulation (> $100 million), or benefit–cost analyses may be included in new or amended legislation. Executive Order 12866 of 1993 (Clinton 1993) established principles for evaluating risks, benefits, and costs of proposed, existing, or final pieces of significant regulation. Similarly, U.S. Executive Order 13045 (Clinton 1997) has led to increased federal attention to the specific susceptibility of children. Regulatory analyses can be useful tools and provide valuable information for decision makers (National Research Council 2002).

Several studies examining the associations between ambient air pollution and health effects have focused exclusively on the health effects of infants and children. This focus is important because children may be at higher risk than adults due to several factors, including differences in exposures, differences in age-specific activity patterns, and varying sensitivity during specific periods of development. Estimates based on U.S. surveillance data indicate that in 1999 asthma accounted for 658,000 emergency department visits, with children < 5 years old having the highest hospitalization and emergency department visit rates (Centers for Disease Control and Prevention 2002). Specific to children, associations with air pollution have been found for hospitalizations, increased symptoms, decreased lung function, low birth weight (LBW), and school absences (Bates 1995b). Associations with postneonatal mortality have been found for ambient pollution levels in the United States (Woodruff et al. 1997). Recent studies in the United States and internationally have found impacts on intrauterine death, birth outcomes, LBW, birth defects, and premature delivery (Bobak 2000; Bobak and Leon 1992; Bobak et al. 1999, 2001; Dejmek et al. 1999; Maisonet et al. 2000; Ritz and Yu 1999; Ritz et al. 2000, 2002; Rogers et al. 2000).

In this article, we expand an existing benefit–cost analysis framework to examine the impacts of the criteria air pollutants except lead on children’s health and to quantify the health benefits associated with reductions in criteria air pollutants during the period 1990–2010. The U.S. EPA prospective (1990–2010) analysis has previously considered the following health end points specifically for children: postneonatal infant death, birth outcomes, LBW, birth defects, and premature delivery.

Address correspondence to E.M. Faustman, Institute for Risk Analysis and Risk Communication, Department of Environmental and Occupational Health Sciences, University of Washington, 4225 Roosevelt Way NE, #100, Seattle, WA 98105 USA. Telephone: (206) 543-4299, Fax: (206) 616-4875. E-mail: faustman@u.washington.edu

This study was funded by the Center for the Study and Improvement of Regulation at Carnegie Mellon University/University of Washington, the U.S. Environmental Protection Agency (EPA-RA26886), and the National Institute of Environmental Health Sciences (NIEHS TP01 ES09601). This article has not been reviewed by the U.S. EPA or NIEHS and should not be assumed to represent agency, department, or U.S. Government Accounting Office views.

The authors declare they have no competing financial interests.

Received 24 February 2003; accepted 14 October 2003.
mortality (not included in the U.S. EPA’s main results); asthma hospitalizations; emergency department visits for asthma; acute bronchitis; upper and lower respiratory symptoms; and respiratory illnesses (U.S. EPA 1999a). We therefore performed our study to identify child-specific health end points that were not included in the prospective analysis, to update the literature where available, to estimate the national health impacts for children of reductions in the criteria air pollutants, and to conduct a preliminary estimation of the associated benefits. We used a model that was developed previously to follow the methodology of the U.S. EPA (1999a) while also considering inter- and intrastudy uncertainty, transparency, and best practice (Farrow et al., 2001). This model has been previously calibrated to and shown to approximate the U.S. EPA 1990–2010 analysis (Farrow et al., 2001).

**Materials and Methods**

To examine impacts of the criteria air pollutants on children, we surveyed the peer-reviewed air pollution literature (last search conducted April 2002) for studies focused exclusively on children or presenting results for children ≤18 years of age in the United States, and the impacts of one of the following: PM ≤10 μm and ≤2.5 μm in diameter (PM<sub>10</sub>, PM<sub>2.5</sub>), O<sub>3</sub>, CO, NO<sub>2</sub>, or SO<sub>2</sub>. The effects of lead were not included because of low ambient concentrations during the time period 1990–2010. The methodology evolved from the U.S. EPA (1999a) and is briefly described below. More detail is presented in Farrow et al. (2001). A literature search was performed in Medline (National Library of Medicine 2002) using the key words “child” (and all variants) and the pollutants of interest for studies examining the epidemiology-based exposure–response relationship between outdoor criteria air pollutant concentrations and children’s health effects. All available studies were used in the analysis below except that of Rogers et al. (2000), which used an unusual exposure metric (total suspended particulates + SO<sub>2</sub>). An important aspect of this meta-analysis type approach is the incorporation of exposure–response parameters and value estimates from multiple sources where possible. We modified results from published studies very little because our explicit intent was to capture the original authors’ modeling and characterization. Information was extracted from each study on the study population and location, pollutants studied, exposure levels, statistical methods, exposure–response function used, lag structure, *International Classification of Diseases*, 9th revision, codes (U.S. Department of Health and Human Services 1991) or symptoms defining a case (if applicable), exposure–response parameter (β coefficient, relative risk, or percent change), and measure of error (standard error (SE) or confidence interval (CI)).

We included 23 original studies examining the association between a considered health effect and an air pollutant (Tables 1–3). In Table 1, health studies examining mortality and hospitalization outcomes are listed by health effect and pollutant considered.

| Table 1. Data from studies analyzing children’s health, mortality, and hospitalizations (ages denote those examined in the present study). |
|---|
| **End points** | **Age (years)** | **Reference** | **Pollutant** | **Location, year** | **Risk coefficient (SE)** | **Exposure measure** |
| Postneonatal mortality | 1 month–1 year | Woodruff et al. 1997 | PM<sub>10</sub> | Various U.S. cities, 1989–1991 | 0.00392 (0.0012) µg/m<sup>3</sup> | Mean PM<sub>10</sub> for first 2 months of life |
| Hospital admissions Respiratory | <2, <5 | Pope 1991 | PM<sub>10</sub> | Utah and Salt Lake Valleys, UT, 1985–1989 | 0.000149 (0.000068) µg/m<sup>3</sup> | Mean monthly PM<sub>10</sub> |
| | <2 | Burnett et al. 2001 | O<sub>3</sub> | Toronto, Canada, 1980–1994 | 0.00661 (0.0014) ppb | Daily 1-hr maximum moving average |
| Asthma | 1–16 | Friedman et al. 2001 | PM<sub>10</sub> | Atlanta, GA, 2000 | -0.0232 (0.044) µg/m<sup>3</sup> | 3-day cumulative 2-day cumulative |
| | | | O<sub>3</sub> | Atlanta, GA, 2000 | -0.0511 (0.041) µg/m<sup>3</sup> | 3-day cumulative 2-day cumulative |
| | 1–16 | Shepherd et al. 1999 | PM<sub>2.5</sub> | Seattle, WA, 1987–1994 | 0.00250 (0.00095) µg/m<sup>3</sup> | Daily average |
| | 1–16 | Friedman et al. 2001 | PM<sub>10</sub> | Atlanta, GA, 2000 | 0.0337 (0.029) µg/m<sup>3</sup> | 3-day cumulative |
| | | | O<sub>3</sub> | Atlanta, GA, 2000 | 0.0406 (0.026) µg/m<sup>3</sup> | 2-day cumulative |
| | | | O<sub>3</sub> | Atlanta, GA, 2000 | 0.00953 (0.027) µg/m<sup>3</sup> | 2-day cumulative |
| | | | CO | Atlanta, GA, 2000 | 0.00622 (0.024) µg/m<sup>3</sup> | 3-day cumulative |
| | | | O<sub>3</sub> | Seattle, WA, 1995–1996 | 0.00673 (0.0033) µg/m<sup>3</sup> | 2-day cumulative |
| Emergency department visits for asthma | 1–16 | Norris et al. 2000 | PM<sub>10</sub> | Seattle, WA, 1995–1996 | 0.0180 (0.064) ppm | Maximum daily 1-hr average |
| | | | SO<sub>2</sub> | Seattle, WA, 1995–1996 | 0.0017 (0.0029) ppb Maximum daily 1-hr average |
| | | | CO | Seattle, WA, 1989–1990 | 0.0013 (0.0025) µg/m<sup>3</sup> | 4-day average |
| | | | O<sub>3</sub> | Seattle, WA, 1989–1990 | 0.00159 (0.0086) ppm | 1-hr maximum |
| | | | CO | Georgia, 1990 | 0.000378 (0.00013) µg/m<sup>3</sup> | 4-day average |
| | | | CO | Georgia, 1990 | 0.000198 (0.000042) µg/m<sup>3</sup> | 1-hr maximum |
many investigators and can be used to assess health impacts in the general form

\[
\text{Cases of health effect} = -\left( \text{baseline incidence} \times \left\{ \exp(-\beta \times \Delta PC) - 1 \right\} \right) \times \text{population at risk,}
\]

where \( \beta \) = study-specific regression coefficient and \( \Delta PC \) = change in pollutant concentration. To allow comparability with previous studies, we used expected average changes in annual air pollutant concentrations for the entire United States on a national level through 2010 based on our analysis of the U.S. EPA 1990–2010 study (Farrow et al. 2001). This led to estimated decreases in expected concentrations of criteria air pollutants (point estimates only): \( \text{PM}_{10} = 2.85 \mu g/m^3, \ O_3 = 1.34 \text{ppm}, \ CO = 1.68 \text{ppm}, \text{NO}_2 = 9.4 \text{ppb}, \text{SO}_2 = 1.15 \text{ppb} \) (Farrow et al. 2001; U.S. EPA 1999a). These changes in concentration are the estimated national average difference between projected criteria air pollutant concentrations in the year 2010 had the CAA not been in place versus those with the CAA in place.

The present analysis was estimated for a projected 2010 U.S. population ± 18 years old of 76,461,986 and projected age distribution of the population (U.S. Census Bureau 2002). Baseline rates were obtained from U.S. national sources (Adams and Marano 1995; Martin et al. 2002; U.S. EPA 1999a) or from individual studies (Gilliland et al. 2001; Ostro et al. 2001; Ware et al. 1986). For analyses of the health impacts, we combined regression coefficients from different studies of the same health outcome using inverse variance weighting methods to form a regression coefficient specific to each end point and pollutant. Using the inverse variance weighting method, we weighted each study by its fractional contribution to the sum of the inverse variance of the considered studies (per end point, per pollutant). Results from multivariate regression models were used when available. To determine the impacts of all pollutants for each health outcome, we added together the impacts caused by separate pollutants. Many of the studies focused on children of a particular age or ethnic group, so the results presented below are for those specific groups. Pollutant-specific health impact estimates have two significant figures to assist with computation and to prevent growth in rounding errors; however, they are likely not significant to more than one figure. If the lower bound includes a negative number, estimates have not been truncated at 0,

**Table 2.** Data from studies analyzing children’s health from nonhospitalization ailments (ages denote those examined in the present study).

| End points | Age (years) | Reference | Pollutant | Location, year | Risk coefficient (SE) | Exposure measure |
|------------|-------------|-----------|-----------|----------------|-----------------------|------------------|
| Upper respiratory symptoms | 10–12 | Pope et al. 1991 | PM$_{10}$ | Utah Valley, UT, 1989–1990 | 0.0036 (0.0015) µg/m$^3$ | Same day |
| Lower respiratory symptoms | 7–14 | Schwartz et al. 1994 | PM$_{10}$, O$_3$ | 6 U.S. cities, 1984–1986 | 0.00192 (0.00096) µg/m$^3$ | Daily average |
| Respiratory illness | 6–7 | Hasselblad et al. 1992 | NO$_2$ | Meta-analysis | 0.0272 (0.017) µg/m$^3$ | Annual average |
| Moderate or worse asthma | 8–13 AA | Ostro et al. 2001 | PM$_{10}$ | Los Angeles, CA, 1993 | 0.000349 (0.00004) ppb | 1-hr maximum |
| Shortness of breath, chest tightness, or wheeze | 8–13 AA | Ostro et al. 2001 | PM$_{10}$ | Los Angeles, CA, 1993 | 0.000349 (0.00017) ppb | 24-hr average |
| Shortness of breath, chest tightness, or wheeze | 6–9 | Peters et al. 1999 | PM$_{10}$ | Southern California, 1986–1990 | 0.000195 (0.00035) µg/m$^3$ | 24-hr average |
| Shortness of breath, chest tightness, or wheeze | 6–9 | Ware et al. 1986 | PM$_{10}$ | 6 cities, 1979–1980 | 0.00101 (0.0018) µg/m$^3$ | 24-hr average |
| Shortness of breath | 8–13 AA | Ostro et al. 1995 | SO$_2$ | Los Angeles, CA, 1992 | 0.000841 (0.00036) µg/m$^3$ | 24-hr average |
| Shortness of breath | 8–13 AA | Ostro et al. 2001 | PM$_{2.5}$ | Los Angeles, CA, 1993 | 0.000275 (0.00013) µg/m$^3$ | 12-hr maximum |

**Table 3.** Data from studies analyzing children’s school absences and birth impacts (ages denote those examined in the present study).

| End points | Age (years) | Reference | Pollutant | Location, year | Risk coefficient (SE) | Exposure measure |
|------------|-------------|-----------|-----------|----------------|-----------------------|------------------|
| School absences | 9–10 | Gilliland et al. 2001 | PM$_{10}$, NO$_2$ | Los Angeles area, 1996 | −0.00440 (0.018) µg/m$^3$ | 24-hr average |
| | 9–10, 6–11 | Ransom and Pope 1992 | PM$_{10}$ | Utah Valley, UT, 1985–1986 to 1990–1991 | 0.0219 (0.0046) µg/m$^3$ | 8-hr average |
| | 9–10, 6–11 | Chen et al. 2000 | PM$_{10}$ | Washoe County, NV, 1996–1998 | 0.0221 (0.0046) µg/m$^3$ | 24-hr average |
| LBW | Singleton, first birth | Maisonet et al. 2001 | PM$_{10}$, CO, SO$_2$ | U.S. cities, 9–1944–1996 | −0.00408 (0.0047) µg/m$^3$ | Average for 3rd month of pregnancy |
| Ventricular septal defect | Singleton | Ritz and Yu 1999 | O$_3$ | Southern California, 1989–1993 | 0.0289 (0.029) ppb | Average last trimester |
| | Singleton | Ritz et al. 2002 | CO | Southern California, 1987–1993 | 0.122 (0.15) ppb | Average for 2nd month of pregnancy |

AA, African-American asthmatics.

$^a$Preceding 14 days. $^b$Boston and Springfield, MA; Hartford, CT; Philadelphia and Pittsburgh, PA; and Washington, DC.
to provide a sense of the uncertainty associated with results. We used available data for each pollutant and health effect considered in a one-dimensional 10,000-run Monte Carlo simulation to determine the health impacts (Burmaster and Anderson 1994; Thompson et al. 1992). Monte Carlo simulation is a statistical technique that allows for the propagation of uncertainty in an analysis. Use of this technique allows us to use information about the uncertainty around the point estimate of effect reported in the original, peer-reviewed studies.

Analyses were conducted in Microsoft Excel (Microsoft Corp., Redmond, WA) and used Decisioneering Crystal Ball (Decisioneering Inc. 2000), an Excel add-on that allows an analyst to perform Monte Carlo simulations.

To consider the potential economic impacts, benefits were the present value benefits of considered health effects as estimated in published studies. Estimates of the reduced number of cases can be combined with existing economic valuation data to determine the benefits associated with reductions in these illnesses. We determined mortality estimates using existing recommendations for the value of a statistical life at $4.8 (SD = 3.2) million in 1990 US$ (U.S. EPA 1999a). Not all health end points considered have available valuation data that are specific for children. Limited child-specific information on the present value of asthma hospitalizations, emergency department visits for asthma, school absences, and LBW is available (Hall et al. 2002; Smith et al. 1997; U.S. EPA 1999b; Weiss et al. 1992).

Smith et al. (1997) estimated a value of $4,900 (SD = 1,300) in 1990 US$ for each asthma hospitalization, $220 (SD = 42) per emergency department visit, and $42 (SD = 8) per school absence. Alternatively, point estimates of values associated with select health end points are available. U.S. EPA (1999b) estimates a value of $18,000 (1990 US$) for all medical costs associated with LBW in infancy, an average annual cost of $34 per patient for emergency department visits, and $2,000 per asthma hospitalization. Yet other alternative data from Weiss et al. (1992) for children ≤17 years old value each case at $2,200 (1990 US$) per asthma hospitalization, $150 per emergency department visit, and $100 per school absence. Unlike the latter two studies, in Smith et al. (1997) CIs are used to represent uncertainty, but no information is presented that allows child-specific values to be estimated. Estimates from Weiss et al. (1992) and estimates of average hospitalization costs from U.S. EPA (1999b) were specific for children <18 years old; however, only point estimates were presented. Although there are moderate differences in the estimates presented by the three sources, no one source can be considered preferable to the others. We adjusted valuation estimates from these studies to 1990 US$ by using the Consumer Price Index Medical Care (U.S. Department of Labor Bureau of Labor Statistics 2002) to facilitate comparison with prior analyses, particularly that of U.S. EPA (1999a), which reports values in 1990 US$.

**Results**

In this study, we analyzed children’s health impacts from changes in ambient concentrations of the criteria air pollutants (excluding lead) due to the CAA from 1990 through 2010 (Figure 1). Reductions in PM$_{10}$ in the year 2010 were estimated to lead to a median of 160 (5th–95th percentiles; 90% CI, 45–270) fewer expected cases of postneonatal mortality (from 1 month to 1 year of birth); 3,000 (500–6,600) fewer respiratory hospitalizations in children 0–2 years of age, or 10,000 (1,000–20,000) fewer in children 0–5 years of age; and 1,300 (480–6,600) fewer emergency department visits in children 1–16 years of age (Figure 1, Table 4). Approximately 2.5 (–1.8 to 3.5) million school absences may also be avoided by children 6–11 years old in the United States. 

Small reductions in ambient O$_3$ concentrations may lead to 700 (400–1,000) fewer respiratory hospitalizations in children ages 0–2 and 1,600 (220, 3,000) fewer emergency department visits for asthma in children ages 1–16, or 750,000 (470,000–1,000,000) fewer school absences in children ages 6–11 (Figure 1, Table 4). Reductions in CO concentrations may lead to 9,400 (4,200–19,000) fewer asthma hospitalizations or 35,000 (8,800–66,000) emergency department visits in children ages 1–16 years. NO$_2$ reductions may lead to 2.2 (–8.4 to 7.9) million fewer school absences in children ages 9–10.

Combining the pollutant-specific estimates, the specified changes in criteria air pollutant concentrations would lead to a total of 10,000 (4,000–20,000) averted asthma hospitalizations and 40,000 (10,000–70,000) fewer emergency department visits in children ages 1–16. Approximately 20 (10–20) million fewer school absences in children ages 6–11 and 10,000 (–20,000 to 70,000) averted LBW infants may also be expected (Table 4).

Estimated reductions in air pollution concentrations in 2010 could lead to reduced postneonatal mortality with estimated benefits of $590 ($150–1,300) million (1990 US$). Because we are aware of only three sources of valuation data, we report valuation results separately using each of the three studies (all 1990 US$). Using estimates from Smith et al. (1997), benefits of $46 ($17–84) million in asthma hospitalizations, $5 ($2–11) million in emergency department visits for asthma, and $700 ($400–1,000) million in school absences are estimated (Table 5). Using estimates from U.S. EPA (1999b) results in benefits of $20 ($6–42) million for asthma hospitalizations, $1.3 ($0.3–3) million for emergency department visits, and $230 (–500 to 1,400) million for LBW costs during infancy (Table 5).

Using estimates from Weiss et al. (1992) for children <17 years old leads to benefits of $22 ($7–47) million in asthma hospitalizations, $5.8 ($1.3–12) million for emergency department visits, and $1.8 ($0.75–2.4) billion for school absences in children 6–11 years of age (Table 5).

**Discussion**

Given the currently available health literature on children’s health effects associated with the criteria air pollutants (excluding lead) and the limited literature on the valuation of children’s health, this analysis should be considered as a starting point and as identifying key research needs for examining a unique and susceptible population in benefit–cost or cost-effectiveness analyses of environmental policies. When additional information on health effects and detailed economic valuation data for children are available, the data can be combined and used in analyses of environmental policies. The results of the present analysis are not intended to and cannot provide absolute estimates of the benefits to children associated with decreases in ambient criteria air pollutant levels, but can provide information about the importance of children’s health effects in aggregate studies based on an assessment of order of magnitude or ranges of expected health benefits.

The magnitude of omitting children’s health impacts can be seen when comparing the mean impact results here with mean U.S. EPA (1999a) results. Inclusion of child-specific data on asthma hospitalizations, emergency department visits for asthma, school absences, and LBW could be expected to add between $1 and $2 billion (depending on source of valuation estimates) to the $8 billion (1990 US$) in mean health benefits from decreased morbidity currently estimated by U.S. EPA (1999a) for the U.S. population. Consideration of postneonatal mortality would add $600 million to the present mean estimate of $100 billion resulting from decreases in adult mortality (U.S. EPA 1999a). Decreases in adult mortality were the key driver in prior analyses of benefits and costs. Although the benefits to infants are a small percentage (<1%) of the estimated benefits to adults, benefits were estimated for adults ≥30 years old, whereas benefits estimated here are for infants only between 1 month and 1 year of age. Future research examining the susceptibility of children and young adults is needed.

Availability of data for additional children’s health end points and consideration of other metrics (e.g., life-years) may be expected to increase estimates of children’s health benefits.
Estimates of morbidity benefits were assessed using cost of illness methods and are considered lower bounds of the estimate (Krupnick 2003; U.S. EPA 1999b). Our current analysis presents results only for specific age or ethnic groups and does not extrapolate findings to the total population of U.S. children. Extrapolation to all children would be expected to lead to an increase in the number of cases averted. Thus, estimated health benefits in this analysis may be considered conservative. The “value of a statistical life” method has long been a subject of contention (Viscusi 1993). Recent attention has focused on using life-years lost or valuing a life without using an age adjustment. To provide comparisons with the U.S. EPA’s estimates of the benefits and costs of the CAA, each estimated premature death of a child was valued at the same value as an adult. These approaches have recently been affirmed by the federal government in the face of opposition to the “senior discount” implicit in valuing life-years saved (Graham 2003; Whitman 2003).

The above estimates for the child-specific impacts of the CAA are comparable with recent studies. Via the modified Delphi technique (an expert elicitation method), 30% of acute exacerbations of pediatric asthma were estimated to be environmentally related, for an estimated $2 billion (1997 US$) per year in environmentally attributable costs of pediatric asthma in the United States (Landrigan et al. 2002). U.S. EPA (1999a) estimated the benefits associated with 950,000 upper respiratory symptoms, 520,000 lower respiratory symptoms, and 330,000 respiratory illness cases to reach $19 million, $6 million, and $6 million (1990 US$) per year, respectively.

In the present analysis, benefits resulting from reduced numbers of LBW infants arose from the first year of birth only, but LBW may also have lifelong effects on health and productivity. Lifetime medical costs due to LBW of $436,000 (1996 US$, undiscounted) have been estimated (U.S. EPA 1999b). Use of lifetime estimates rather than those from the first year of birth alone would lead to increased estimates of health benefits. The benefits of reduced birth defects were not explicitly calculated in the present analysis because of mismatches in health and economic end points. However, given available economic data on other types of cardiac defects, additional benefits in the hundreds of millions could be inferred.

Many assumptions were included in the present analysis. Prior analyses have focused on geographically detailed estimates of exposures, whereas we did not include modeling of ambient exposures, regional variation, or human activity patterns affecting exposure. Average nationwide ambient concentrations were estimated from U.S. EPA (1999a). Although this approximation neglects the seasonal and regional variation of ambient air pollution, our purpose was to generate a preliminary estimate of the impacts in children in the entire United States over time. The extent to which air pollutants are merely a marker for some other compound will also affect the findings of this analysis. Because of the complex interplay of copollutants found in the United States, it may be difficult to distinguish the role of each pollutant.

The results of this analysis depend on the available information in the peer-reviewed literature. Some of the studies used in the present analysis (e.g., Woodruff et al. 1997) were not included in the U.S. EPA (1999a) analysis, reportedly because of lack of confidence in the new end point of postneonatal mortality. Child-specific associations are the focus of this

### Table 4. Estimated reduced numbers of select health end points by pollutant.

| Pollutant | Postneonatal mortality<sup>a</sup> (1 month–1 year) | Asthma hospitalizations<sup>a</sup> (1–16 years) | Emergency department visits<sup>a</sup> (1–16 years) | School absences<sup>b</sup> (9–10 years) | School absences<sup>b</sup> (6–11 years) | LBW<sup>a</sup> (singletons) |
|-----------|---------------------------------------------------|-----------------------------------------------|-------------------------------------------------|------------------------------------------|------------------------------------------|----------------------------------|
| PM<sub>2.5</sub> | 160 (45–270) | 430 (150–700) | 1,300 (480–6,600) | 0.85 (–0.67 to 1.2) | 2.5 (–1.8 to 3.5) | –3,300 (–13,000 to 7,200) |
| O<sub>3</sub> | — | –10 (–1,300 to 1,300) | 1,600 (220–3,000) | 0.26 (0.16–0.37) | 0.75 (0.47–1.0) | — |
| CO | 9,400 (4,200–19,000) | 35,000 (8,800–66,000) | 4.6 (3.0–6.4) | 14 (8.5–19) | 16,000 (–13,000 to 69,000) | — |
| NO<sub>2</sub> | — | — | — | 2.2 (–8.4 to 7.9) | — | — |
| SO<sub>2</sub> | — | — | 380 (–920 to 1,600) | — | 300 (–6,000 to 6,500) | — |
| Total<sup>c</sup> | — | 10,000 (4,000–20,000) | 40,000 (10,000–70,000) | 8.0 (2.0 to 10) | 20 (10–20) | 10,000 (–20,000 to 70,000) |

<sup>a</sup>data unavailable. Note lack of available child-specific data for some end points and age groups.
<sup>b</sup>50th percentile [5th–95th percentile (90% CI)].
<sup>c</sup>in millions. % pollutant-specific estimates have two significant figures to assist with computation; totals may not add due to rounding.

### Table 5. Values per case from the literature and estimated benefits associated with age-group–specific reductions in select health end points (1990 US$).

| End point | Value per case<sup>d</sup> | Estimated benefits (in millions)<sup>e</sup> |
|-----------|-----------------|------------------------------------------|
| Postneonatal mortality | 4.8 ± 3.2 million | 580 (150–1,300) |
| Asthma hospitalizations | 2.00 | 20 (6–42) |
| Emergency department visits | 150 | 22 (7–47) |
| School absence<sup>f</sup> | 1,800 (750–2,400) |
| LBW | 18,000 | 230 (–500 to 1,400) |

<sup>d</sup>Mean ± SE. U.S. EPA (1999b) and Weiss et al. (1992) are point estimates only.
<sup>e</sup>Monetized value based on each study, 50th percentile [5th–95th percentile (90% CI)].
<sup>f</sup>Mortality estimates from U.S. EPA (1999a); morbidity estimates from U.S. EPA (1999b).
<sup>g</sup>Annual average cost per patient.
<sup>h</sup>Estimate of cases averted in children 6–11 years old.
preliminary study, and all available evidence was used. Any choices or assumptions made by the original investigators (e.g., choice of exposure–response function, adjusting for key variables) are implicitly included in this analysis. Differences in study design, regional air pollutant characteristics, and sources of data used may affect the comparability of studies but should not significantly affect their aggregate interpretation. The results of this analysis may be affected by results of the effort to reanalyze results of several existing studies because of software errors (Health Effects Institute 2002). However, the impact on the present analysis is not expected to be significant because few studies used the affected statistical procedure.

Future quantitative analyses of children’s health benefits may wish to evaluate effects separately for different ages in order to use other metrics such as years of life lost or quality-adjusted life-years (Fabian 1994). Increased data from cohort studies will allow estimation of life-years for use in these measures (National Research Council 2002). An age-specific analysis may better reflect higher-risk age groups. For example, Ransoms and Pope (1992) reported absence by grade, with a higher effect seen in the younger grades. Similarly, Burnett et al. (1994) found that infants ≤ 1 year old had significantly more respiratory hospitalizations (15% of admitting) associated with air pollution than did the middle-aged and elderly groups (4%) examined.

For many of the children’s health effects considered, the paucity of existing health effects data and economic data represents an opportunity for health researchers to present informative end points and data for economic analyses. Similarly, it presents an opportunity for health economists to provide key data for a susceptible population and an opportunity for increased collaboration between health risk assessors and economists for improved environmental health decision making. To take advantage of these opportunities, agencies need to consider funding priorities in children’s health and health economics.

The estimates of health benefits are conservative. Estimates of the number of cases averted are presented only for specific age groups. Some health effects were unable to be included in the analysis. Estimates of the benefits are also low because we present data for only a subset of health effects considered (those with economic valuation information available on children’s health effects). Cost-of-illness estimates do not include pain and suffering, altruism, or lost leisure time. However, the results of this analysis suggest that air pollution imposes a significant burden on U.S. children and have also allowed us to identify significant data gaps that impede our understanding of the full benefits of air pollution reductions for children’s health.

REFERENCES

Adams PF, Marano MA. 1995. Current Estimates from the National Health Interview Survey, 1994. Vital Health Statistics Vol 10(103). Hyattsville, MD: National Center for Health Statistics.

Bates DV. 1995a. Adverse health impacts of air pollution—continuing problems. Scand J Work Environ Health 21:405–411.

—. 1995b. The effects of air pollution on children. Environ Health Perspect 102(suppl 6):49–53.

Bobak M. 2000. Ozone and PM10 pollution, low birth weight, and prematurity. Environ Health Perspect 108:173–176.

Bobak M, Leon DA. 1992. Air pollution and infant mortality in the Czech Republic, 1986–88. Lancet 340:1016–1014.

Bobak M, Pikhart H, Leon DA. 1999. Air pollution, low birth weight and prematurity. Epidemiology 10:3650.

Bobak M, Richards M, Wadsworth M. 2001. Air pollution and birth weight in Britain in 1946. Epidemiology 12:358–359.

Burmaster DE, Anderson PD. 1994. Principles of good practice for the use of Monte Carlo techniques in human health and ecological risk assessments. Risk Anal 14:477–481.

Burnett RT, Dales RE, Raizenne ME, Krewski D, Summers PW, Roberts ER, et al. 1994. Effects of low ambient levels of ozone and sulfates on the frequency of respiratory admissions to Ontario hospitals. Environ Res 65:172–194.

Burnett RT, Smith-Dooran M, Stieb D, Raizenne ME, Brook J, Dales RE, et al. 2001. Air pollution and hospitalization for acute respiratory illnesses in children less than 2 years of age. Am J Epidemiol 153:444–452.

Centers for Disease Control and Prevention. 2002. Surveillance for asthma—United States, 1980–1999. Morb Mortal Wkly Rep 51:1–13.

Chen L, Jenniels BL, Yang W, Omaye ST. 2000. Elementary school absenteeism and air pollution. Inhal Toxicol 12:197–161.

Cilentes L, Borja-Aburto VH, Gouveia N, Thurston G, Davis DL. 2001. Assessing the health benefits of urban air pollution reductions associated with climate change mitigation (2000–2020): Santiago, São Paulo, Mexico City, and New York City. Environ Health Perspect 109(suppl 3):419–425.

Clinton WJ. 1993. Executive Order 12866. Regulatory Planning and Review. Fed Reg 58:51735.

—. 1997. Executive Order 13045. Protection of Children from Environmental Health Risks and Safety Risks. Fed Reg 62:19883–19888.

Decisioneering Inc. 2000. Crystal Ball Manual. Broomfield, CO:G.D. Press.

Dejmek J, Selevan SG, Benes I, Solansky I, Sram RJ. 1999. Fetal growth and maternal exposure to particulate matter during pregnancy. Environ Health Perspect 107:475–480.

Dockery DW, Cass GR, Spengler JD, Fuehrer JS, Speizer FE, Health Effects Institute. 2002. Air pollution and asthma—United States, 1980–1999. Morb Mortal Wkly Rep 51:1–13.

Dockery DW, Cusson MM, Lem SM, Spengler JD, Koutrakis P, et al. 1996. Health effects of acid aerosols on North American children: respiratory symptoms. Environ Health Perspect 104:500–505.

Fabian RT. 1994. The Quality approach. In: Valuing Health for Policy (Tolley G, Kendek D, Fabian R, eds). Chicago:University of Chicago Press, 118–136.

Farrow RS, Wong E, Ponce RA, Faustman EM, Zerbe RO. 2001. Facilitating regulatory design and stakeholder participation: the FERET template with an application to the Clean Air Act. In: Improving Regulation (Fischbeck PS, Farrow RS, eds). Washington, DC:Resources for the Future, 429–442.

Friedman MS, Powell KE, Hutwagner L, Graham LM, Teague WG. 2001. Air impacts on school absenteeism due to respiratory illnesses. Inhal Toxicol 13:309–312.

Gauderman WJ, et al. 2001. The effects of ambient air pol-

health and PM10 pollution in Utah Valley, Salt Lake, and Cache valleys. Arch Environ Health 46:90–97.

—. 1996. Adverse health effects of air pollutants in a non- smoking population. Toxicology 111:149–155.

—. 2000. Epidemiology of fine particulate air pollution and human health: biologic mechanisms and who’s at risk? Environ Health Perspect 108(suppl 6):617–723.

Gauderman WJ, et al. 2001. Air pollution and exacerbation of asthma in African-American children in Los Angeles. Inhal Toxicol 13:309–312.

Gauderman WJ, et al. 2001. Air pollution and exacerbation of asthma in African-American children in Los Angeles. Epidemiology 12:200–208.

Peters JM, Avol E, Navidi W, Benford SJ, Gauderman WJ, Lurmann F, et al. 1999. A study of temporal trends in California communities with differing levels and types of air pollution. J Prevalence of respiratory morbidity. Am J Respir Crit Care Med 159:769–787.

Pope CA III. 1991. Respiratory hospital admissions associated with PM10 pollution in Utah, Salt Lake, and Cache valleys. Arch Environ Health 46:90–97.

—. 1996. Adverse health effects of air pollutants in a non- smoking population. Toxicology 111:149–155.

—. 2000. Epidemiology of fine particulate air pollution and human health: biologic mechanisms and who’s at risk? Environ Health Perspect 108(suppl 6):617–723.

Ritz B, Yu F. 1999. The effect of ambient carbon monoxide on low birth weight among women born in Southern California between 1989 and 1993. Environ Health Perspect 107:21–25.

Ritz B, Yu F, Chapa G, Friin S, et al. 2000. Effect of air pollution on preterm birth among children born in Southern California between 1989 and 1993. Epidemiology 11:502–511.

Ritz B, Yu F, Friin S, Chapa G, Shier GM, Harris JA. 2002. Ambient air pollution and multiple birth defects in Southern California. Am J Epidemiol 155:17–25.

Rogers JF, Thompson SJ, Addy CL, McKeown RE, Cowen DJ, Pratt WW. 1995. Air pollution and asthma exacerbations among African-American children in Los Angeles. Inhale Toxicol 7:711–722.

—. 2001. Air pollution and exacerbation of asthma in African-American children in Los Angeles. Epidemiology 12:200–208.

Ritz B, Yu F, Chapa G, Friin S, et al. 2000. Effect of air pollution on preterm birth among children born in Southern California between 1989 and 1993. Epidemiology 11:502–511.

Ritz B, Yu F, Friin S, Chapa G, Shier GM, Harris JA. 2002. Ambient air pollution and multiple birth defects in Southern California. Am J Epidemiol 155:17–25.

Rogers JF, Thompson SJ, Addy CL, McKeown RE, Cowen DJ, Pratt WW. 1995. Air pollution and asthma exacerbations among African-American children in Los Angeles. Inhale Toxicol 7:711–722.

—. 2001. Air pollution and exacerbation of asthma in African-American children in Los Angeles. Epidemiology 12:200–208.

Ritz B, Yu F, Chapa G, Friin S, et al. 2000. Effect of air pollution on preterm birth among children born in Southern California between 1989 and 1993. Epidemiology 11:502–511.

Ritz B, Yu F, Friin S, Chapa G, Shier GM, Harris JA. 2002. Ambient air pollution and multiple birth defects in Southern California. Am J Epidemiol 155:17–25.
Samet JM, Dominici F, Curriero FC, Coursac I, Zeger SL. 2000a. Fine particulate air pollution and mortality in 20 U.S. cities, 1987–1994. N Engl J Med 342:1742–1749.

Samet JM, Zeger SL, Dominici F, Curriero FC, Coursac I, Dockery DW, et al. 2000b. The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and Mortality from Air Pollution in the United States. Research Report 94 Part II. Boston, MA. Health Effects Institute.

Schwartz J, Dockery DW, Neas LM, Wypij D, Ware JH, Spengler JD, et al. 1994. Acute effects of summer air pollution on respiratory symptom reporting in children. Am J Respir Crit Care Med 150:1234–1242.

Schwartz J, Slater D, Larson TV, Pierson WE, Koenig JQ. 1993. Particulate air pollution and hospital emergency room visits for asthma in Seattle. Am Rev Respir Dis 147:826–831.

Segala C. 1999. Health effects of urban outdoor air pollution in children. Current epidemiological data. Pediatr Pulmonol 18(suppl):8–9.

Sheppard L, Levy D, Norris G, Larson TV, Koenig JQ. 1999. Effects of ambient air pollution on nonelderly asthma hospital admissions in Seattle, Washington, 1987–1994. Epidemiology 10:23–30.

Smith DH, Malone DC, Lawson KA, Okamoto LJ, Battista C, Saunders WB. 1997. A national estimate of the economic costs of asthma. Am J Respir Crit Care Med 156:787–793.

Thompson KM, Burmaster DE, Crouch EAC. 1992. Monte Carlo techniques for quantitative uncertainty analysis in public health risk assessments. Risk Anal 12:53–63.

U.S. Census Bureau. 2002. Annual Projections of the Resident Population by Age, Sex, Race, and Hispanic Origin: Lowest, Middle, Highest, and Zero International Migration Series, 1999 to 2100 (NP-D1-A). Washington, DC. U.S. Census Bureau. Available: http://www.census.gov/population/www/projections/natdet-D1A.html [accessed 22 November 2002].

U.S. Clean Air Act Amendments of 1990. 1990. Public Law 101-549.

U.S. Department of Health and Human Services. 1991. International Classification of Diseases, 9th revision: Clinical Modification. Washington, DC. U.S. Department of Health and Human Services.

U.S. Department of Labor Bureau of Labor Statistics. 2002. Consumer Price Index Medical Care. Washington, DC. U.S. Bureau of Labor Statistics. Available: http://www.bls.gov/cpi/home.htm [accessed 18 December 2002].

U.S. EPA. 1997. The Benefits and Costs of the Clean Air Act, 1970 to 1990. EPA 410-R-97-001. Washington, DC. U.S. Environmental Protection Agency, Office of Air and Radiation, Office of Policy, Planning, and Evaluation.

———. 1999b. Cost of Illness Handbook. Washington, DC. U.S. Environmental Protection Agency. Available: http://www.epa.gov/oppts/coi/ [accessed 29 November 2002].

Viscusi WK. 1993. The value of risks to life and health. J Econ Lit 31:1912–1946.

Ware JH, Ferris BG Jr, Dockery DW, Spengler JD, Stram DO, Speizer FE. 1986. Effects of ambient sulfur oxides and suspended particles on respiratory health of preadolescent children. Am Rev Respir Dis 133:834–842.

Weiss KB, Gergen PJ, Hodgson TA. 1992. An economic evaluation of asthma in the United States. N Engl J Med 326:862–866.

White MC, Etzel RA, Wilcox WD, Lloyd C. 1994. Exacerbations of childhood asthma and ozone pollution in Atlanta. Environ Res 65:56–68.

Whitman CT. 2003. Statement of Christine Todd Whitman, Aging Initiative Public Listening Session. Washington, DC. U.S. Environmental Protection Agency. Available: http://www.epa.gov/aging/listening/2003/balt_ctw.htm [accessed 14 July 2003].

Woodruff TJ, Grillo J, Schoendorf KC. 1997. The relationship between selected causes of postneonatal infant mortality and particulate air pollution in the United States. Environ Health Perspect 105:608–612.