



Risk in Perspective

MORTALITY RISKS FROM OZONE EXPOSURE

Introduction



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“Better understanding of ozone mortality risks has significant implications for air pollution policy.”

Ground level ozone is a known cause of respiratory illness, but until recently its effect on mortality rates was unclear. Ozone is one of six pollutants for which the U.S. Environmental Protection Agency (EPA) is required to set National Ambient Air Quality Standards (NAAQS) under the Clean Air Act.

Ozone forms when nitrogen oxides and volatile organic compounds are emitted from motor vehicles, industrial operations, and other sources, and then react in the presence of sunlight. Ozone formation is also affected by measures to control other air pollutants (such as particulate matter). Understanding the relationship between ozone exposure and mortality can significantly affect decisions related to the stringency of air pollution controls and has important implications for the impacts of these controls on human health.

EPA is currently considering changes in the ozone NAAQS and has commissioned a National Research Council (NRC) study of these issues. HCRA faculty member Dr. Helen Suh is a member of the NRC committee, which is charged with evaluating the scientific and technical data for estimating ozone mortality risks and determining the benefits of related standards.

In this issue of *Risk in Perspective*, we describe some of our work on the association between exposure and risk, on the uncertainty about this relationship, and on the implications for the valuation of mortality risk reductions. This research was funded by the Harvard Center for Risk Analysis, the U.S. Environmental Protection Agency, the National Institute of Environmental Health Sciences, and the Health Effects Institute.

Relationship between Exposure and Mortality Risk

Based on advice from its Science Advisory Board and its review of the scientific literature, EPA has not included separate estimates of the mortality risks resulting from ozone exposure when considering the benefits of air pollution standards. This approach reflects concern about both the extent to which the studies that consider the impacts of ozone may actually reflect the results of exposure to particulate matter (which is separately addressed in EPA's analyses) and the difficulty of synthesizing diverse estimates of ozone's effects.

In 2003, EPA commissioned three independent reviews of the evidence on the relationship between ozone exposure and mortality risk. Because EPA was interested in the extent to which the conclusions

were sensitive to the methods used and other analytic decisions, the teams worked separately. Three papers, ultimately published in the July 2005 issue of *Epidemiology*, used statistical techniques (generally referred to as meta-analysis) to synthesize the results of different studies. One paper also included a composite estimate from a new multi-city analysis. HCRA's Dr. Jonathan Levy led one of the three research teams (Levy, Chemerynski, and Sarnat, 2005).

Dr. Levy's team focused on peer reviewed time-series studies that considered the relationship between ozone exposure and mortality. They found 71 such studies, some of which reported estimates from several cities. After removing duplicative studies as

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well as those that did not include the needed data, the team had 28 studies which provided 48 city-specific estimates of relative risks. They next selected comparable estimates from each study, focusing on estimates of same-day ozone concentrations. They converted the estimates into percentage increases in mortality per $10 \mu\text{g}/\text{m}^3$ of 1-hour maximum ozone.

Dr. Levy's team considered several factors that could affect the relationships between ozone concentrations and mortality risks. For example, they classified studies based on the characteristics of the models used. In addition, they addressed the relationship between ozone concentrations and the concentrations of other pollutants using regression analysis. Because both ozone formation and personal exposure vary by season, they considered relationships seasonally as well as across the entire year. They also assessed the prevalence of air conditioning, which reduces personal exposure. They combined the resulting data into a meta-regression to estimate the relationship between ozone exposure and mortality risks across the different studies.

The researchers found that, across the 48 estimates from the 28 studies, a $10 \mu\text{g}/\text{m}^3$ increase in 1-hour maximum ozone exposure leads to between an 1.1 percent *decrease* and an 1.7 percent *increase* in mortality, with many of the estimates clustering between a 0.1 percent and a 0.5 percent increase. After removing the two most extreme estimates, which come from studies with small sample sizes,

they found a mean estimate of a 0.21 percent increase in daily mortality per $10 \mu\text{g}/\text{m}^3$ increase in 1-hour maximum ozone exposure (0.41 percent increase per 10 ppb; 1 ppb = $1.96 \mu\text{g}/\text{m}^3$). Figure 1 illustrates the results across studies.

The research team stratified the studies in a number of ways and assessed whether the variability in the estimates could be explained by selected factors. They found that the estimates were similar in North America and Europe, in hot and cold climates, and in places with high and low average ozone concentrations. The effects of ozone on mortality risks were greater in the summer than in the winter. The most robust predictors of variability between the studies were (1) the modeling assumptions related to the lag between exposure and incidence (i.e., same-day ozone exposures had a greater effect than previous-day exposures) and (2) the prevalence of air conditioning (i.e., the effect of ozone was lower in cities with more air conditioning).

The two other teams conducted similar studies using somewhat different approaches. Bell, Dominici and Samet (2005) performed a meta-analysis of 144 effect estimates from 39 time series studies and assessed data from 95 cities from the National Morbidity, Mortality and Air Pollution Study (NMMAPS). In both analyses, they found strong evidence of an association between short-term ozone exposure and mortality, with larger effects for cardiovascular and respiratory mortality, the elderly, and

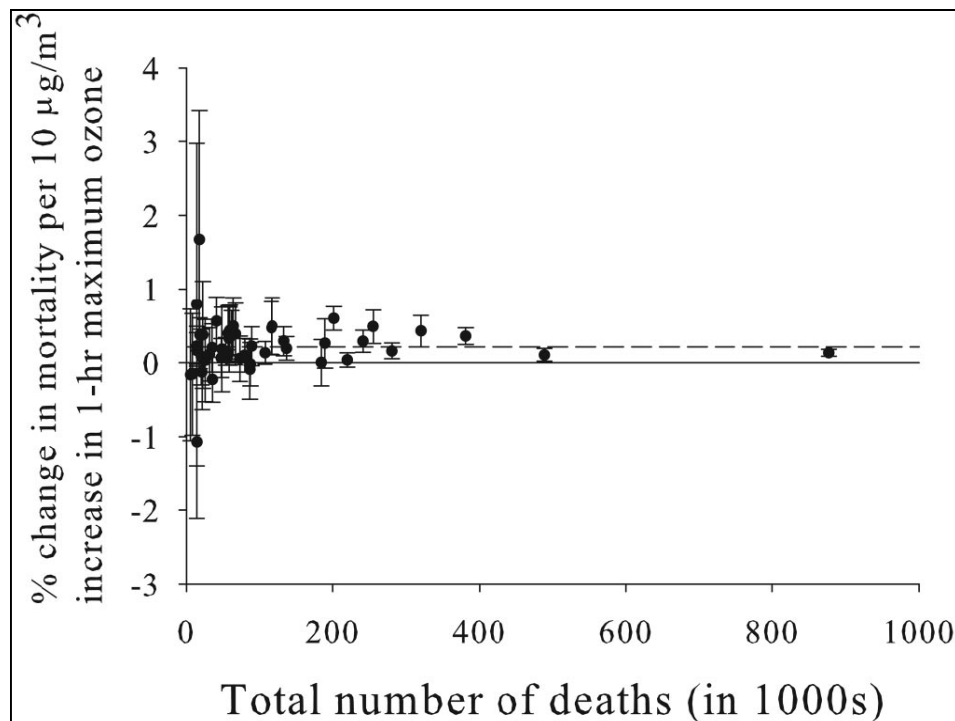


FIGURE 1. Percent change in daily mortality per $10\text{-}\mu\text{g}/\text{m}^3$ increase in 1-hour maximum ozone for studies eligible for meta-regression, sorted by total number of deaths (error bars represent 95% confidence intervals, and the dotted line represents the grand mean estimate in a no-covariate meta-regression model). (Replicated from Levy, Chemerynski, and Samet, 2005, p. 463.)

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current day exposure. The results of their meta-analysis suggested that a 10 ppb increase in daily ozone exposure (with a time lag of zero, one, or two days) was associated with a 0.87 percent increase (95 percent posterior interval = 0.55 percent to 1.18 percent) in mortality, while the increase (with a time lag of zero days) was 0.25 percent (95 percent posterior interval = 0.12 percent to 0.39 percent) for the NMMAPS data. These values correspond to an approximate 0.35 percent and 0.1 percent increase in mortality per 10 ppb increase of 1-hour maximum concentrations.

Ito, De Leon, and Lippman (2005) assessed data from 43 studies and conducted additional analysis of data from seven U.S. cities. They found a combined estimate of a 0.39 percent increase (95 percent confidence interval = 0.26 percent to 0.51 percent) in mortality from a 10 ppb increase in one-hour daily maximum ozone.

These analyses were remarkably consistent in their results despite differences in the data used and analytic methods. They each suggest that there is a relationship between ozone exposure and mortality. When expressed in comparable terms, all three studies suggest that there is a 0.4 percent increase in short-term mortality for each 10 ppb increase in 1-hour maximum ozone over the course of the year, with most of the risk concentrated in the warmer seasons.

As noted by Goodman (2005), the studies also identify areas where additional research would be useful. In particular, they suggest that more multi-city studies are needed. Because of the possibility that findings are more likely to be published if they show strong associations, multi-city studies have some advantages over meta-analyses although they raise other methodological challenges. More generally, additional work is needed to better characterize uncertainty.

Remaining Uncertainties

Each of the analyses described above discusses a number of sources of uncertainty, including possible confounding by temperature or other air pollutants and differences between outdoor concentrations of, and personal exposure to, ozone. HCRA faculty have explored these uncertainties in a number of other studies.

Because ozone concentrations increase when temperature increases, some of the observed increase in daily mortality may be due to temperature rather than ozone if adequate controls for temperature are not included in the analysis. HCRA Director Dr. Joel Schwartz explored this issue using data from 14 U.S. cities on over one million deaths (Schwartz 2005).

To control for individual risk factors and temperature, Dr. Schwartz matched data for each individual studied and compared their status on different days with the same temperature. He found that a 10 ppb increase in maximum hourly ozone concentrations was associated with a 0.23 percent (95 percent confidence interval = 0.01 percent to 0.44 percent) increase in mortality. This result was identical to the results he obtained when he instead controlled for temperature statistically using the same methods as the studies discussed above. His findings suggest that the relationship between ozone exposure and mortality is not confounded by temperature.

Another concern relates to the extent to which the estimated effects of ozone may in fact reflect the effects of other pollutants. Both the studies discussed above and other research suggest that ozone has an effect on mortality that is separate from the effects of total particulate mass. However, sulfates and other secondary aerosols are

formed by photochemical processes similar to those that form ozone. Hence, the observed ozone effects may be due in part to these particles. For example, HCRA faculty, using data from the Harvard Six Cities study, have found that sulfates are associated with daily mortality (Laden, Neas, Dockery, and Schwartz 2000). More research is needed to see if the effects of ozone are independent of these other pollutants.

An additional area of uncertainty relates to the extent to which the outdoor (ambient) concentrations of pollutants are correlated with the levels of personal exposure. Because ambient concentration data are widely available, they are often used in epidemiological studies. However, individuals spend the majority of their time indoors and it is unclear whether ambient measurements are a good predictor of exposure.

HCRA Director Dr. Joel Schwartz and Dr. Helen Suh, along with Dr. Petros Koutrakis (Director of Harvard's Exposure, Epidemiology, and Risk Program) and others, have explored these issues in a series of studies that compare personal exposure to ambient concentrations. For example, they monitored the personal exposure of 99 individuals to fine particulate matter, sulfate, elemental carbon, nitrogen dioxide, sulfur dioxide, and ozone for 24 hours per day over eight to twelve consecutive days (Koutrakis, Suh, Sarnat, Brown, Coull, and Schwartz, 2005). They found that outdoor concentrations of ozone were associated with personal exposures to sulfates, often more strongly than with personal exposures to ozone, again raising the issue of confounding by this other pollutant.

Implications for Benefits Valuation

Incorporating the effects of ozone exposure into the analyses that support regulatory decision-making presents several challenges. In particular, it is unclear whether the associated mortality primarily affects individuals with pre-existing health conditions (e.g., respiratory or heart disease), and whether those who die from the pollution would otherwise have died within a relatively short period from other causes. HCRA Director Joel Schwartz has addressed these issues for particles, but more analysis is needed to assess these effects for ozone exposure.

While the Clean Air Act prohibits EPA from considering costs when setting air quality standards, EPA assesses the benefits and costs of alternative control strategies in accordance with government-wide requirements. EPA generally determines the benefits of reductions in mortality risk using estimates of the “value per statistical life” or VSL. VSL is an analytic construct that describes the value of small changes in risk (e.g., a one in 10,000 reduction in the chance of dying this year); it is not the value of saving a particular person’s life.

The most widely accepted VSL studies consider deaths of workers through occupational accidents. These deaths may shorten life by roughly 35 years on average and are likely to primarily affect individuals in good health. In contrast, because those affected by air pollution risks in general, and by ozone in particular, may be significantly older and in poorer health, the loss of longevity may be measured in weeks or months rather than years.

HCRA Director Dr. James Hammitt has explored the extent to which VSL may vary depending on these factors (Hammitt 2007). It may seem intuitive to expect that in-

dividuals would be willing to pay more for longer increases in life expectancy, and less if they are in poor health. However, this intuition ignores the effects of life expectancy and health on an individual's ability to use wealth to improve his or her well-being. An increased life expectancy in better health provides more opportunities for spending. Hence there is a trade-off between spending more for risk reduction and saving for future expenditures over a longer and healthier lifespan.

Dr. Hammitt concludes that the effects of life expectancy and health on VSL are ambiguous. It is unclear whether individuals who anticipate being in poor health would pay more or less for small extensions in life expectancy than would the average worker included in the VSL studies. More empirical research is needed to estimate the effects of these factors on VSL, and to determine whether ozone-related mortality risk reductions are likely to be valued more or less than the risks of accidental deaths addressed by the available research.

In conclusion, recent research provides evidence that reductions in ozone exposure will lead to reductions in premature mortality. However, the magnitude of this reduction is uncertain and more research is needed to address potential confounding factors. In addition, determining the value of these risk reductions presents difficult challenges. Ongoing research at HCRA and elsewhere is attempting to address many of the crucial questions surrounding the relationships between exposure, mortality risks, and economic valuation, which will help support the development of optimal air pollution control strategies.

For further reading, see:

Bell, M.L., Dominici, F., Samet, J.M. 2005. “A Meta-Analysis of Time-Series Studies of Ozone and Mortality with Comparison to the National Morbidity, Mortality, and Air Pollution Study.” *Epidemiology*. 16(4): 436-445.

Goodman, S.N. 2005. “The Methodologic Ozone Effect.” *Epidemiology*. 16(4): 430-435.

Hammitt, J.K. 2007. “Valuing Changes in Mortality Risk: Lives Saved vs. Life Years Saved.” *Review of Environmental Economics and Policy*. 1(2): forthcoming.

Ito, K., De Leon, S.F., Lippmann, M. 2005. “Associations between Ozone and Daily Mortality: Analysis and Meta-Analysis.” *Epidemiology*. 16(4): 446-457.

Koutrakis, P., Suh, H.H., Sarnat, J.A., Brown, K.W., Coull, B.A., Schwartz, J. 2005. “Characterization of Particulate and Gas Exposures of Sensitive Subpopulations Living in Baltimore and Boston.” Health Effects Institute Research Report No. 131.

Laden, F., Neas, L.M., Dockery, D.W., Schwartz, J. 2000. “Association of Fine Particulate Matter from Different Sources with Daily Mortality in Six U.S. Cities.” *Environmental Health Perspectives*. 108(10): 941-947.

Levy, J.I., Chemerynski, S.M., Sarnat, J.A. 2005. “Ozone Exposure and Mortality: An Empiric Bayes Metaregression Analysis.” *Epidemiology*. 16(4): 458-468.

Schwartz, J. 2005. “How Sensitive is the Association between Ozone Exposure and Daily Deaths to Control for Temperature?” *American Journal of Respiratory and Critical Care Medicine*. 171: 627-631.