Fine Particulate Air Pollution and Mortality: Response to Enstrom’s Reanalysis of the American Cancer Society Cancer Prevention Study II Cohort

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Background
The first analysis of long-term exposures to air pollution and risk of mortality using the American Cancer Society Cancer Prevention Study II (ACS CPS-II) cohort was published in 1995.1 Subsequently, extensive independent reanalysis2 and multiple extended analyses3-7 were conducted. These studies have consistently demonstrated that exposure to fine particulate matter air pollution (PM2.5) is associated with increased risk of mortality, especially cardiopulmonary or cardiovascular disease mortality. A recent analysis by Enstrom, based on early data from the ACS CPS-II cohort, reports no significant relationship between PM2.5 and total mortality.8 The author asserts that the original analyses, reanalyses, and the extended analyses found positive PM2.5–mortality relationships because of selective use of CPS-II and PM2.5 data.

Expanded Analyses of the ACS CPS-II Cohort
The assertion regarding selective use of the CPS-II and PM2.5 data is false. The scope of analyses of the ACS CPS-II cohort conducted over more than 2 decades were explicitly expanded over time to characterize population health risks of PM2.5 in more detail and with greater accuracy. Table 1 provides an outline of key published studies of this expansive body of air pollution research. The highlights of the obvious progress made during the course of these studies include the following:

1) increased mortality follow-up from 7 to 22 or 26 years;
2) increased number of participants included in the analyses from approximately 295,000 to 670,000;
3) increased number of deaths (a key determinant of study power) included in the analyses from approximately 21,000 to 237,000;
4) improved assessment of PM2.5 exposures (and exposures of co-pollutants) from metro-level averages for cities with air pollution monitoring to modeled PM2.5 exposures at geocoded residential addresses throughout the United States; and
5) improved statistical models, including improved control for individual and ecological covariates, and better representation of spatial patterns in the data.

As shown in Figure 1, estimates of the percentage increase in mortality risk per 10 μg/m³ increase in PM2.5 for all-cause and for cardiovascular disease mortality from studies using the ACS CPS-II cohort have been remarkably consistent across the expanded analyses over the last 20+ years. The recent analysis by Enstrom8 shows an estimated PM2.5–mortality association that is smaller than observed in the original analysis, the

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| Citation | Authors | Approx. No. Participants (Deaths) for Key PM Measures | Geographic Units of Exposure | Years of Follow-Up | Comments |
|----------|---------|-----------------------------------------------------|------------------------------|-------------------|----------|
| Am J Respir Crit Care Med. 1995;151:669-674.1 | Pope et al | PM$_{2.5}$: 295 000 (21 000) SO$_4$: 550 000 (39 000) | 50 metro areas | 7 (1982-1989) | Original analysis. Mortality, especially cardiopulmonary, associated with PM$_{2.5}$ and SO$_4$. |
| Health Effects Institute 2000; HEI Special Report.3 | Krewski et al | PM$_{2.5}$: 300 000 (23 000) SO$_4$: 559 000 (43 000) | 50 metro areas | 7 (1982-1989) | Independent reanalysis that substantively reproduced original results, developed improved modeling, and provided substantial sensitivity analysis. |
| JAMA. 2002;287:1132-1141.13 | Pope et al | PM$_{2.5}$: 500 000 SO$_4$: 560 000 | 116 metro areas | 16 (1982-1998) | All-cause, lung-cancer, and cardiopulmonary mortality, associated with PM$_{2.5}$ and SO$_4$. Improved statistical modeling, including random effects. |
| Circulation. 2004;109:71-77.9 | Jerrett et al | PM$_{2.5}$: 23 000 (6000) | 267 zip code areas in metro Los Angeles | 18 (1982-2000) | Relatively large PM$_{2.5}$ associations with all-cause, lung-cancer, and cardiopulmonary mortality. |
| Epidemiology. 2005;16:727-736.10 | Jerrett et al | PM$_{2.5}$: 74 000 (20 000) | Modeled exposures at geocoded home addresses throughout California | 18 (1982-2000) | Cardiopulmonary mortality was associated with PM$_{2.5}$, SO$_4$, and elemental carbon. Correlations across pollutants make independent estimates difficult. |
| Lancet. 2009;374:2091-2103.11 | Smith et al | PM$_{2.5}$, SO$_4$, and elemental carbon: 350 000 (93 000) | 86 metro areas | 18 (1982-2000) | All-cause, lung-cancer, and cardiopulmonary mortality associated with PM$_{2.5}$ and SO$_4$ even controlling for ecologic covariates. |
| Health Effects Institute 2009; Research Report Number 140.4 | Krewski et al | PM$_{2.5}$: 500 000 SO$_4$: 560 000 | 116 metro areas | 18 (1982-2000) | Evaluated associations with ozone, independent of PM$_{2.5}$, however, PM$_{2.5}$–mortality associations were observed as in previous studies. |
| Am J Respir Crit Care Med. 2011;184:1374-1381.12 | Turner et al | PM$_{2.5}$: 178 000 never smokers (1000 lung cancer deaths) | 117 metro areas | 26 (1982-2008) | Long-term exposure to PM$_{2.5}$ pollution was associated with small but significant increase in risk of lung cancer mortality. |
| Am J Respir Crit Care Med. 2013;188:593-599.13 | Jerrett et al | PM$_{2.5}$: 74 000 (20 000) | Modeled exposures at geocoded home addresses throughout the United States | 18 (1982-2000) | Evaluated interactions between cigarette smoking and PM$_{2.5}$ exposures for lung cancer mortality. The associations between all-cause and cardiovascular mortality and PM$_{2.5}$ were similar to previous studies but, given the very large cohort and large number of deaths, the statistical precision of the estimate was remarkable. |
| Am J Epidemiol. 2014;180:1145-1149.14 | Turner et al | PM$_{2.5}$: 430 000 | Modeled PM$_{2.5}$ exposures at geocoded home addresses throughout California | 6 (1982-1988) | Evaluated the interactions between cigarette smoking and PM$_{2.5}$ exposures for lung cancer mortality. |
| Circulation Res. 2015;116:108-115.6 | Pope et al | PM$_{2.5}$: 670 000 (237 000) | Modeled PM$_{2.5}$ exposures at geocoded home addresses throughout the United States | 22 (1982-2004) | The focus of this study was on ozone exposure but mortality was associated with PM$_{2.5}$ (both near-source and regional) as observed previously. |
| Environ Health Perspect. 2016;124:785-794.15 | Thurston et al | PM$_{2.5}$: 446 000 | 100 metro areas | 22 (1982-2004) | Evaluated source-related components of PM$_{2.5}$. Exposures from fossil fuel combustion, especially coal burning and traffic were associated with increased ischemic heart disease mortality. |
| Am J Respir Crit Care Med. 2016;193:1134-1142.16 | Turner et al | PM$_{2.5}$: 670 000 (237 000) | Modeled PM$_{2.5}$ exposures at geocoded home addresses throughout the United States | 22 (1982-2004) | Evaluated interactions between cigarette smoking and PM$_{2.5}$, PM$_{2.5}$ was associated with all-cause and cardiovascular mortality in both smokers and never smokers with evidence for a small additive interaction. |
| Environ Res. 2017;154:304-310.17 | Turner et al | PM$_{2.5}$: 429 000 (146 000) Current or never smokers | Modeled PM$_{2.5}$ exposures at geocoded home addresses throughout the United States | 22 (1982-2004) | PM$_{2.5}$ exposures associated with using 7 exposure models and 11 exposure estimates. PM$_{2.5}$–mortality risks were observed using all of the exposure models. Smaller associations observed using remote sensing exposure estimates; larger effects observed using exposure models that included ground-based information

Abbreviations: ACS CPS II, American Cancer Society Cancer Prevention Study II; PM$_{2.5}$, particulate matter air pollution.
reanalysis, multiple subsequent extended analyses, or meta-
analyses of studies throughout the world.18

**Deficiencies in Enstrom’s Reanalysis**

Enstrom’s recently published analysis8 is the least advanced
analysis of the ACS CPS-II cohort to date (see Table 1). The
Enstrom’s analysis uses a data set with a shorter follow-up
period, fewer participants, and fewer deaths than any previous
PM2.5—mortality analyses that used the CPS-II cohort, includ-
ing the original 1995 analysis. He controls for a relatively
limited number of individual-level covariates and does not
control for any ecologic covariates. Moreover, the key defi-
cency in the Enstrom’s reanalysis is the absence of advanced
modeling approaches for exposure assessment that have been
developed over the last 2 decades. Estimates of PM2.5—mortal-
ity associations are affected by the quality of the PM2.5 data and
the accuracy of matching participants and exposures. In a
recent analysis,7 we evaluated PM2.5 exposures using multiple
exposure assessment methods. Figure 1 illustrates that there
were significant PM2.5—mortality risk associations for all
PM2.5 measures, but the associations were lower for the pres-
umably less accurate measures that used remote sensing with-
out ground-based data. Based on measures of model quality,
the PM2.5 exposure values that best fit (lowest Akaike Infor-
mation Criteria, AIC) the data resulted in relatively larger
PM2.5—mortality associations (see Figure 1). In contrast,
Enstrom8 asserts that he estimates smaller PM2.5—mortality
associations because he uses the “best” PM2.5 data. He provides
neither evidence in support of this assertion nor any measures
of the relative quality of models using alternative PM2.5 data. It
is not clear how or why his “IPN” PM2.5 data differ from the
“Health Effects Institute” PM2.5 data—especially given that
these data come from the same monitoring network.

Furthermore, Enstrom’s PM2.5 exposure assessment is likely
subject to greater exposure misclassification because of inade-
quate assignment of geographic units of exposure. Although
other published ACS CPS-II studies assigned geographic areas
of exposure based on participants’ residence information, the
Enstrom’s analysis used the ACS Division and Unit numbers to
assign PM2.5 exposures (see letter from ACS). The ACS Divi-
sion and Unit numbers, however, were for the ACS volunteers
that recruited the participants. These volunteers did not always
live in the same area or even in the same state as the partici-
pants. Enstrom does not document the extent of this
participant-exposure mismatching, but it has the potential for
substantial exposure misclassification and resultant attenuation
bias. Our published research using the ACS CPS-II data is
based on participant-exposure matching that is accurate,
includes highly spatially resolved exposure models, and uti-
\[\text{Figure 1. Nationwide estimates of percentage increase in mortality risk per 10 } \mu g/m^3 \text{ increase in PM}_{2.5} \text{ from various published studies using the ACS CPS-II cohort (indicated by circles) with comparison estimates from meta-analysis of the literature (indicated by diamonds). The size of the circles is relative to the length of the follow-up period. Gray and white circles indicate metro-level and county-level geographic units of exposure, respectively. Black circles indicate that exposures were modeled at geocoded residential addresses. Asterisks indicate that, in addition to controlling for individual covariate, the models also controlled for ecological covariates. Note. (1) Krewski et al2 report the results of an independent, confirmatory reanalysis of the ACS cohort organized by the Health Effects Institute. (2) In the investigation of alternative measures of PM_{2.5} conducted by Jerrett et al,7 the highest quality models (those with the lowest AIC) produced the highest risk estimates; remote sensing models with no ground-based data produced the lowest risk estimates, likely because of greater exposure misclassification. (3) The lowest risk estimate reported by Enstrom8 is based on a dated and short follow-up of the ACS cohort and is likely subject to exposure mismatching. ACS CPS II indicates American Cancer Society Cancer Prevention Study II; PM_{2.5}, particulate matter air pollution.} \]
include an unconventional mix of unpublished and non-peer-reviewed correspondence (including letters, e-mails, and transcript of a teleconference call), presentation slides, press releases, and a compilation of manuscript rejections. Key published extended analyses of the ACS CPS-II cohort, studies of other cohorts, or even major reviews and evaluations of the literature are not cited or discussed.

**Broader Evidence**

The PM$_{2.5}$-mortality associations observed from the various analyses of the ACS CPS-II cohort are consistent with a much broader body of evidence from other studies. As examples, these include studies of other cohorts from the United States, Europe, and Canada. In addition, meta-analytic estimates of the PM$_{2.5}$-mortality associations based on a 2013 meta-analysis of the overall literature are also provided for comparison purposes in Figure 1.

Previous studies of the ACS CPS-II cohort consistently demonstrated PM$_{2.5}$-mortality associations with cardiovascular mortality. There has also been substantial work in exploring and understanding the biological pathways and mechanisms linking PM$_{2.5}$ exposures and cardiovascular disease and death. Similarly, the ACS CPS-II cohort has demonstrated PM$_{2.5}$-mortality associations with lung cancer mortality, and recently, the International Agency for Research on Cancer concluded, based on multiple sources of evidence, that particulate matter in outdoor air pollution is a cause of human lung cancer (group 1). Enstrom presents no results for cardiovascular or lung cancer mortality and largely dismisses the substantial and growing literature regarding relevant pathophysiological pathways and related biological mechanisms.

The Global Burden of Diseases, Injuries, and Risk Factors Study 2015 (conducted by the Institute for Health Metrics and Evaluation) identified ambient PM$_{2.5}$ air pollution as the 5th leading risk factor for global mortality, contributing to approximately 4.2 million deaths in 2015. These results are based on recent and comprehensive estimates from ACS CPS-II cohort studies and 23 other peer-reviewed studies of long-term exposure to PM$_{2.5}$ and mortality from cause-specific cardiovascular and respiratory disease and lung cancer. These results underscore the importance of PM$_{2.5}$ as a substantial determinant of mortality in the general population. Consequently, these results also suggest substantial health benefits from further reductions in ambient air pollution.

In summary, we welcome thoughtful criticism of our research. But the study by Enstrom does not contribute to the larger body of evidence on the health effects of PM$_{2.5}$, as it does not utilize adequate approaches for exposure assessment, suitable methods for linking participants to exposure, and sufficient statistical control for potential confounding factors and fails to recognize the larger body of evidence on PM$_{2.5}$ exposure and disease risk.

**Declaration of Conflicting Interests**

The author(s) provided the following declaration of interests with respect to the research, authorship, and/or publication of this article:

Daniel Krewski reports to serving as Chief Risk Scientist and CEO at Risk Sciences International (http://www.risksciences.com), a Canadian company established in 2006 in partnership with the University of Ottawa conducting work in air quality risk assessment for both public and private sector clients. He also holds an Industrial Research Chair in Risk Science under a peer-reviewed university–industry partnership program administered by the Natural Sciences and Engineering Research Council of Canada, which involves methodological research in air pollution risk assessment. He also recently served as Chair of the US Health Effects Institute Diesel Epidemiology Panel, which conducted an evaluation of recent epidemiological evidence on quantitative risk assessment of diesel emissions and lung cancer. Michelle C. Turner reports personal fees from ICF Incorporated, LLC, outside this work.

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