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Vulnerability to air pollution health effects

Anna Makri[a,*], Nikolaos I. Stilianakis[a,b]

[a]*Joint Research Centre, European Commission, Ispra (Va), Italy*
[b]*Department of Biometry and Epidemiology, University of Erlangen-Nuremberg, Erlangen, Germany*

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Abstract

Introduction: Ambient air pollution can have adverse effects on the health of exposed populations, but individuals or groups are not equally vulnerable, and pollution reduction benefits are likely to be unevenly distributed within a population. While the use of total-population risks is a valid approach for public health protection, it is increasingly recognized that more attention on vulnerable groups is necessary. This paper describes population vulnerability to the health effects of air pollutants using risk analysis concepts and based on available evidence.

Methods: Publications reporting air pollution health risks for specific sub-populations, or more conceptual discussions of vulnerability, were selected following a literature search of the PubMed database. Only studies in the context of developed countries were included. Information on population characteristics and factors that can influence risk was assessed from the perspective of the vulnerability framework, and was used to outline interactions with biological susceptibility, exposure, and social coping.

Results: Population characteristics encompass several factors that interact and confer vulnerability. Age, for example, regarded as significant mostly in terms of physiology, also relates to exposure through behaviours and activities that can be more amenable to prevention. Children are recognized as a high-risk group but their vulnerability may differ by childhood stage, while pregnant women are not explicitly identified as a vulnerable group despite growing evidence for reproductive risks. Social–economic factors have received little attention, although they can affect coping capacity as well as interact with susceptibility and exposure to air pollution.

Conclusions: Evidence for vulnerability components often lies in different fields of study and has not been evaluated in an integrated manner. Better understanding of population vulnerability can improve the scientific basis to assess risks and develop policies or other health protection initiatives to reduce the impacts of air pollution.

Keywords: Vulnerability; Vulnerable populations; Risk analysis; Air pollution; Health policy

Introduction

Epidemiological studies have established the link between ambient air pollutants and health effects. Time-series analyses conducted in large cities in the United States found associations between variations in daily deaths and air pollution levels in days prior (immediate mortality) (Atkinson et al., 2001; Brunekreef

*Corresponding author. Forum for Global Health Protection, 61 Old Street, London EC1V 9HW, UK. Tel.: +44 20 7251 0012; fax: +44 20 7253 8193.
E-mail address: anita@fghp.org (A. Makri).

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and Holgate, 2002; Dockery and Pope, 1994; Samet et al., 2000a, b). Cohort studies (and their re-analyses) of annual average particulate matter exposure and age-specific death rates in various cities and regions strengthened the evidence-base for these associations (Dockery et al., 1993; Krewski et al., 2000; Pope et al., 1995, 2002). They also showed that risks are likely to increase with longer exposures, particularly with respect to cardiovascular mortality (Brunekreef and Holgate, 2002). Studies conducted in Europe have supported these findings (Aga et al., 2003; Hoek et al., 2002; Katsouyanni et al., 1997, 2001; Nafstad et al., 2004; Touloumi et al., 1997). In addition to the effect on mortality, studies have documented that outdoor air pollution can lead to greater morbidity (indicated by higher disease incidence, more use of health services, restricted activity), lower life expectancy and greater disease severity (Kappos et al., 2004).

Evidence linking exposure to air pollutants and mortality supports a no-threshold assumption, i.e., a linear concentration–response relationship. Assuming linearity, a very small change in ambient pollution levels can have substantial impacts on large populations, even if that change is associated with only a small increase in risk, since virtually all members of the population are exposed. This is more pronounced when morbidity outcomes are considered, since they affect more people compared to mortality. In addition to the number of those affected, it is important to consider their characteristics: health impacts may be greater for individuals and groups that are more susceptible, more exposed, or otherwise more vulnerable. As a result of vulnerability differences, a change in exposure may have substantial effects on a portion of the population even if the overall change in risk is small, and reduction of pollution levels may lead to especially pronounced health benefits in population groups with highest vulnerability.

The risk or severity of health outcomes associated with exposure to ambient air pollution is not uniform within populations. One way of evaluating differential risks is to derive health effect estimates for a number of defined end points and population strata. Epidemiologic studies often consider different outcomes, age groups or underlying health conditions, as well as socio-economic factors. Similarly, exposure assessments examine population differences in behaviours, activities, and the environment. These factors have not been explored together as inter-related population factors that influence vulnerability.

Air pollution vulnerability factors and population groups

Factors and population groups associated with vulnerability to the effects of air pollutants have been described in different ways. The World Health Organization specifies vulnerable population groups based on innate factors, acquired environmental, social or behavioural factors, and unusually high exposures (WHO, 2004). This conceptualization represents a broad view of vulnerability, and explicitly differentiates between innate and acquired characteristics. However, acquired factors can also be biological in nature, as is the case with pre-existing diseases: both age and underlying diseases are associated with physiological capacity to cope with air pollution but the former is an innate (or intrinsic) factor while the latter is acquired (or extrinsic). Also, both intrinsic and acquired factors could influence the level of exposure, in addition to the physiological capacity to respond. For instance, unusually high exposures to ambient air pollutants may arise from behaviours associated with age (intrinsic factor), and/or co-exposures associated with occupation (acquired factor), and/or housing characteristics associated with social–economic position (acquired factor).

Sub-populations considered by the WHO as vulnerable to air pollution include – in addition to young children, elderly, and persons with certain underlying diseases – foetuses, those exposed to other toxicants that add to or interact with air pollutants, and the socio-economically deprived (WHO, 2004). Furthermore, Bell et al. (2002) identify as potentially vulnerable those exposed occupationally, ethnic and economic groups with high prevalence of chronic disease, as well as genders with differing exposure and/or responses to air pollution. Host factors, mostly age and underlying disease, have often been used to define susceptible populations in epidemiological and other studies of air pollution health impacts. Studies have also considered the effect of other, mostly exposure-related factors such as outdoor activity, residential location, and socio-economic status.

Specific aims

This paper identifies and evaluates information on population characteristics associated with vulnerability to ambient air pollution from a risk analysis perspective, based on available literature sources. It underscores the potential value in developing a better understanding of interactions between vulnerability components, and briefly discusses the relevance of this approach with regard to policy and practice.

Materials and methods

Using risk analysis concepts, population characteristics and factors associated with vulnerability to health effects of ambient air pollution exposure were identified and described by bringing together relevant information from different sources and disciplines. Literature searches were performed, using the PubMed database to identify studies reporting air pollution health risks for specific sub-populations. Peer-reviewed articles, and reports from the World Health Organization or research institutions performing active research in the area of health effects of air pollution were included in the study if they presented epidemiologic, exposure, risk, or health impact assessments for specific sub-populations. Publications that have conceptually addressed issues related to vulnerable populations or vulnerability were also taken into account. Studies referring to air pollution risks in developing countries were excluded given significant differences in the social and institutional context, and often in air pollution levels. The search was conducted in the year 2005, and publications available up to that time were included.

We focused on the risk-specific information contained in the selected publications. This information was organized according to the components of the vulnerability framework, and informed more general discussions of the issue.

The working definition of vulnerability encompasses susceptibility, exposure and social coping as described below. In this context, exposure relates to factors that modulate human exposure and dose, rather than physical attributes of environmental pollutant concentrations. Social coping specifically refers to how conditions in the social environment affect susceptibility, exposure, and the capacity to manage risks and potential health outcomes.

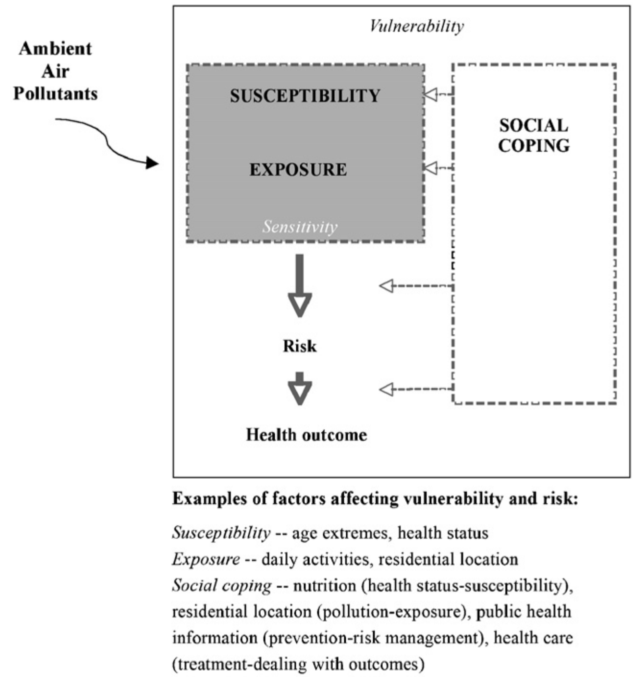

Fig. 1. Concept and components of population vulnerability to ambient air pollution.

Vulnerability and risk analysis

The risk analysis framework refers to a set of analytical concepts used to guide evaluation of a given risk from specified exposures. According to the definition put forth by the US National Academy of Sciences in 1983 (NRC, 1983), the core components of this paradigm are hazard identification, dose–response assessment, exposure assessment, and risk characterization. This has been modified to account for differences between the agents assessed (e.g. chemical vs. microbial risks), and increasingly risk communication is becoming an integral part of the process.

From this perspective, risks can be understood as a product of exposure and vulnerability – the human capacity to be harmed by or to cope with exposure. Coping is influenced by biological, social, political, or other factors; these factors may, however, also influence exposure. Thus vulnerability encompasses characteristics that can modify the level of risk by influencing both the exposure and the capacity to cope with it (Kasperson and Kasperson, 2001). These relationships are illustrated in Fig. 1.

In addition to vulnerability, the terms susceptibility or sensitivity are often used to communicate the notion that individuals differ in their capacity to experience effects from an exposure. These are defined differently depending on the discipline (Parkin and Balbus, 2000). Susceptibility can communicate the absence of immunity to an infectious agent, a genetic predisposition to disease, or a relatively higher probability of being affected by a toxic agent. Similarly, sensitivity can refer to a relatively higher response to a stimulus. In the context of health risk assessment, sensitive persons or groups are identified by their response to lower doses of an agent, a higher likelihood of manifesting adverse effects at a given dose, or greater severity of outcomes at a given dose. For example, Hattis et al. (2001) have characterized population variability in the sensitivity to air pollutants by estimating that susceptible individuals may respond to lower doses of particulate matter than the average person in a population.

Here, specific definitions are attached to these terms, building from biological aspects of the concept up to the social–economic and institutional environment (Kasperson and Kasperson, 2001; Charnley and Putzrath, 2001; Parkin and Balbus, 2000). Susceptibility relates to intrinsic or acquired factors that influence biological coping capacity (e.g. age, underlying disease). Sensitivity refers to both biological factors and factors that influence exposure (e.g. activity patterns). The overall concept of vulnerability encompasses factors that influence the social–economic–institutional environment (e.g. health care access), in addition to those related to biology and exposure.

These concepts articulate the premise that health impacts of air pollution may be greater for people who are biologically susceptible; exposed to higher pollutant concentrations or doses; and/or socially disadvantaged in ways that influence risk determinants and management options. A number of population characteristics relate to these vulnerability components. For instance, underlying disease can increase susceptibility and commuting can influence exposure, while low socio-economic status may be associated with residence in high-exposure areas and/or limited access to health services for disease prevention. A single population characteristic might influence more than one vulnerability component; for instance, age could affect both susceptibility and exposure through underlying disease and activity patterns, respectively. Also, population characteristics may interact (e.g. age and underlying disease), or their effects on vulnerability may be indirect (e.g. effect of inadequate health care on susceptibility mediated by poor health status).

Results

Populations associated with differential biological capacity to respond to air pollution exposure are foetuses and children, the elderly, and persons with pre-existing diseases. Higher risks have been shown for these groups. Differential risks for women and men are less clear, although evidence on reproductive and birth outcomes point to pregnant women as a susceptible group that has not been explicitly identified. In addition, epidemiologic evidence of higher risks for racial minorities and social–economically disadvantaged populations may be party related to physiological capacity due to pre-existing diseases as well as health status. Health status can be affected by nutrition, co-exposures and access to health care or other services.

Populations associated with differential exposure to ambient air pollution include commuters, residents of areas with high traffic or other pollution sources, and children and workers active in outdoor environments. Exposure is also influenced by domestic activities, housing quality, workplace co-exposures, heavy physical activity, or generally time spent outdoors. There is a higher likelihood that women cook and clean, socio-economically deprived persons live in poor housing and have high-exposure jobs, the elderly spend most of their time indoors, newborns and infants spend more time indoors and adolescents outdoors.

Socio-economically disadvantaged populations are often identified based on income or education – attributes that reflect more than one pathway to potentially higher health risk. For instance, low income can limit ability to minimize exposure (e.g. housing location and quality, air conditioning) or to cope with disease (e.g. access to health care, preventive and social services), while low education may be associated with behaviours that can increase susceptibility and risk (e.g. poor nutrition, indoor pollution). Social–economic status may also reflect differences in risk management options and social infrastructure, such as availability of public health information or air conditioning.

Susceptibility

The definition of susceptible populations can vary depending on characteristics of the exposure (type, timing) and health effect (type, latency, long- or short-term) (Künzli, 2005; Levy et al., 2002; Pope, 2000). Populations may be affected in ways not immediately life threatening, or severe enough to be readily observed and reported. Symptoms may be short-term, small, transient and/or reversible, yet with potentially long-term implications – especially if the exposure is continuous or repetitious.

Much of the information available from epidemiological studies relates to short-term exposure, and indicates that health effects are not limited to the advancement of death by a few days for old and frail populations (“harvesting”). In addition to the elderly, young children and persons with pre-existing diseases are known to be at higher risk from air-pollution-related health effects. Acute high exposures can also lead to morbidity and less severe symptoms that are likely to affect larger numbers and more diverse groups of people; they may also have wider implications such as absence from work or school (Pope, 2000).

Age: children and elderly

Studies of different air pollutants, exposure levels and locations suggest disproportionate health impacts for children (Kim, 2004; Schwartz, 2004; WHO, 2005). Health effects can be persistent and chronic, while exposure at certain ages may affect lung development or have additional consequences such as school absenteeism (Gauderman et al., 2004; Gilliland et al., 2001; WHO, 2005). Physiologic immaturity and developmental changes largely account for children’s differential susceptibility to air pollutants (Moya et al., 2004; WHO, 2005). Young children inhale more air per unit time and accounting for body weight, while the smaller surface area of their lung means that relatively more inspired air reaches the lung. Children’s airways are narrower compared to adults, and pulmonary function is immature until just before adulthood.

Exposure to ambient air pollutants can lead to earlier death and higher risks of death and disease for elderly populations mainly associated with cardiorespiratory health (Aga et al., 2003; Anderson et al., 2003; Filleul et al., 2004; Gouveia and Fletcher, 2000; Sandström et al., 2003). Old age is associated with several factors that can contribute to compromised physiological capacity to cope with air pollution such as biological effects of past exposures and weakened immune responses (Sandström et al., 2003). In addition, susceptibility for the elderly is largely attributed to a higher prevalence of underlying conditions, particularly cardiovascular and respiratory diseases.

Pre-existing diseases or health conditions

Several diseases have been associated with greater risks from air pollution, in particular cardiorespiratory diseases and more recently diabetes (Goldberg et al., 2006; Goodman et al., 2004; O'Neill et al., 2005; Zanobetti et al., 2003; Zanobetti and Schwartz, 2002). These affect physiological capacity to respond to exposure by compromising organ function and overall ability to maintain a stable body environment. Although mostly associated with advanced age, underlying conditions in children and adults, such as asthma, can also enhance susceptibility to air pollution (Gent et al., 2003; Kim, 2004; Künzli, 2005).

Gender

Epidemiological studies have found higher risks of respiratory symptoms for young women, and higher mortality rates for elderly women, but findings are limited and inconsistent (Boezen et al., 2005; Künzli et al., 2005). Evidence linking adverse reproductive outcomes and air pollution is accumulating and points to differential susceptibility for pregnant women. Exposure to air pollutants, notably particulate matter, is associated with mortality in infancy (from respiratory causes and sudden infant death syndrome), and there is evidence for birth weight reduction effects (Kim, 2004; Sram et al., 2005; WHO, 2005).

Other characteristics (genetics, race, and nutrition)

Human responses to air pollution vary within and across populations partly due to individual genetic background, but relationships between exposure and genetic factors are complex and not well understood (Kleeberger, 2005).

Studies have found relationships between racial background and higher risk of air pollution-associated mortality and morbidity (Gwynn and Thurston, 2001; O'Neill et al., 2003).

Indications that a diet rich in fish and fresh fruit could have a protective effect on lung function need confirmation to clarify the relationship between nutrition and population risk to ambient air pollution (Schwartz and Weiss, 1994a, b).

Exposure

Exposure to air pollutants is typically assessed by assigning monitoring data to individuals or populations in an area of interest, assuming that they are equally exposed. However, personal exposure varies depending on several factors including time spent in different environments (e.g. home, outdoors), daily movements or activities (e.g. commuting, work), lifestyle or behaviours (e.g. smoking, exercise) (USEPA, 2004). Thus, time–activity patterns as well as individual (or population) characteristics are important to consider. Low socio-economic status, education, and occupation have been associated with differential exposures at home and at work, while behaviours and traits associated with age or gender can also influence exposure.

Studies have shown that variations in population activity, in time or in relation to other factors (e.g. microenvironments, pollution sources) are important to consider in exposure assessment. Relationships between outdoor and personal exposure can differ by pollutant as well as by population group. Exposure patterns also depend on season, time spent outdoors, indoor exposures, or housing characteristics including ventilation and particle infiltration efficiency (USEPA, 2004; Sarnat et al., 2001).

Time–activity patterns

Urban dwellers, traffic workers and people of low socio-economic class living in "down-market" residential areas near busy in-city highways may be exposed to high air pollution levels, with associated effects on their health (Finkelstein et al., 2004, 2005; Gunier et al., 2003). Heavy traffic near residential and school areas has also been linked with respiratory health in children (Ciccone et al., 1998; Kim et al., 2004).

Commuting in heavy traffic is an important factor influencing exposure, as are the location and quality of micro-environments in residence, work, school, or care centres. Exposure to traffic-related air pollutants has been associated with respiratory health in adults and children (Bayer-Oglesby et al., 2006; Ciccone et al., 1998; Heinrich et al., 2005; Janssen et al., 2003; Ryan et al., 2005). Transport-related health effects have been documented in detail in a review by the World Health Organization (Krzyzanowski et al., 2005). Indoor activities and pollution sources can also contribute significantly to population exposure (Monn, 2001). Notably, cigarette smoke interacts with air pollution to increase mortality risks from certain circulatory diseases (Brook et al., 2004).

Individual or population characteristics

Socio-economic conditions contribute to poor health partly by being associated with atypically high exposures, where transport and place of residence or work are important factors (O'Neill et al., 2003). Educational attainment is a significant modifier of the relationship between air pollution exposure and health risk, which likely relates to differential exposure as well as health status (Hoek et al., 2002; Krewski et al., 2000; Pope et al., 2002).

Age can affect air pollution exposure in addition to susceptibility. Depending on developmental stage, children's stature, behaviours, activities, and time spent in different environments (home, school, and outdoors) could lead to exposure that differs from adults (Makri et al., 2004; Moya et al., 2004). For the elderly, confinement to indoor environments may decrease exposure to ambient air pollutants, although living alone may also lead to elevated risk (Filleul et al., 2004).

Exposure may differ by gender quantitatively and qualitatively. There is some evidence of higher personal exposure to fine particulates for men (Rotko et al., 2000). Women often spend more time in and around the home, engaging in domestic activities (e.g. cleaning/dusting, cooking) that can contribute to differential exposure (Künzli et al., 2005). The time spent commuting as well as the location and nature of work may also differ between men and women.

Social coping

Social coping refers to factors, associated with social–economic conditions, which influence exposure, susceptibility, and the capacity for managing risks and health outcomes. Social–economic conditions are described by complex variables that reflect inequalities in the physical environment (e.g. high pollution levels), the service environment (e.g. poor health care access), and the social environment (e.g. welfare systems), including political and economic conditions (O'Neill et al., 2003). These can apply to both the individual and area/neighbourhood/population level (e.g. behaviours vs. location of residence), each having an independent effect on health (Künzli, 2005; O'Neill et al., 2003). However, the correlations between these variables make their contribution to health risk difficult to evaluate.

Positive relationships were found between income or inequalities and air-pollution-related health outcomes (Finkelstein et al., 2003, 2005; Jerrett et al., 2004; Wheeler and Ben-Shlomo, 2005). Studies of particulate matter exposure suggest that the poorly educated, racial minorities, and other socially disadvantaged populations have a disproportionate share of mortality and morbidity (Lipfert, 2004). Family status, occupational exposure, and confinement may also modify the relationship between exposure to certain pollutants and health outcomes (Filleul et al., 2004; Rotko et al., 2000).

Exposure

Low-income populations often live under conditions likely to elevate personal exposure to air pollutants – notably in areas with high pollution and housing of low quality. Poor housing offers little protection from indoor infiltration of ambient pollution, extreme temperatures, or allergens (Lipfert, 2004). Certain types of work (e.g. in traffic or construction) may lead to higher exposure, with a potential for cumulative effects of work and ambient exposure (Filleul et al., 2004; Rotko et al., 2000).

Susceptibility

Disadvantaged populations tend to have a higher prevalence of diseases that predispose to or can be exacerbated by air pollution (e.g. cardiovascular diseases and asthma, respectively), linked with availability and access to health services, education, lifestyle and behavioural factors, or work-related exposures (Lipfert, 2004; O'Neill et al., 2003; Samet and White, 2004). For instance, adequate medication to alleviate symptoms and avoid aggravation of pre-existing health conditions depends on availability of and access to health care. Smoking is more common among persons of low social–economic status.

Risk and health management

Often overlooked in assessments of air pollution health impact are risk mitigation behaviours and management options, which are influenced by conditions in the social–economic and institutional environment. These might include availability of health care, central air conditioning, or public information about pollution levels and the associated health effects (Bell et al., 2002; Lipfert, 2004). Availability of and access to such options are often poor for populations with low income, unemployment, or dependence on social services. Social–economic disadvantage may, for example, reflect low capacity to avoid high air pollution exposures, assuming that residential proximity to high-traffic or other high-exposure locations is avoided by whoever can afford it (Künzli, 2005; O'Neill et al., 2003). Ability to utilize available resources may also be limited by the level of education.

Availability of risk management options and coping behaviours depends on social infrastructure as well as income and education. For instance, urban planning and traffic density near residential areas can hinder communication and collaboration among neighbours, which limits social networks important for diversifying management options and for building political power (Bell et al., 2002). This can be critical for the elderly who often live alone and are dependent on easy access to services. Risk perception and health management practices, such as illness diagnosis and treatment, may

Table 1. Vulnerability components, population characteristics and factors, high-risk groups identified from the literature

Vulnerability component	Population characteristics and associated factors that contribute to vulnerability				
	Age	Disease or poor health status	Gender	Time–activity patterns	Social–economic conditions
Susceptibility	Physiological immaturity Physiological effects of ageing Pre-existing diseases Nutrition	Compromised organ functions Diminished ability to maintain homeostasis	Physiological differences Pregnancy		Health and other services Nutrition Work Smoking
Exposure	Mobility, confinement Height Exploratory behaviours and playing Outdoor and indoor activities		Outdoor and indoor activities Domestic activities Work	Outdoor and indoor activities Transport Residential location Housing quality Work	Transport Residential location Housing quality Work Smoking
Social coping	Isolation Dependence on caregivers		Risk perception Health management practices		Risk management options Health and other services Public information and health education Social networks Risk mitigating technologies
Population groups identified in literature					
	Children: fetuses, infants – adolescents Elderly	Elderly Children Young adults Socio-economically deprived persons	Pregnant women Young women	Commuters Residents near high-traffic areas Children Young adults Persons physically active outdoors Workers – traffic, blue collar	Poor and low-income persons Poorly educated persons Elderly and other socially isolated persons Racial and ethnic minorities

also differ by social–economic status or other population characteristics.

Table 1 summarizes relationships between population characteristics and associated factors that contribute to vulnerability, with population groups for which evidence of differential risks is available. It illustrates contributions of different vulnerability components to potentially higher risks from air pollution exposure, depending on population characteristics and the factors associated with them. Representing their inter-relationships systematically, as shown here, can help in evaluating the relative influence of vulnerability factors on population health risk. For example, to evaluate vulnerability for a population of children, the effects of age, as well as time–activity patterns and perhaps social–economic conditions could be considered (columns) – where for each, factors across any of the three vulnerability components may be relevant (rows).

Interaction effects between vulnerability factors will be important to consider. For example, stress associated with low socio-economic position could affect biological functions and increase susceptibility. Such a pathway is, however, difficult to isolate without studies specifically designed to disaggregate socio-economic contributors to risk differences. In the case of transport-related pollution, although commuters are highly exposed, they may also be less vulnerable than persons spending much of their time indoors due to factors related to age (e.g. biological function, mobility), health status, or social–economic position (e.g. illness, unemployment). In a less obvious example, good health care could translate to a higher proportion of frail individuals (Bell et al., 2002); this may change the vulnerability profile of a population. However, a lack of access to adequate health services may also modify the exposure–effect relationship for various sub-populations through deterioration of the underlying health status. Given the multiple potential inter-relationships, assessments targeted at particular locations or populations using empirical information are needed. Local, small-scale data can be useful in their capacity to reveal important population differences (Lipfert, 2004).

Although detailed information on differences in exposure and susceptibility is limited, this report provides a broad basis and a starting point for future work on population vulnerability to ambient air pollution.

Discussion

This paper presents an assessment of available information on vulnerability and ambient air pollution using the risk framework. Individuals and population groups can be differentially vulnerable to the health effects of air pollution due to differences in biological characteristics, time spent on daily activities, and/or social–economic conditions.

A single population characteristic, such as age, encompasses several factors (e.g. physiology, behaviour) that relate to more than one aspect of vulnerability. For example, persons at age extremes can be more susceptible due to differences in physiological capacity and differentially exposed to certain pollutants due to activity patterns. Similarly, a single population group may be vulnerable due to any number of factors. In the case of elderly persons, vulnerability might depend on their health status (differential susceptibility due to ageing and pre-existing diseases) and/or daily activities (differential exposure due to limited mobility) and/or access to care (differential social coping capacity due to dependence on caregivers).

Epidemiological studies have evaluated differential risk for biologically susceptible populations primarily, and to a lesser extent for the socio-economically deprived. Taking the example of the elderly, higher risks for this population are well documented. The importance of ageing as a susceptibility factor is known and age can be easily defined for quantitative study, while some investigations have also considered underlying diseases and their effect on risk for this population. However, the relationship between advanced age and differential risk encompasses pathways of vulnerability that include exposure and social factors in addition to physiology. Although more difficult to define, these components can be more amenable to prevention. The elderly may be differentially vulnerable mostly due to ageing and disease, but it remains crucial to prevent exposure episodes that heighten physiological stress, and to improve access to services for better management of their health. Resources can then be directed towards measures such as improving management of chronic diseases, minimizing high pollution levels and exposure opportunities at nursing home facilities, or reducing local pollution.

Similarly, risk differences are often identified for children but physiological immaturity is only one explanatory factor – an intrinsic characteristic that provides few options for prevention. Instead, the influence of behaviours and activities at different developmental stages, quality of school and home environments, or commuting to and from school could also account for differential risks and point towards options for intervention. Strategies for reducing risk might include improvement of air quality in school environments, child-focused information dissemination and behaviour change initiatives, or other measures specifically designed to reach children. Likewise, although reproductive risks are usually discussed from the perspective of effects on children, a focus on pregnant women may be more relevant with respect to prevention.

Overall, risk management efforts can be informed by characteristics of specific populations, and may require a combination of strategies informed by comprehensive evaluation of factors that contribute to their vulnerability.

Implications for policy and practice

Vulnerability concepts could be used to support or expand the set of available interventions to reduce air pollution health risks. Emission control and abatement strategies have reduced ambient concentrations and peak episodes of air pollution in Europe, but the increasing costs and resources needed for further pollution reductions are raising questions about whether to aim for providing protection to every citizen. As an alternative, policies that focus resource allocation and risk reduction measures on specific populations may be more efficient. A case study using data for the Washington, DC area has demonstrated that considering potentially vulnerable groups in assessments of risk can provide insight into how air pollution reduction benefits are distributed within a population, demographically and geographically (Levy et al., 2002).

The potential benefits of using information on factors that contribute to vulnerability extend beyond cost effectiveness, by pointing towards pathways of influence useful to consider in designing policies to complement emission reductions. The assessment of vulnerability can be developed as a tool for guiding decision making and priority setting. Considering characteristics and factors for this purpose, rather than pre-defined populations, is advantageous as it avoids discrimination issues and allows different populations to be targeted depending on pollutants and contextual factors in a particular region or situation. With geographic or health impact analysis, vulnerability factors can also be evaluated at the regional level or for a specific population. Better understanding of vulnerability could also be used to provide needed information about specific populations to patient support organizations and health professionals.

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