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Particulate matter (PM) air pollution and health: regulatory and policy implications

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Abstract Particulate matter (PM), an ambient air criteria pollutant, is a complex mixture of chemical agents in particles ranging from nanometer-sized molecular clusters to dust particles too large to be aspirated into the lung airways (>10 μm in aerodynamic diameter). Although particle composition is known to affect health risks, our current health-based PM standards are limited to the mass concentrations within two specified size ranges (those below 2.5 μm, which are largely attributed to combustion products, and those below 10 μm, which includes mechanically generated dusts). Both size ranges have been associated with excess mortality and morbidity in numerous epidemiological studies. There is an urgent need for routine air monitoring data on components of the PM mass. Such data are needed to enable epidemiological studies that can define the roles of PM chemical components in causing adverse health effects in order to guide more targeted emission controls for the most hazardous components, thereby gaining public health benefits with the least impact on societal costs of emission controls.

Keywords Particulate matter (PM) · PM components · Mortality · Morbidity · Metals · Health benefits

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Background

Both peak and cumulative exposures to particulate matter (PM) in ambient air are significantly associated with adverse health effects and account for more mortality and morbidity than any other regulated environmental pollutant. In particular, it is well known that: (1) the mass concentration of fine PM in ambient air, i.e., particles less than 2.5 μm in aerodynamic diameter ($PM_{2.5}$) has generally been significantly associated with excess cardiovascular mortality and morbidity in urban areas around the world; (2) the mass concentration of coarse thoracic PM in ambient air, i.e., particles between 10 and 2.5 μm in aerodynamic diameter ($PM_{10–2.5}$) has often been significantly associated with excess respiratory mortality and morbidity in urban areas; (3) that the associations with adverse health effects are usually stronger for combustion products of solid and liquid fossil fuels combustion (e.g., transition metals and black carbon) than for other components of PM air pollution, suggesting that mass concentrations are, at best, crude indicators of health risks, and (4) interventions that have reduced exposures to metals and black carbon led to prompt improvements in public health.

It is also well known that PM: (1) includes a wide range of particle sizes, (2) is a complex mixture of chemical components, and (3) particle size and composition affect delivered dose and biological responses. However, in the absence of a substantial body of data on the effects of specific chemical components and particle sizes on specific health endpoints, current regulations specified by the National Ambient Air Quality Standards (NAAQS) for ambient air PM are still limited to mass concentrations within two ranges of aerodynamic diameter ($PM_{2.5}$ and PM_{10}), and are therefore inefficient tools for the protection of public health from the adverse effects of PM pollution

(Lippmann 2010). For this presentation at a Conference summary session on implications to regulatory policy, I have selected examples below that I believe best demonstrate the need for much more PM component concentration information that can guide the formulation of better targeted standards and guidelines for public health protection.

Examples of evidence for stronger associations of PM component concentrations than for overall PM mass concentrations

The evidence for some PM components having much greater impacts on health-related indices than other components is briefly illustrated below for studies involving PM exposures of human populations, laboratory animals, and cells *in vitro* for which speciation data were available. More complete summaries of most of these studies were provided by Lippmann and Chen (2009). In each case, sufficient data were available on PM composition to demonstrate that some of the components were much more influential than were other components.

Human exposure-response studies with PM components:

1. *Hong Kong sulfur in fuel oil intervention.* A mandated reduction in the sulfur content of fuels for electric power production led to a sharp and persistent drop in the airborne concentrations of sulfur dioxide (SO_2), nickel (Ni), and vanadium (V), but not in the airborne concentrations of other pollutant gasses or metals. The drop in the airborne concentrations of SO_2, Ni, and V was associated with corresponding drops in monthly mortality and hospital admissions for bronchial hyperreactivity (Hedley et al. 2002, 2004).
2. *Daily mortality in relation to $PM_{2.5}$ components.* Average daily mortality rates in United States (US) cities studied in the National Mortality and Morbidity Air Pollution Study were significantly related to average concentrations of Ni and V, but not to other PM components (Lippmann et al. 2006).
3. *Daily mortality in relation to $PM_{2.5}$ components*. In 25 US cities, daily mortality could be accounted for by variations in their concentrations of a small number of $PM_{2.5}$ components [i.e., sulfate ($SO_4^=$), aluminum (Al), arsenic (As), Ni, and silicon (Si)] (Franklin et al. 2008).
4. *Annual mortality rates among US military veterans in relation to $PM_{2.5}$ components.* The $PM_{2.5}$ components that were significantly associated with annual mortality rates were average annual urban area concentrations of traffic density, Ni, and V (Lipfert et al. 2006).
5. *Physician-diagnosed pediatric asthma and symptoms or medication usage in relation to $PM_{2.5}$ components.* The effects reported within the previous 12 months were elevated for 149 asthmatic children in New Haven, CT and vicinity. Factor analysis/source apportionment identified six sources of $PM_{2.5}$, i.e., motor vehicle, road dust, sulfur (S, for regional $PM_{2.5}$), biomass burning, oil combustion, and sea salt. Forty-two percent of the $PM_{2.5}$ was attributed to motor vehicles and 12% to road dust. There was a 10% increased likelihood of wheeze per 5 $\mu g/m^3$ of the motor vehicle source, and a 28% likelihood increase for shortness of breath associated with road dust, but no increased health outcome risks for $PM_{2.5}$ per se, or the other source factors (Gent et al. 2009).
6. *Elevation in medicare hospital admissions in relation to $PM_{2.5}$ components.* In data for 106 US counties for 1999–2005, there was a positive and statistically significant association between short-term effects of $PM_{2.5}$ on cardiovascular hospitalizations, with V (average concentration=3 ng/m^3), Ni (average concentration=2 ng/m^3), and elemental carbon (EC; average concentration= 715 ng/m^3). In multi-pollutant regressions with V and EC, Ni remained significant, whereas V and EC did not. For respiratory hospitalizations, none of them remained significant in multi-pollutant regressions (Bell et al. 2009).
7. *Associations of 3-month averages of $PM_{2.5}$ and the Ni, V, Zn, and EC within the $PM_{2.5}$ on symptoms in infants.* The Columbia Center for Children's Environmental Health studied a birth cohort in Manhattan and the Bronx in New York City (NYC) of infants living near Environmental Protection Agency (EPA) speciation sites. Symptoms for the prior 3 months were collected every 3 months from 3 to 24 months of age. About 90% of the children were on Medicaid, and 30% were reported to have or might have asthma based on a doctor's questionnaire entry at 24 months. Symptoms of wheeze and cough were significantly associated with Ni, V, and zinc (Zn) whereas EC was associated with only cough, and $PM_{2.5}$ was not associated with either symptom (Patel et al. 2009).
8. *Biomarkers for cardiac effects in a Ni smelter city in China.* In Jinchang, Ni was 204 ng/m^3, which was 76-fold higher than in Zhangye (2.7 ng/m^3). Ambient $PM_{2.5}$ mass in Jinchang (43 $\mu g/m^3$) and Zhangye (45 $\mu g/m^3$) is similar. In terms of biomarker differences, interleukin-6 and C-reactive protein were significantly higher in Jinchang than Zhangye subjects; the arm's arteriole intima median thickness (IMT) was significantly thicker in Jinchang than in Zhangye subjects; circulating endothelial progenitor cells (CEPCs) were significantly lower in Jinchang than in Zhangye subjects; vascular endothelial growth factor was higher in Jinchang than Zhangye subjects, but were not

statistically significant; IMT correlated negatively with the number of CEPCs. It was concluded that Ni is a component responsible for $PM_{2.5}$-induced cardiovascular effects, and that the reduced capacity of endothelial repair may partially explain the critical roles of Ni in $PM_{2.5}$-associated CVD (Niu et al. 2011).

9. *Mortality and hospital admissions during a Utah Valley steel mill strike in relation to metal contents.* There were significantly lower community rates of mortality and hospital admissions during a 14-month strike than in the preceding and following years (Pope 1989, 1991, and 1992). The metal contents on air sampling filters were also lower during the strike than in the preceding and following years, corresponding to in vitro toxicity of the metal extracts from the filters (Frampton et al. 1999; Ghio and Devlin 2001; and Dye et al. 1997, 1999, 2001).
10. *Reduced mortality rates during a southwestern copper smelter strike.* There were significantly lower mortality rates in four southwestern US States in which there was a 10-month strike at their copper smelters (Pope et al. 2007).
11. *Association between pulse rates of COPD clinic patients and the airborne concentration of Ni.* There was a significant association between the pulse rate of COPD clinic patients in NYC and the concentration of Ni in air samples collected outside and inside their apartments and in their personal air samples (Hsu et al. 2011).
12. *Associations of circulating biomarkers with the concentrations of ultrafine PM and primary, but not secondary OC.* Studies of elderly residents of retirement communities having a history of coronary artery disease in Southern California showed significant associations of circulating biomarkers of inflammation, antioxidant activity, and platelet activation that were associated with the concentrations of ultrafine PM and primary, but not secondary organic carbon (OC); Delfino et al. (2008); Similar associations were reported for circulating biomarkers (Delfino et al. 2009) and for primary OC and an increase in blood pressure (Delfino et al. 2010a) and electrocardiographic ST segment depression (Delfino et al. 2010b).

CAP exposures in animal inhalation studies

1. *Increases in heart rate and decreases in heart rate variability in relation to $PM_{2.5}$ metals.* $ApoE^{=}$ mice undergoing 6-h daily (weekday) inhalation exposures for 6-months to concentrated ambient fine PM (CAPs) in Tuxedo, NY had significant increases in heart rate (HR) (Hwang et al. 2005) and decreases in HR variability (HRV) (Chen and Hwang 2005) on 14 days, characterized by relatively high concentrations of Ni, Cr, and Fe and unusually low concentrations of all other measured components. Back trajectory analyses indicated the influence of an upwind metals source, i.e., the Sudbury, Ontario Ni smelter (Lippmann et al. 2006).
2. *Increases in heart rate and decreases in heart rate variability in relation to traffic-related $PM_{2.5}$ and metals.* In $ApoE^{=}$ mice undergoing 6-h daily (weekday) inhalation exposures for 6-months to CAPs in both Tuxedo, NY and in New York City simultaneously, there were significant increases in HR and decreases in HRV associated with both traffic markers and a variety of transition metals and lags between concentrations and effects (Chen et al. 2010).

In vitro exposures to different ambient air PM mixtures

1. *NfkB activity in BEAS-2b lung cells in relation to $PM_{2.5}$ sources.* Daily $PM_{2.5}$ samples collected over 6 months in a Biosampler impinger were analyzed for PM components, and aliquots were used to expose BEAS-2b lung cells followed by assays for Nf*k*B activity. The only significant association found was for the residual oil combustion source, which accounted for only 2% of the PM mass (Maciejczyk and Chen 2005).
2. *NfkB activity in BEAS-2b lung cells in relation to elemental components.* In a follow-up study using the PM collected in three separate 6-month studies, the associations of individual elements, rather than source categories, was analyzed. The elements having significant associations with NfkB activity were Ni, barium, manganese, and Fe (Maciejczyk et al. 2010).
3. *NfkB activity in microglial cells in relation to elemental components.* The composite PM samples from the first 6-month study for high NfkB activity in lung cells and low NfkB activity were applied in a dose–response study to microglial cells, and the only elements having significant dose-related associations were Ni and V (Sama et al. 2007).

Current evidence for influential PM components

Recent epidemiological studies and CAP inhalation studies have provided speciation data that illustrate the potential for identifying influential components. In particular, excess mortality has been associated with Ni, V, Al, As, $SO_4^{=}$, OC, and black carbon (BC), while excess morbidity has been associated with Ni, V, Al, As, Br, Cd, Cr, Cu, Fe, K, Pb, Se, $SO_4^{=}$, Zn, OC, and BC (Lippmann and Chen 2009).

Atherosclerotic plaque progression can be produced by chronic inhalation of ambient air $PM_{2.5}$, sidestream cigarette smoke (SS), and diluted whole diesel engine exhaust

(WDE), and Lippmann and Chen (2009) demonstrated that CAPs at ~110 μg/m^3 produced more plaque than either SS or WDE having PM concentrations at ~450 μg/m^3. It is noteworthy that both the SS and WDE exposures also included much higher concentrations of gaseous pollutants than the CAP exposures, including carbon monoxide, nitrogen dioxide, and various aldehydes and polycyclic aromatic hydrocarbons. The greater plaque progression following the CAP exposures is likely due to their higher concentrations of transition metals.

Research needs to support a policy and regulatory initiative for improved public health protection from the adverse health effects of PM

The most direct and cost-effective way to reduce the health impacts and control costs imposed by exposure to PM in ambient air is to focus control efforts on the most toxic PM components. Unfortunately, we currently lack sufficient data on the exposure–response relationships to justify adequate emission controls for these toxic components. However, we do know what research can provide such data in a reasonable time frame. Foremost among these needs are:

Characterization of ambient air PM We need PM component concentrations on a daily basis in a variety of urban areas, their spatial variability across the area, and their association with geographic variables (traffic, land use, etc.) for: (1) $PM_{2.5}$, (2) $PM_{10–2.5}$, and (3) ultrafine PM mass and number concentrations (Lippmann 2009).

Associations of PM components with adverse health effects We now know that some transition metals and primary organic compounds are considerably more toxic than other $PM_{2.5}$ components, but we lack sufficient information to focus control efforts. We also need to identify and characterize the especially influential components of $PM_{10–2.5}$ and UFP.

Further identification of sensitive subpopulations and risk factors There is still a paucity of information on the effects of genetic variation and other personal risk factors (metabolic syndrome, obesity, stress, etc.) on responsiveness to PM exposure that can be addressed by epidemiologic and controlled laboratory exposures.

Further identification of organ systems affected by PM exposure Subchronic animal inhalation studies with CAPs have demonstrated that adverse effects can be found in the liver and nervous system as well as in the cardiovascular and respiratory systems, but explorations to date have been too limited to fully evaluate the extent and significance of these responses (Lippmann and Chen 2009).

Regulatory and policy implications

The index pollutants for the PM NAAQS (mass concentrations of $PM_{2.5}$ and PM_{10}) are inherently imperfect measures of PM toxicity, and identification of the more toxic components of ambient air PM and their various health effects would provide a basis for more targeted airborne concentration limits and efficient control strategies. The need to identify the most toxic PM components and their exposure–response relationships is more urgent than ever in view of the challenge now confronting the EPA Administrator in setting new and more stringent annual average and daily maximum PM NAAQS in the near future The mass-based concentration ranges recommended by the EPA Office of Air Quality Planning and Standards, and endorsed by the Clean Air Scientific Advisory Committee as needed to protect the public health, extend from difficult to achieve at the upper end to needing draconian controls at the lower end. In any case, it is likely that there will be legal challenges to any NAAQS more stringent than the current limits, and perhaps, attempts to revise the Clean Air Act to weaken the Administrator's authority in setting standards. Furthermore, it is likely that we will find, over the next 5 years, that PM will be having adverse health effects at concentrations as low as or even lower than those specified at the lower ends of the current recommended ranges.

Therefore, an expanded program of speciation monitoring and epidemiological research is needed to identify the most toxic PM components and their specific health effects and exposure–response relationships, especially for the cardiovascular effects that account for a large fraction of the excess mortality associated with $PM_{2.5}$ concentrations. Future epidemiological research productivity will be dependent on the extent to which there is increased frequency and spatial coverage by monitoring networks providing speciation of the PM that only EPA can provide.

Conclusions

Exposures to ambient air $PM_{2.5}$ are responsible for more excess mortality, morbidity, and lost time and function than any other class of anthropogenic environmental pollution. However, we do not know yet which of the myriad components of the ambient $PM_{2.5}$ is most influential in causing the known adverse health effects and have little knowledge of other adverse effects that may be occurring in sensitive subpopulations or in organ systems that have yet to be sufficiently studied. Reliance of crude indices of exposure, such as overall mass concentration, even when restricted to specific particle size ranges based on regional particle deposition probabilities, precludes the setting of optimal ambient air quality standards and/or hazardous air

pollutant emission standards and control strategies in terms of societal costs and efficiency.

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References

Bell ML, Ebisu K, Peng R, Samet JM, Dominici F (2009) Hospital admissions and chemical composition of fine particle air pollution. Am J Respir Crit Care Med 179:1115–1120

Chen L-C, Hwang JS (2005) Effects of subchronic exposures to concentrated ambient particles (CAPs) in mice. IV. Characterization of acute and chronic effects of ambient air fine particulate matter exposures on heart-rate variability. Inhal Toxicol 17:209–216

Chen LC, Hwang JS, Lall R, Thurston GD, Lippmann M (2010) Alteration of cardiac function in ApoE$^{-/-}$ mice by subchronic urban and regional inhalation exposure to concentrated ambient $PM_{2.5}$. Inhal Toxicol 22(7):580–592

Delfino RJ, Staimer N, Tjoa T, Polidori A, Arhami M, Gillen DL, Kleinman MT, Vaziri ND, Longhurst J, Zaldivar F, Sioutas C (2008) Circulating biomarkers of inflammation, antioxidant activity, and platelet activation are associated with ultrafine particles and primary combustion aerosols in elderly subjects with a history of coronary artery disease. Environ Health Perspect 116:898–906

Delfino RJ, Staimer N, Tjoa T, Gillen DL, Polidori A, Arhami M, Kleinman MT, Vaziri ND, Longhurst J, Sioutas C (2009) Air pollution exposures and circulating biomarkers of effect in a susceptible population: clues to potential causal component mixtures and mechanisms. Environ Health Perspect 117:1232–1238

Delfino RJ, Tjoa T, Gillen DL, Staimer N, Polidori A, Arhami M, Jamner L, Siotas C, Lomghurst J (2010a) Traffic-related air pollution and blood pressure in elderly subjects with coronary artery disease. Epidemiol 21:396–404

Delfino RJ, Gillen DL, Tjoa T, Staimer N, Polidori A, Arhami M, Siotas C, Lomghurst J (2010b) Electrocardiographic ST segment depression and exposure to traffic-related aerosols in elderly subjects with coronary artery disease. *Environ Health Perspect* (doi:10.1289/ehp.1002372, available at http://dx.doi.org/) Online Oct. 2010.

Dye JA, Adler KB, Richards JH, Dreher KL (1997) Epithelial injury induced by exposure to residual oil fly-ash particles: role of reactive oxygen species? Am J Respir Cell Mol Biol 17:625–633

Dye JA, Adler KB, Richards JH, Dreher KL (1999) Role of soluble metals in oil fly ash-induced airway epithelial injury and cytokine gene expression. Am J Physiol 277:L498–L510

Dye JA, Lehmann JR, McGee JK, Winsett DW, Ledbetter AD, Everitt JI, Ghio AJ, Costa DL (2001) Acute pulmonary toxicity of particulate matter filter extracts in rats: coherence with epidemiological studies in Utah Valley residents. Environ Health Perspect Suppl 109:395–403

Frampton MW, Ghio AJ, Samet JM, Carson JL, Carter JD, Devlin RB (1999) Effects of aqueous extracts of PM_{10} filters from the Utah Valley on human airway epithelial cells. Am J Physiol 277:L960–L967

Franklin M, Koutrakis P, Schwartz J (2008) The role of particle composition on the association between $PM_{2.5}$ and mortality. Epidemioology 19:680–689

Gent J, Koutrakis P, Berlanger K, Triche E, Holford T, Bracken M, Leaderer B (2009) Symptoms and medication use in children with asthma and traffic-related sources of fine particle pollution. Environ Health Perspect 117:1168–1174

Ghio AJ, Devlin RB (2001) Inflammatory lung injury after bronchial instillation of air pollution particles. Am J Respir Crit Care Med 164:704–708

Hedley AJ, Wong CM, Thach TQ, Ma S, Lam TH, Anderson HR (2002) Cardiorespiratory and all-cause mortality after restrictions on sulphur content of fuel in Hong Kong: an intervention study. Lancet 360:1646–1652

Hedley AJ, Chau PYK, Wong CM (2004) The change in sub-species of particulate matter [PM_{10}] before and after an intervention to restrict sulphur content of fuel in Hong Kong. Poster presented at Better Air Quality/Asian Development Bank Meeting at Agra, India

Hsu SI, Ito K, Lippmann M (2011) Effects of thoracic and fine PM and their components on heart rate and pulmonary function in COPD patients. J Expos Sci Environ Epidemiol (in press)

Hwang JS, Nadziejko C, Chen LC (2005) Effects of subchronic exposures to concentrated ambient particles (CAPs) in mice. III. Acute and chronic effects of CAPs on heart rate heart-rate fluctuation and body temperature. Inhal Toxicol 17:199–207

Lipfert FW, Baty JD, Miller JP, Wyzga RE (2006) $PM_{2.5}$ constituents and related air quality variables as predictors of survival in a cohort of US military veterans. Inhal Toxicol 18:645–657

Lippmann M (2009) Semi-continuous speciation analyses for ambient air particulate matter: an urgent need for health effects studies. J Expos Sci Environ Epidemiol 19:235–247

Lippmann M (2010) Targeting the components most responsible for airborne particulate matter health risks. J Expos Sci Environ Epidemiol 20:117–118

Lippmann M, Chen L-C (2009) Health effects of concentrated ambient air particulate matter (CAPs) and its components. Crit Rev Toxicol 39(10):865–913

Lippmann M, Ito K, Hwang JS, Maciejczyk P, Chen LC (2006) Cardiovascular effects of nickel in ambient air. Environ Health Perspect 114:1662–1669

Maciejczyk PB, Chen LC (2005) Effects of subchronic exposures to concentrated ambient particles (CAPs) in mice: VIII. Source-related daily variations in in vitro responses to CAPs. Inhal Toxicol 17:243–253

Maciejczyk P, Zhong M, Lippmann M, Chen LC (2010) Oxidant generation capacity of source-apportioned $PM_{2.5}$. Inhal Toxicol 22(Suppl 2):29–36

Niu J, Liberda EN, Qu S, Guo X, Li X, Luo B, Zhang L, Zhao N, Zhong M, Ito K, Wildman R, Liu H, Chen L-C, Qu Q (2011) Nickel and disrupted endothelial repair: implications in the cardiovascular effects of $PM_{2.5}$ (in press)

Patel MM, Hoepner L, Garfinkel R, Chillirud S, Reyes A, Perera F, Millert R (2009) Ambient metals and elemental carbon in fine particulate matter predict wheeze and cough in very young urban children. Am J Respir Crit Care Med 180:1107–1113

Pope CA III (1989) Respiratory disease associated with community air pollution and a steel mill in Utah Valley. Am J Public Health 79:623–628

Pope CA III (1991) Respiratory hospital admissions associated with PM_{10} pollution in Utah Salt Lake and Cache Valleys. Arch Environ Health 46:90–97

Pope CA III, Schwartz J, Ransom MR (1992) Daily mortality and PM_{10} pollution in Utah Valley. Arch Environ Health 47:211–217

Pope CA III, Rodermund DL, Gee MM (2007) Mortality effects of a copper smelter strike and reduced ambient sulfate particulate matter air pollution. Environ Health Perspect 115:679–683

Sama P, Long TC, Hester S, Tajuba J, Parker J, Chen L-C, Veronesi B (2007) The cellular and genomic response of an immortalized microglia cell line (BV2) to concentrated ambient particulate matter. Inhal Toxicol 19:1079–1087