This article focuses on evidence from accountability studies regarding potential improvements in human health due to reducing exposure to air pollution.

Epidemiological studies of air pollution are fundamentally attempts to exploit various dimensions of exposure variability in real-world settings. Most of these studies rely on naturally occurring exposure variability. For example, daily time-series studies—as well as episode and case-crossover studies—exploit naturally occurring day-to-day variability. These studies demonstrate that short-term (i.e., one to several days) increases in exposure can result in increases in risk of respiratory and cardiovascular disease and death. These studies also demonstrate that subsequent short-term reductions in exposure result in comparable risk decreases and provide estimates of improvements in health that could be expected from an intervention that results in short-term reductions in air pollution exposure.

Studies of long-term exposure—including various cross-sectional studies, prospective cohort studies, and long-term longitudinal panel studies—exploit long-term spatial variability. These studies demonstrate that long-term air pollution exposure (i.e., over years or decades) is associated with increased

Atlanta Olympic Park, site of the 1996 Summer Olympic Games.
risk of cardiovascular disease and death, lung cancer risk, deficits in lung function growth, and other adverse health endpoints. These studies provide underlying estimates—or at least realistic priors—regarding health improvements that could be expected from planned interventions that result in long-term reductions in air pollution exposures. As discussed by Hubbell elsewhere in this issue, such studies have been used as damage functions in prospective analyses of the benefits of the U.S. Clean Air Act.

“Accountability” studies are a subset of epidemiological studies that exploit natural or policy-related interventions that potentially result in changes (usually reductions) in air pollution exposure and pollution-related health impacts. Accountability studies of policy-related interventions are important, in part, because these interventions typically impose economic costs on society. It is reasonable to ask if there are compensating, tangible, and measurable improvements in air quality and public health. This article is not a comprehensive review, but illustrates evidence of human health effects from accountability studies by providing selected examples of studies of various types of interventions, including labor disputes and intermittent operation of industrial sources, temporary Olympics-related interventions,
long-term local interventions, national controls and standards, and household-level interventions.

**Labor Disputes and Intermittent Operation of Industrial Sources**

Several accountability studies have assessed impacts of unplanned interventions or natural experiments that occurred when labor disputes resulted in the intermittent operation of major industrial sources of air pollution. In Utah Valley in the 1980s, for example, a local steel mill was the largest single source of local air pollution, contributing approximately half of fine particulate matter pollution. This steel mill shut down for a 13-month period due to a labor dispute and subsequent change in ownership. Retrospective analyses of this natural experiment indicated that the mill closure resulted in substantially reduced concentrations of air pollution with corresponding reductions in pediatric respiratory hospital admissions.\(^4\)

Subsequent epidemiological studies in the valley also observed air pollution associations with lung function and respiratory symptoms, school absences, respiratory and cardiovascular mortality,\(^5\) and preterm birth.\(^6\) Evidence from the epidemiological studies of Utah Valley was bolstered by toxicological studies that found that particulate matter extracted from archived filters of air pollution monitors elicited acute airway injury and inflammation in experimentally exposed rats and humans.\(^7\)

Another study retrospectively explored a natural experiment associated with an 8.5-month copper smelter strike in the 1960s that occurred throughout four Southwest states in the United States. During the strike, a regional decline in suspended sulfate particles, changes in metal content of particle exposure, and an improvement in regional visibility were observed.\(^8\) In addition during the strike, a small (1.5–4.0%) but statistically significant decrease in mortality was observed—even while controlling for time and mortality trends elsewhere.\(^9\)

**Temporary Olympics-Related Interventions**

Temporary interventions to reduce traffic congestion in downtown Atlanta during the 1996 Olympic Games resulted in an interesting potential opportunity to evaluate the impact of reduced air pollution on human health. An initial analysis suggested that these interventions resulted in reductions in air pollution, especially ozone, and significant reductions in childhood asthma events.\(^10\) As discussed by van Erp et al. elsewhere in this issue,\(^11\) however, subsequent analyses indicate that the reductions in ozone were due to a combination of metrological conditions and reduced traffic and find little compelling evidence of direct intervention-related health benefits.\(^12\)

The 2008 Beijing Olympic Games also provided an opportunity to evaluate potential health benefits from temporary interventions to control air pollution. Concentrations of most measured air pollutants were generally lower during the Olympics intervention period as compared to periods before and after the Olympics. Acute changes in various biomarkers of inflammation and thrombosis, as well as various measures of cardiovascular physiology, were observed in a panel of healthy young adults.\(^13,14\) Another analysis using the Beijing Olympics interventions found reductions in air pollution (with a focus on black carbon) and exhaled nitric oxide, a biomarker of acute respiratory inflammation.\(^15\) These findings provided evidence that reduced air pollution exposure contributed to improved health, although the clinical significance of the findings remains unclear.

**Long-Term Local Interventions**

There have been a number of studies of local interventions that resulted in long-term or permanent reductions in air pollution exposure. For example, in 1990, there were important air pollution interventions in Dublin and in Hong Kong. A ban on coal sales in Dublin Ireland in 1990 resulted in an immediate, remarkably large, and permanent reduction in particulate matter air pollution. Studies of this intervention found corresponding significant reductions in respiratory and cardiovascular death rates in Dublin.\(^16,17\) The health effects of subsequent bans of coal sales in other Irish cities are also being studied with somewhat more ambiguous results (see accompanying article by van Erp et al.\(^11\)). Also in 1990, an intervention reduced the sulfur content of fuel used in power plants and vehicles in Hong Kong—leading to an immediate reduction in sulfur dioxide and a change in metal concentrations. A reduction in seasonal deaths,
especially respiratory and cardiovascular deaths was observed.18

Erfurt, Germany experienced substantial improvements in air quality following German unification. Restructuring of industries, a changed car fleet and fuel replacement, the exchange of brown coal for natural gas in power plants and domestic heating, and related interventions resulted in substantial decreases in air pollution concentrations with declining relative risks of mortality.19

In 2003, traffic management measures, including a congestion charging scheme, were implemented in central London. Accountability related analyses based on this intervention have been conducted. In the first year, the program resulted in reductions in traffic volume and congestion; however, air pollution monitoring and modeling indicated that there were, at best, only very small reductions in central London air pollution concentrations and minimal mortality benefits.20,21 A low-emission zone, which encompasses most of Greater London, is providing further opportunity to study potential health benefits of air pollution interventions in London.22 (Also see accompanying article by van Erp et al.11)

National Controls and Standards
Over the last several decades, the U.S. Clean Air Act, its amendments, and related public policy efforts to improve air quality have provided opportunities for accountability studies. A recent study of differential increases in life expectancy related to differential declines in air pollution between 1980 and 2000 in the United States was basically a large, nationwide natural experiment study.23 This study asked a key accountability relevant question: did cities with bigger improvements in air quality over these two decades have bigger improvements in health, measured by life expectancy? The answer was basically yes. On average, greater reductions in air pollution were associated with greater increases in life expectancy, even after controlling for socioeconomic, demographic, and smoking variables.
The Harvard Six-Cities study[^24] was originally designed to prospectively study differential changes in air pollution across six U.S. cities due to the implementation of the U.S. Clean Air Act, its amendments, and related national ambient air quality standards. Extended analyses of the Harvard Six-Cities cohort[^25,26] with longer follow-up periods can be considered, at least in part, as accountability studies because differential changes in air pollution did eventually occur. These changes, however, were due only in part to the planned interventions associated with the Clean Air Act and enforcement of air quality standards. Economic factors (especially in the steel and coal industries) and other changes influenced air pollution levels. Nevertheless, extended analyses of the Harvard Six-Cities cohort indicate that reductions in air pollution resulted in substantive declines in mortality risk.

**Household-Level Interventions**

Several household-level interventions that reduce exposure to air pollution have provided evidence of corresponding improvements in health. For example, a program to replace old wood stoves with U.S. Environmental Protection Agency (EPA)-certified stoves or other heating sources was implemented in Libby, MT—a rural mountain valley community that often experienced high winter-time levels of air pollution from residential wood smoke. Ambient fine particulate matter concentrations were reduced by approximately 30% and reductions in indoor concentrations were also observed, although the reductions were highly variable across homes. The stove replacement intervention was at the household-level; however, reductions in air pollution were associated with decreased reports of childhood wheeze and other respiratory ailments that were not limited to children living in homes with wood stoves.[^11,27,28]

In the Western Highland region of Guatemala, many homes use open-fire stoves for cooking. A randomized trial of improved cook stoves with chimneys provided evidence of substantial reductions in air pollution exposure along with lower blood pressure among studied women.[^29] Other examples of household-level interventions include the filtration of indoor air in homes located in Copenhagen, Denmark. Reductions in air pollution concentrations were found to improve vascular function in the aged but not in healthy younger adults.[^30,31] Another study of indoor air filtration in homes was conducted in Smithers, British Columbia, Canada—a community highly impacted by wood smoke. Air filters reduced the indoor fine particulate pollution by 60%. This pollution reduction was associated with improved vascular function and decreased inflammatory biomarkers.[^32]

**Conclusion**

There is now a limited, but growing body of accountability studies that provides evidence that reducing air pollution exposure can result in improvements in health.

[^24]: The Harvard Six-Cities study
[^25]: Extended analyses of the Harvard Six-Cities cohort
[^26]: With longer follow-up periods
[^27]: Decreased reports of childhood wheeze
[^28]: Not limited to children living in homes with wood stoves
[^29]: Improved cook stoves with chimneys
[^30]: Reductions in air pollution concentrations
[^31]: Improved vascular function in the aged but not in healthy younger adults
[^32]: Improved vascular function and decreased inflammatory biomarkers
Accountability studies, however, are rarely or never ideal. They have limitations similar to other epidemiological study designs. For example, there are often only very small changes in exposures or larger changes are applicable only to small populations, resulting in limited statistical power. Exposure changes are often not truly exogenous, but are associated with other changes that may affect health, resulting in the potential of confounding. The temporal changes in exposure are not always sharp, well-defined, or easily distinguished from more general temporal trends. The intrinsic appeal and the potential opportunities for accountability studies, coupled with problems of limited statistical power, lack of distinct exogeneity, and difficulties in establishing clear identification strategies, also result in substantial potential for reporting and publication bias.

Nevertheless, as illustrated with the examples in the article, intervention studies are adding to the epidemiological evidence regarding health effects of air pollution. At present, a variety of accountability studies provide evidence that interventions causing a reduction in exposure to air pollution can also result in measurable improvements in human health.