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HEALTH AND AIR QUALITY: DIRECTIONS FOR POLICY-RELEVANT RESEARCH

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The NERAM International Colloquia series is a program of five annual meetings involving scientists, regulators, industry representatives, and other stakeholder groups to improve the linkage between emerging scientific evidence on the population health impacts of exposure to particulate matter and clean air policy decisions. Health and Air Quality 2001, the first meeting in the colloquium series, focused on the findings of prospective cohort studies of particulate air pollution and mortality and implications for risk management. A further objective of the colloquium was to identify research directions to reduce information gaps and uncertainties faced by policy makers. This article discusses priority themes for future research to generate evidence in support of policy decisions to improve air quality and population health. These research themes

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include development of population health indicators to characterize the public health burden of air pollution; individual exposure and outcome studies to the currently available database on the association between air pollution and adverse health effects; identification of sensitive subpopulations; techniques to assess the independent effects of individual pollutants on population health; comparative risk assessment; methods for characterization and communication of uncertainty in risk estimates; effectiveness of policy interventions to guide allocation of limited population health protection resources; improved predictions of the benefits of interventions through appropriate economic analyses: targeted interventions; and approaches for effective stakeholder engagement in risk management policy decisions. Future meetings in the NERAM Colloquium series will provide a forum for discussion of the current state of knowledge and policy implications of findings associated with these key research themes.

One of the primary objectives of the NERAM Colloquium on Health and Air Quality 2001 was to engage researchers, regulators, industry representatives, and policy makers in a process to identify priority areas for future research to guide effective air quality policy development. A comprehensive list of areas for further research was compiled as delegates identified key issues in plenary sessions, break-out group discussions, and written submissions. The following 10 priority research themes were selected as being of sufficient importance for further discussion at future NERAM Colloquia. This article describes the rationale for the selection of these priority themes and the research activities needed to clarify science and science policy issues related to these themes.

POPULATION HEALTH IMPACTS

Epidemiological analyses provide measures of the risks associated with air pollution exposure. Typically, epidemiological studies yield estimates of relative risk associated with some change in outdoor concentration of a pollutant. These estimates have served the regulatory process by providing an indication of the levels at which effects are seen and the seriousness of the risks from a biomedical perspective. However, these estimates do not readily translate into indicators of population health impact. For that purpose, translational measures are needed. Such measures are needed to place the risk posed by air pollution in perspective; comparative risk assessment cannot readily be accomplished without such population health indicators.

A number of measures of population health impact have been developed for this purpose. These include such approaches as estimating the numbers of premature deaths or potential years of person-life lost (PYLL), the numbers of excess events reflecting morbidity in the population (e.g., hospitalizations or visits to a clinic), and measures that incorporate quality of life, including quality-adjusted life years (QALYs) and disability-adjusted life years (DALYs). The Global Burden of Disease project currently underway within the World Health Organization has selected DALYs as the common metric for characterizing public health burden, while acknowledging that research should continue on developing other measures of population health impact.

Ambient air pollution has been associated with a spectrum of health effects, ranging from effects on well-being and quality of life to increased risk of premature death. Depending on the level of economic development and the capacity and willingness to implement controls, there may be a wide range in the valuation of different population health impacts of air pollution across countries. Consequently, there may be a need to use a suite of risk measures, each having well-characterized features and covering the full spectrum of adverse effects. This is an area of research in air pollution risk assessment that received little emphasis to date. The following research topics are therefore proposed for consideration, with the recognition that they should be explored with the involvement of both air pollution researchers and policymakers.

- Survey existing approaches for consideration of their relevance to air pollution and health.
- Convene a workshop involving persons working on public health consequences of air pollution and those working on the estimation of disease burden.
- Consider how to incorporate effects on well-being and quality of life into indicators of population health risk.
- Address more subtle forms of injury at the population level that do not cause apparent disease at the individual level.
- Consider measures that would be appropriate in different countries, ranging from developing to highly developed.
- Consider risks among susceptible populations and disparities in the distribution of exposures among population subgroups.

INDIVIDUAL EXPOSURES AND OUTCOMES

The majority of the presently available data on the population health impacts of urban air pollution has been derived from epidemiological studies in which ecologic measures of exposure are derived from fixed-site ambient air pollution monitors. Many of the more detailed health studies following small panels of individuals have also relied on ecologically based exposure information (for example, environmental monitoring data from 1–5 central site ambient monitoring stations with 1- to 24-h measurements). While individuals may be exposed to higher or lower absolute concentrations due to their microenvironmental exposures, the ecologic approach assumes that the monitor(s) reliably indicate the population-average day-to-day changes in exposure or, in a cross-sectional sense, that the monitors in different geographic locations accurately reflect exposure differences among the populations being studied. Individual exposure variations about the population-average exposures based on ambient monitoring data, which are due to their unique interaction among time-activity and microenvironmental concentrations, are assumed to be random across the population. Furthermore, these individual variations are not expected, on average, to differ among geographic areas. Under these assumptions, it should be possible to translate reductions in the ambient concentration as measured at the monitoring stations to reductions in risk, and hence to improved population health. However, these assumptions may not be valid due to the following uncertainties:

- The individual component of exposure may vary by population subgroup, with susceptible people, who may constitute a significant portion of the at-risk group, systematically experiencing exposure levels that differ from that of the population average.
- The risk attributed to each pollutant in the mix may be uncertain due to differential exposure measurement error. In this case, the risk attributed to a more hazardous pollutant may be smaller than its true value if the exposure error is large relative to those of the other less hazardous pollutants in the mix.
- The individual component of exposure may vary among geographic locations (city to city, for example), so that the relationship between population average exposure and the ambient monitor measurements is not the same in all locations.

These uncertainties can be addressed by measuring individual exposures to multiple pollutants in a range of geographic locations. Measurements are needed for a variety of population subgroups, particularly those expected to be at greatest risk. The resulting data should then be quantitatively related to the fixed-site ambient monitor measurements, with the goal being elucidation of robust relationships between air pollution and health outcome by population subgroup and air pollutant. This information can then be combined with epidemiological information on cause-specific mortality and morbidity for high-risk subgroups. Examination of high-exposure and high-risk subgroups will permit more refined risk models to be developed. This information can also be used to quantify pollutant-specific exposure errors to assist in the development of methods to assess the independent effect of each of the pollutants in the complex mix of ambient air pollutants to which we are exposed, as well as the interactions among these pollutants.

More knowledge of the underlying biological mechanism(s) and demonstration of specific, clinically significant, effects on human health is needed to ensure that the current body of evidence on health risks and the assessment of such evidence are translated into concrete policy responses such as emission reduction strategies with clear deadlines for achievement of established targets. New knowledge derived from clinical studies involving controlled exposure chambers, panel studies using personal exposures, and toxicological studies with laboratory animals will need to be reconciled with results from epidemiological studies relying on ecologic measures of exposure. This will require the ability to link the exposure levels considered in this more biologically motivated research to the environmental exposures experienced by the general population, as well as at-risk population subgroups. This will facilitate projection of the exposure-response information from the biological research to the general population, leading to better predictions of specific health benefits associated with reductions in ambient pollutant levels from proposed air pollution mitigation policies.

A potential limitation of this biologically based approach to air pollution risk assessment is that it may not be possible to determine dose-response information for some of the most relevant health outcomes. This is because these outcomes may only be expressed in highly susceptible individuals, who may not be candidates for inclusion in clinical studies. However, studies following panels of susceptible individuals as they go about their daily activities can be designed to provide more detail on individual exposures and outcomes. The personal exposure data required for this type of research would also contribute information for addressing the differential exposure uncertainties discussed above.

In order to achieve the goal of linking the exposure levels considered in the "biological" research to the environmental exposures experienced by the population, it is necessary to ensure that the biological research includes exposures expected to be relevant to the environment, and to document the relationship between actual (personal) exposure and ambient fixed-site measurements for a range of population subgroups and for all the common urban air pollutants. This information will allow links to be made between the results of epidemiological studies employing ecologic exposure measures and other more detailed research findings. Such links will be necessary to refine risk models, to improve predictions of the benefits of interventions, and to strengthen the evidence relating air pollutants to adverse health effects of public health significance.

IDENTIFICATION OF SENSITIVE SUBPOPULATIONS

Our current understanding of who is at risk from exposure to particulate matter in ambient air at levels currently experienced by North Americans is limited. Some evidence suggests that children, the elderly, and persons with preexisting heart and lung diseases are more sensitive or vulnerable to exposure to ambient particulate matter. This group comprises a relatively large proportion of the population. A greater understanding of the host conditions necessary for air pollution to play a role in either developing a chronic condition or exacerbating preexisting conditions would allow policy makers to more specifically target control strategies to reduce exposure to those most affected.

Epidemiological studies that examine subjects with specific health conditions are required. For example, Goldberg et al. (2000) linked deceased persons to their drug and physician billing records in the last year of life in order to determine their chronic health conditions. Standard time-series methods were then used to relate daily variations in ambient particle concentrations to deaths from nonaccidental causes stratified by preexisting health condition. Based on the use of this type of person-oriented administrative health data, persons with congestive heart failure (CHF) were identified as being more susceptible to particle pollution-related deaths than the general population. To further elucidate the effect of particles on those with CHF, a pilot panel study is currently being conducted in Montreal on patients with CHF. Here, several health outcomes are measured daily on CHF patients and linked to ambient concentrations of particle and gas phase pollution. It is this type of detailed assessment of the effect of a person's health condition on the association between short-term air pollution exposure and acute health response that is required to better identify those persons most at risk.

MULTIPLE POLLUTANTS

Ambient air pollution is a complex chemical mixture comprising both gaseous and particle phases. Pollutants originate from multiple sources including transportation, industrial operations, and home heating. Secondary pollutants are formed in the atmosphere from primary sources and can travel long distances before being deposited on the ground. Daily variations in pollutant concentrations are primarily attributed to changes in weather conditions and, as such, pollutants often vary together in time at a single location. This phenomenon makes it difficult to identify the extent to which each pollutant contributes to the risk posed by the atmospheric mix.

A number of epidemiological studies have linked several pollutants to adverse health effects at levels currently observed in the troposphere. These pollutants include ozone, carbon monoxide, sulfur dioxide, nitrogen dioxide, and size-fractionated particulate mass. Questions arise as to the contribution that each of these pollutants independently make to the total effect of the atmospheric mixture on population health. This issue is of importance since mitigation strategies developed to control air pollution often target only one or several of these pollutants. We cannot be certain that the most toxic components have been appropriately targeted for control. Methods need to be developed to assess the independent effect of each of the pollutants in the atmospheric mixture, possibly by using statistical techniques such as principal component analysis and by examining the effects of single pollutants on health in several locations in which the effects of different mixtures of air pollutants can be assessed. Monitoring data that include chemical and physical characteristics of particulate matter are also required.

The joint effects of pollutant interactions on health are also of interest. For example, does preexposure to ozone sensitize subjects to the effects of particulate matter? And could the presence of gaseous pollutants alter the chemical structure of particles, thereby enhancing their toxicity?

COMPARATIVE RISK ASSESSMENT

Public awareness of potential health hazards in the environment has never been greater than today. Demands to "do something" about chemical and other contaminants in water, food, air, and soil are daily occurrences, which renders it difficult for policy makers to make reasoned choices on how to best allocate society's limited resources in protecting human health.

From a population health perspective, it is vitally important to ensure resource allocations are appropriately identified and committed. Environmental determinants of health, such as exposure to chemical contaminants, are but one of a number of determinants of population health status; other important health determinants include education, income, personal health practices, child development, and available health services (Federal, Provincial, and Territorial Advisory Committee on Population Health, 1994). An increasing body of evidence indicates that many of these factors may interact in complex ways that are not yet fully understood. For example, socioeconomic status as reflected by educational attainment has been shown to modify the assocation between long-term exposure to particulate air pollution and mortality, with the risk decreasing with increasing education attainment (Krewski et al., 2003). The population health approach to risk assessment underscores the need to provide policy makers with well-grounded information on comparative risks to facilitate wise decisions about where the most effective interventions can be developed and applied.

There is ongoing debate about which components of air pollution present the greatest health impact and how to appropriately characterize their interactions; this information is necessary in order to devise optimal air pollution mitigation strategies. Similarly, knowledge of comparative risks between specific air pollutants and elucidation of their exposure-response relationships is needed. Additionally, these risks and dose-response considerations must be continuously compared with other risks identified within the population health paradigm. While this may seem intuitively obvious, such a broad-based assessment of risk requires additional knowledge of multiple health determinants and their interactions.

At the population level, we have incomplete and inconsistent understanding of the immediate causes of death (Thomas & Hrudey, 1997). Inconsistencies arise, for instance, via incorrect diagnosis by an attending physician or at autopsy, or practitioners may not consistently apply a disease classification across a city or region. This has raised difficulties in the interpretation of time-series studies of air pollution and mortality. Additional difficulties arise in the interpretation of population health risks associated with ambient air pollution because such risks arise from a combination of both short-term and long-term exposures that involve both voluntary and involuntary behaviors. The political and social considerations involved in conducting objective comparisons between different types of population health risks, followed by the subsequent generation of balanced, long-term mitigation strategies, are not to be trivialized.

In order to identify how society can best allocate its finite health protection resources, we must ensure air quality risk estimates are as accurate as possible and placed in context with other population health risks. Because the successful management of air quality issues inevitably involves many socially important concepts such as energy production, urban transportation, and city planning, it is important to generate and communicate comparative risk information to policy makers and the public.

CHARACTERIZATION AND COMMUNICATION OF UNCERTAINTY

Estimates of environmental health risks, including risks associated with particulate matter in ambient air, are subject to a number of uncertainties that need to be considered in risk management decision making (Bartlett et al., 1996). In a comprehensive assessment of lung cancer risk associated with residential radon exposure, the U.S. National Research Council (1999) conducted a formal uncertainty analysis of the number of lung cancer cases in the United States that may be attributable to radon in homes (cf. Krewski et al., 1999). This analysis included not only statistical uncertainty associated with sampling error, but also examined other sources of uncertainty such as extrapolation from occupational to environmental exposure conditions and exposure measurement error. Overall uncertainty can be conveniently expressed in the form of distribution of plausible risks, which provides a more complete expression of uncertainty than traditional confidence limits on risk. Such methods also permit disaggregation of uncertainty and interindividual variability in risk when individual rather than population-based measures of risk are considered.

With the advent of risk-analytic methods that permit characterization of total uncertainty arising from a number of sources, as well as identification of sources contributing most to overall uncertainty, a more complete characterization of uncertainties in the risks associated with ambient particulate matter is now possible. Application of such methods can be used to better gauge the plausible population health impacts of particulate air pollution and strengthen the basis for setting research priorities (NRC, 2001).

More complete characterizations of the risks of particulate air pollution will present challenges in risk communication specifically with respect to the concept of total uncertainty and the distinction between uncertainty and variability. Policy guidance for decision-making uncertainty will need to be developed in order to balance the need for a precautionary approach in the presence of uncertainty to protect population health and the need to allocate finite risk management resources in proportion to the actual (although perhaps not well- determined) level of risk.

Specific activities that may be undertaken in this regard include the following.

- Further development and application of risk analytic methods to better characterize the health risks associated with particulate air pollution.
- Identification of the sources that contribute most to uncertainty in particulate risk estimates and examination of opportunities for the reduction of major sources of uncertainty. Such analyses may be useful in determining the value of obtaining additional information, which may or may not serve to appreciably reduce overall uncertainty on specific aspects of the health risks of particulate matter.

- Distinction between interindividual variability in risk due to differences in both individual exposure and susceptibility (which cannot be reduced through further study) and uncertainty in risk.
- Development of effective ways of communicating information on uncertainty and variability in the health risk of particulate matter to health scientists, decision makers, and the public so that such information can be understood by interested and affected parties, and better inform risk management decision making with respect to particulate matter.

EFFECTIVENESS OF INTERVENTIONS

In developing and testing policy initiatives designed to reduce the effects of air pollutants on health, it would clearly be helpful to develop means of assessing such benefits. This has, however, proved a difficult task, as levels of air pollutants are now generally not so high in developed countries that modest reductions produce obvious improvements in health. To detect the adverse effects of current levels of air pollutants in developed countries on health, relatively sophisticated epidemiological techniques are needed. Such techniques will likely be needed to assess benefits of reductions in levels of air pollutants.

Research activities to evaluate the effectiveness of policy initiatives include the following.

- Development of indicators of health-benefit,* including daily mortality and morbidity rates and, on a longer time scale, life expectancy. These indicators are subject to a wide range of influences; some are much more important than air pollution. In addition, it is likely that events such as the triggering of a hospital admission of a patient with chronic respiratory disease, for example, may be due to a combination of factors. How these factors interact remains uncertain, and whether some are necessary needs to be clarified.
- It is appreciated there may be subgroups of the population that are more susceptible to the adverse effects of many air pollutants. Studies of such groups are more likely to provide the earliest and clearest indication of whether air quality policies are resulting in measurable population health benefits.
- Our current understanding of the effects of the classical air pollutants (particles, sulfur dioxide, nitrogen dioxide, carbon monoxide, and ozone) is based on models constructed from data collected in epidemiological studies. Such models are essentially descriptive. It has been suggested that such models might be used and perhaps tested by examining their power to predict the effects of reduced levels of air pollutants. It is also important to understand that the benefits of air pollution risk management policies are likely to accrue slowly and therefore might not be detected in the period

*This issue has recently been addressed by the U.S. National Research Council (2002) in its report *Estimating the Public Health Benefits of Proposed Air Pollution Regulations*.

immediately following the introduction of the policy. This is clearly the case if we are considering the effects of long-term exposure to air pollutants on life expectancy.

- One situation where benefits can be monitored is provided by an intervention that affects a local, dominant, and important source of air pollution, such as the temporary closure of the steelworks in the Utah Valley. Such cases are, however, likely to be uncommon. It is also likely that the effects of a repeat of a major episode of air pollution could be predicted. The episode in the Meuse Valley of Belgium in 1930 was studied in detail, and it was predicted that if such an episode occurred in a city like London, some 3800 extra deaths might occur. An episode did occur in 1952, and about 4000 deaths were reported.

ECONOMIC ANALYSIS

Because of the significant costs associated with the mitigation of urban air pollution, it is important to demonstrate that such expenditures will confer a significant population health benefit. In this regard, methods of economic analysis such as cost-effectiveness analysis or cost-benefit analysis can be of great value in informing risk-management decisions about particulate matter and other pollutants. Cost-benefit analysis was in fact used in a recent review of a proposed regulation to reduce the sulfur content of Canadian gasoline from the current level of approximately 350 ppm to as low as the California standard of 30 ppm, an intervention that would lead to a reduction in sulfate-based particulates associated with vehicle emissions (Atmospheric Science Expert Panel, 1997). Such methods are discussed further in a recent report prepared by Royal Society of Canada (2001).

Specific issues pertaining to the use of economic methods for the evaluation of risk management interventions include the following:

- What are the most appropriate methods of analysis? Cost-effectiveness analysis is useful in identifying the least costly approach to reducing exposure, but does not compare exposure reduction costs to health and other benefits. Cost-benefit analysis, in which all costs and consequences are valued in monetary units, permits a direct comparison of costs and benefits. A disadvantage of cost-benefit analysis is the difficulty in valuing health benefits, particularly mortality, in monetary terms. Cost-utility analysis represents an intermediate approach that seeks to find the least costly approach to achieving gains in quality-adjusted life expectancy.
- In order to identify alternative mitigation options, the sources of particulate air pollution and pathways by which they result in exposure of human populations need to be well characterized. Source apportionment methods may be of value in identifying the most important sources of particulate air pollution as well as the sources that are most amenable to control by regulatory, technological, and lifestyle interventions.

- The role of economic analysis in risk management decision making needs to be clearly defined. Although such analyses can provide valuable guidance to decision makers, other factors, including equity issues associated with the distribution of costs and consequences, will also need to be weighed in decisions to implement specific interventions.

TARGETED INTERVENTIONS

Reducing levels of air pollutants from the already low levels that exist in many developed countries will be costly. As levels of pollutants fall, the costs of further reductions are likely to increase and may outweigh benefits to health. This calls for interventions to be targeted to where they are likely to do greatest good. In developing such an approach a number of points should be kept in mind.

- Subpopulations may be at increased risk because of increased susceptibility to the effects of air pollutants and also because of increased exposure to air pollutants. The former case is exemplified by patients suffering from asthma, the latter by those living close to roads. It is difficult to imagine an intervention based on a reduction in sources of pollutants that would be targeted specifically at those suffering from asthma, although a targeted intervention to reduce levels of pollutants near roads could be contemplated.
- Policies directed at reducing the effects of air pollutants on health should be targeted at those pollutants that have a significant effect on health and that can be controlled.

It is important to grasp firmly the concept that effects upon health are due to the products of three features: the inherent toxicity of the pollutant, the ambient level of that pollutant, and the population exposed to that pollutant. Air pollution risk management policy should be focused on reductions in levels of pollutants that offer the greatest benefit per unit cost of reduction. Reducing levels of very toxic pollutants may not be cost-efficient unless significant benefits to health are predicted to occur.

One approach that can aid susceptible populations is the provision of warnings and health advice. This should be practical advice. Advising all those with known cardiovascular disease to avoid exposure to urban air pollution is impractical, but advising patients with asthma to consider increasing medication when levels of pollutants are high is possible. Communications research is needed to devise better ways of transmitting health advisories to ensure that messages are accepted.

All control strategies should be carefully evaluated. This can be done by modeling as long as good inventories on sources of pollutants are available. Developing such inventories is an essential part of developing an air pollutant control strategy.

The role of cost-benefit evaluation in policy development is accepted in many countries. This approach becomes especially important as levels of air pollutants fall and further reductions become expensive and, perhaps, are resisted by some stakeholders. When levels of pollutants are high, public concern about adverse effects may be such that detailed cost-benefit assessments are not needed. When, on the other hand, levels are low and effects, albeit considerable, can only be detected by sophisticated epidemiological techniques, clearer justification in terms of health gain relative to air pollution control costs will be needed. Development of better techniques for assessing the value that people place on reducing risks to health posed by air pollution should also be a research priority.

Recent developments in the fields of environmental justice and equity should be taken into account in policy development. It remains a fact that the poor experience a poorer environment than the rich. Unless impacts are very carefully analyzed, it may be that well-intentioned policies to reduce levels of air pollutants may widen this rich-poor gap. Air pollution control policies may have wide-ranging effects, which need to be studied carefully and fully. For example, raising personal transport costs by increasing the cost of motoring may have only a small effect on the lifestyle of people living in cities, but could have a profound effect on people in rural areas. The need for strategic rather than tactical thinking in the field of environmental policy development is clear.

INVOLVING INTERESTED AND AFFECTED PARTIES

Recent paradigms for health risk management (Jardine et al., 2002), including the framework for risk assessment and risk management developed by the U.S. Presidential/Congressional Commission on Environmental Health Risk Assessment and Risk Management (1997), have emphasized the need for effective risk communication among all stakeholders and the involvement of interested and affected parties in the risk management decision-making process. Stakeholder participation can serve to enrich decision making through broader input and consultation on both scientific and policy issues, build trust and foster an open transparent decision making process, and increase acceptance of risk management policy decisions. The involvement of interested and affected parties is in fact an integral component of the strategic options process mandated by the Canadian Environmental Protection Act to develop risk management programs for toxic substances on the Priority Substances List (Armstrong & Newhook, 1992).

Specific approaches that may be used to engage interested and affected parties in risk management decision making include the following:

- Application of a comprehensive framework for risk management decision making that includes provision for stakeholder involvement at all stages.
- Broad consultation on both scientific assessments of risk and on options for managing such risks.
- Community involvement in environmental health risk management.

• Public education to better inform individuals about the basis for both risk assessment and risk management.

Research to identify best practice in effective engagement of stakeholders in decision making at the community, provincial, and federal levels would complement and strengthen the practical application of frameworks for environmental risk management.

Public health professionals in Ontario have recently criticized the effectiveness of the provincial Air Quality Index as a tool for communicating the health risks associated with poor air quality (Toronto Public Health, 2001). There is a need for ongoing assessment of the findings of current health effects research to improve the development of smog warning systems and the content of public health messages to reduce risk, particularly for susceptible populations.

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