Particulate air pollution and health: Emerging issues and research needs related to the development of air quality standards

Patrick A Hessel PhD, John R Goldsmith MD MPH, H-Erich Wichmann MD PhD,
William E Wilson PhD, Colin L Soskolne PhD

Department of Public Health Sciences, University of Alberta, Edmonton, Alberta; Department of Epidemiology and Health Services Evaluation, Faculty of Health Sciences, Ben Gurion University of the Negev, Beer Sheva, Israel; GSF-Institute of Epidemiology, Neuherberg, Germany; the National Center for Environmental Assessment, United States Environmental Protection Agency, North Carolina, United States of America

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The health effects of particulate air pollution were highlighted at the Eighth Annual Conference of the International Society for Environmental Epidemiology, held in Edmonton, Alberta in August 1996. Despite consistent evidence for adverse respiratory and cardiovascular health effects related to particulate air pollution, there are significant gaps in the knowledge of the mechanisms whereby particulate air pollution affects human health. Questions regarding the appropriate measure of dose for assessing exposures relevant to health outcomes and the methods used to analyze dose-response data remain unanswered. Health effects have been demonstrated across the range of exposures that have been examined, and further research in low exposure settings is necessary to explore the lower end of the dose-response curve. Although a significant body of literature has been generated, comprehensive risk assessments have not been undertaken. Examination of the chronic effects of particulate air pollution and identification of high risk populations are necessary. Although there are significant unanswered questions regarding the health effects of particulate air pollution, the available information suggests that particulate air pollution at levels consistent with current standards is associated with measurable health effects.

Key Words: *Air pollution, Air quality standards, Environmental health, Particles*

Pollution par les matières en suspension et santé : nouveaux enjeux et nouvelles avenues de recherche ayant trait à l'établissement de normes pour la qualité de l'air

RÉSUMÉ : Les effets de la pollution par les matières en suspension sur la santé ont été soulignés dans le cadre de la VIII^{e} Conférence annuelle de l'*International Society for Environmental Epidemiology*, qui avait lieu à Edmonton, en Alberta, en août

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Correspondence and reprints: Dr PA Hessel, Department of Public Health Sciences, 13-103 Clinical Sciences Building, University of Alberta, Edmonton, Alberta T6G 2G3. Telephone 403-492-4159, fax 403-492-4159, e-mail pat.hessel@ualberta.ca

1996. Malgré les preuves accablantes confirmant les effets nocifs de la présence de matières en suspension dans l'air pour la santé respiratoire et cardiovasculaire, on note une importante lacune dans nos connaissances des mécanismes par lesquels ce type de pollution affecte la santé de l'être humain. Certaines questions au sujet du dosage approprié des expositions par rapport aux répercussions sur la santé et certaines questions sur les méthodes utilisées pour analyser les données dose-réponse restent en suspens. Les effets sur la santé ont été démontré avec un vaste éventail d'exposition et il faut pousser la recherche dans les contextes où l'exposition est faible afin de mieux connaître l'extrémité de la courbe où le rapport dose-réponse est plus bas. Bien que beaucoup d'articles aient été publiés, on ne dispose encore d'aucune méthode complète d'évaluation des risques. L'examen des effets chroniques de la présence dans l'air de particules en suspension et l'identification des populations à risque élevé s'imposent. Bien que plusieurs restent en suspens au sujet des effets de la pollution par les matières en suspension, les renseignements disponibles donnent à penser que ce type de pollution produit des effets mesurables sur la santé aux normes actuellement en vigueur.

The Eighth Annual Conference of the International Society for Environmental Epidemiology was held in Edmonton, Alberta from August 17 to 20, 1996. Among the most dominant topics discussed at the meeting was the health effects of particulate air pollution. A symposium sponsored by the United States Environmental Protection Agency (EPA) was held on the afternoon of August 19, 1996 to identify research needed to support the development of air quality standards for particulate matter. Currently, the EPA is drafting a revised standard for particulate air pollution. The following report briefly highlights some key data supporting reconsideration of standards worldwide, presents a review of outstanding methodological issues related to the health effects of particulate air pollution and outlines research needs. The discussion excludes toxic particulate matter such as lead fume, silica and asbestos. An extensive review of the epidemiological literature on particulate air pollution and health has recently been published (1).

AIR POLLUTION AND HEALTH

Disasters: A series of disasters in the Meuse Valley, Belgium in 1930 (2); Donora, Pennsylvania in 1948 (3); and London, England in 1952 (4) dramatically demonstrated the potential effects of ambient air pollution on mortality and morbidity. These disasters were triggered by a combination of high levels of emissions (industrial and/or residential) coupled with unusual atmospheric conditions. Although many cities in developing countries are subject to very high levels of air pollution, current interest in developed countries is mainly in the areas of acute and chronic effects of much lower pollution levels.

Terminology: A variety of measures have been used to describe particulate air pollution. Those based on particle size include total suspended particulates (TSP), the mass of particles less than about 25 to 40 µm in diameter, and particle mass (PM) measurements, which include PM_{10}, the mass of particles less than about 10 µm in aerodynamic diameter – an indicator of particles that enter the lung (thoracic particles) – and $PM_{2.5}$, the mass of particles less than about 2.5 µm in aerodynamic diameter – an indicator of particles capable of penetrating to the alveolar region. PM_{10} and $PM_{2.5}$ are measured with samplers that have a 50% acceptance at 10 and 2.5 µm, respectively. Particles are also described as fine-mode or coarse-mode particles, which differ in their sources, formation mechanisms and physical, chemical and biological properties as well as size (5,6) (Figure 1). $PM_{2.5}$, sometimes called fine PM, is considered an indicator of fine-mode particles. The arithmetic difference between PM_{10} and $PM_{2.5}$, sometimes called coarse PM, is considered an indicator of the portion of coarse-mode particles deposited in the thoracic regions of the human respiratory tract. Another frequently used indicator is black smoke, a measure of the black carbon or soot less than 4 to 6 µm in aerodynamic diameter. Fine particles include the accumulation mode and the nuclei mode (Figure 2) (5,6). Ultrafine particles, defined as particles below about 0.1 µm in aerodynamic diameter, make up most of the particles by number.

Particulate air pollution and mortality: The authors of a series of studies using data from Philadelphia, Pennsylvania (7-9) found associations between air pollution levels and daily mortality from the early 1970s to the early to mid-1980s. Relationships were seen for sulphur dioxide and TSPs; the independent effects of these two pollutants could not be distinguished. However, one report at the meeting (10), which used a different approach for analysis (11), found only direct effects of particulate matter and inconsistent results when the years were examined separately. A number of studies conducted in a variety of settings have shown positive associations between daily levels of particulate air pollution and mortality (12-20).

The Air Pollution on Health: European Approach (APHEA) project, a multicentre study of the short term health effects of air pollution in Europe, used mainly black smoke as the exposure measure. Positive associations were found between daily measurements of black smoke and mortality (21). Of interest was the finding that the risk estimates (the increase in mortality associated with a given increase in black smoke) were higher for centres in Western Europe than those for Eastern Europe, suggesting that the nature of the particles in the two areas might differ, resulting in differing toxicity.

Two recent studies examined the relationships between daily fluctuations in particulate air pollution and daily mortality for both PM_{10} and $PM_{2.5}$. In the Harvard Six Cities Study (a time series from 1979 to 1985 in six United States cities) (22) and a time series in Philadelphia from 1991 to 1994 (23), these relationships were stronger for $PM_{2.5}$ than for PM_{10}.

When data from a number of studies were combined, there appeared to be an increase of approximately 1% in daily mortality associated with an increase of 10 $\mu g/m^3$ in

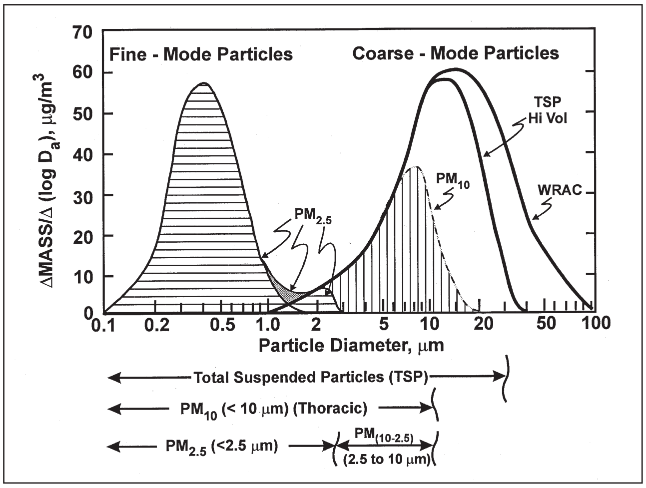

Figure 1) *An idealized distribution of ambient particulate matter showing fine-mode particles and coarse-mode particles. Also shown are the fractions of each mode collected by particle mass (PM) -selective samplers ($PM_{2.5}$ [mass of particles less than about 2.5 μm in aerodynamic diameter] and PM_{10} [mass of particles less than about 10 μm in aerodynamic diameter]), an estimate of particles collected by the high volume sampler (Hi Vol), known as total suspended particles (TSP), and an estimate of the total distribution of ambient particles measured by the Wide Range Aerosol Classifier (WRAC). Da Aerodynamic diameter*

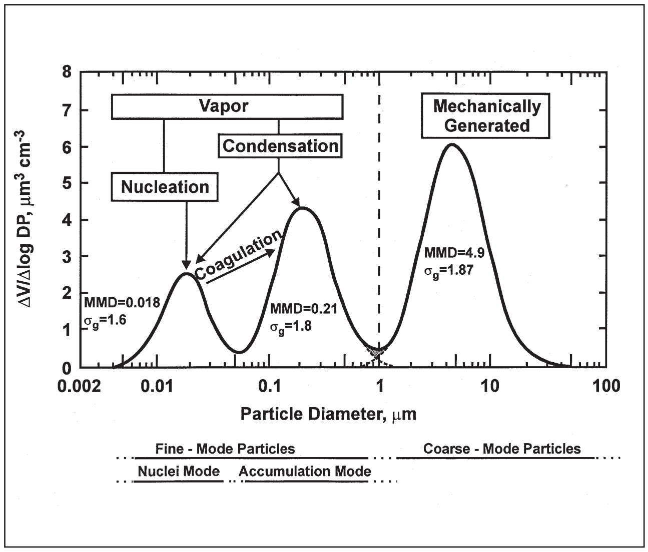

Figure 2) *Measured volume size distribution showing fine-mode and coarse-mode particles, and the nuclei and accumulation modes within the fine-particle mode. Geometric mean diameter by volume (DGV), equivalent to volume median diameter and geometric standard deviation (σ_g), are shown for each mode. Transformations and growth mechanisms (eg, nucleation, condensation and coagulation) are also shown. MMD Mass median diameter; DP Diameter of particles; V Volume*

PM_{10} (24). For a similar increase in PM_{10}, respiratory mortality increased by 3.4% and cardiovascular mortality increased by 1.8%. One report raised the question of how much these estimates might vary with better methods of accounting for the inevitable confounding by time of year changes and weather variables (10). Because the baseline mortality rate for cardiovascular disease is higher than for respiratory disease, the actual number of excess deaths associated with particulate air pollution is higher for cardiovascular disease than for respiratory disease.

Most studies have examined acute fluctuations in mortality rates in relation to short term fluctuations in air quality. However, two studies provide evidence for effects of chronic particle exposures on mortality. The Harvard Six Cities Study (25) and a data set from the American Cancer Society (26) indicate that overall mortality rates were higher in those communities with higher annual average levels of particulate air pollution.

Particulate air pollution and morbidity: A number of morbidity indicators vary in relation to fluctuations in particulate air pollution. Studies have generally focused on respiratory outcomes such as emergency department visits (27,28) or hospital admissions for respiratory conditions (29-35), respiratory symptoms (13,36-41) and lung function (36,37,41-46). Asthma patients have more respiratory symptoms (47,48) and use more medication (49) during episodes of high particulate air pollution.

METHODOLOGICAL ISSUES AND AVENUES FOR FUTURE RESEARCH

Measurement of particulate matter: Currently, most regulations and research findings are based on measures of PM_{10} or on cruder measurements such as TSP or black smoke. Deposition models indicate that coarse particles, fine particles and ultrafine particles have different deposition characteristics in the respiratory tract. Epidemiological studies measuring both PM_{10} and $PM_{2.5}$ have shown stronger associations between mortality and $PM_{2.5}$ (22,23,25), perhaps indicating that the composition or dimensions of fine particles affect their ability to exert a toxic effect. Gradients between indoor and outdoor levels have also been shown to be lower for fine particles than for larger particles, implying that ambient measurements of fine particles may be more representative of 24 h exposures than the measurements of larger particles. The upcoming revision of the United States PM standard will probably add a standard for $PM_{2.5}$ and maintain a standard for PM_{10}.

Deposition models indicate that ultrafine particles are capable of penetrating to the alveolar regions of the lung. There is interest in determining the contribution of ultrafine particles to health effects. Some recent epidemiological (50) and toxicological (51) studies provide evidence for health effects of ultrafine particles. Further, measures of doses other than those based on the mass of particles may be relevant. The number of particles or the surface area of respirable particles may be important. Indeed, first analyses of this type suggest that the number of ultrafine particles may be of specific importance for short term effects in asthmatics (50).

The health effects of particles have been evaluated primarily on the basis of their concentration and size. The differing risk estimates from particulate air pollution in Eastern and Western Europe (25) have focused attention on the need to examine the source and composition of particles. It was hypothesized that particles in Western Europe emanate largely from diesel exhaust, whereas those in Eastern Europe result from the inefficient combustion of coal, and that differences in the composition of particles from these two sources might explain the differences in risk estimates. In addition to clarifying variations in observed risk estimates, documentation of the composition and sources of particulate air pollution will provide information needed to design and implement strategies to reduce ambient levels. Quantifying the positive and negative impacts of changes in allowable levels of ambient particles will be difficult in the absence of information on the composition and sources of particles.

Existing studies have generally applied exposure data collected from one or several locations in a community or region to the population. Improvements in exposure assessment, including personal exposure assessment and consideration of indoor particulate levels, should be incorporated into studies.

Exposures to individual pollutants inevitably vary with time of year and weather. These changes are accompanied by changes in the levels of other pollutants. Studies examining the associations between air quality and mortality from Philadelphia (7-9) have drawn attention to the difficulty of separating the independent effects of a single pollutant from interactive effects with other variables. Even the separation of effects of sulphur dioxide from particulate matter is complicated because sulfate particles are formed from sulphur dioxide.

Mechanism(s) of action: There was some urgency expressed about identifying the mechanism(s) whereby particulate air pollution affects human health. Hypotheses involving particle number, the active surface of particles, acidity of the particles, presence of transition metals (especially iron) on or in the particles, presence of bioaerosols and the activity of particles in conjunction with gases were proposed. Studies of animal models, as well as possible controlled human exposures, were suggested. Despite the lack of a cogent biological model, there was general agreement that the epidemiological data demonstrating health effects below current United States standards warrant reconsideration of currently allowable levels.

Public health impact/risk assessment: Despite the consistency of the data relating particulate air pollution to a variety of adverse health effects, no studies have attempted to measure its public health impact. It was questioned, for example, whether the acute changes in mortality in response to fluctuations in particulate air pollution might represent a minor advance in the date of death of people who are already severely compromised. Differences in long term mortality rates associated with long term average levels of particulate air pollution levels (15) argue against this phenomenon (sometimes referred to as 'harvesting' or 'premature death') as the sole explanation for the correlation between acute changes in mortality and daily fluctuations in particulate air pollution. Nonetheless, no studies have addressed the impact of particulate air pollution in terms of, for example, potential years of life lost or quality-adjusted life-years.

It was emphasized that the calculation of risk estimates for the relationships between mortality and morbidity, and particulate air pollution does not constitute a full risk assessment. Further, currently available data do not permit highly confident estimations of the relative benefits and costs of reductions in ambient particulate air pollution.

Studies at low exposure levels: Health effects associated with particulate air pollution have been documented at levels below current standards. Reported dose-response curves have been fairly linear across the range of exposures that have been studied and with current models. Whether these curves will remain linear at lower exposures or with different models remains to be seen. The possible effect of measurement error could obscure underlying nonlinear relationships.

Cohort studies: The majority of the existing literature on health effects of particulate air pollution is based on short term correlational (ecological) analyses. This type of study does not permit individual assessment of the relationship between exposure and disease. As noted above, it is not possible to determine the effect of fluctuations in particulate air pollution on life expectancy or quality of life from this type of study. However, that would be possible if existing large scale cohort studies could be expanded to incorporate air pollution components. In addition, studies of suspected high risk populations (eg, those with asthma, chronic obstructive pulmonary disease or coronary heart disease) should permit assessment of more subtle, possibly subclinical, effects.

SUMMARY OF RESEARCH NEEDS

To better understand the health effects of particulate air pollution, and to plan and implement strategies to reduce these health effects, the following avenues of research have been suggested.

1. Exploration of the health effects of specific fractions of particulate matter, and alternative dose metrics such as particle number and surface area.
2. Identification of the source and nature of particulate air pollution.
3. Improvement in exposure estimation, including examination of the relative contributions of outdoor and indoor exposures.
4. Application of methods for studying the interaction of pollution variation with health variables in the presence of the confounding effects of weather and time of year.
5. Identification of mechanisms whereby particulate air pollution affects human health.
6. Comprehensive risk assessment, including public health impact and cost-benefit considerations associated with changes in legislated limits.
7. Studies at low exposure levels to explore the lower end of the dose-response curve.
8. Identification and study of high risk populations, preferably through cohort studies.
9. Examination of the chronic effects of particulate air pollution.
10. Study of subtle, possibly subclinical, indicators of the effects of particulate air pollution.

Although many outstanding questions remain regarding the health effects of particulate air pollution (most notably the lack of plausible, demonstrated biological mechanisms underlying reported associations of health effects with low ambient PM levels), the existing data nevertheless highlight the need to reconsider existing air quality standards. The situation is, in some ways, similar to the problem confronted by John Snow in 19th century London (52). Despite the lack of understanding of the mechanisms of cholera transmission and infection, he was able to institute measures that alleviated a major cholera epidemic. It would be preferable to base changes in air quality standards and other control strategies on a more complete understanding of the biological mechanism and health effects. Still, several national governments and international health organizations view the data that are currently available as being sufficient to warrant the revision of present standards. Proposed revisions to new United States air quality standards for PM, for example, include the addition of new 24 h and annual average standards for $PM_{2.5}$ (to protect against fine-particle effects), in addition to retaining the existing PM_{10} standards. At the same time, a significant intensification of research will be required to address the unresolved issues.

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