Ambient air pollution and health

Klea Katsouyanni

Department of Hygiene and Epidemiology, University of Athens Medical School, Athens, Greece

The adverse health effects of air pollution became widely acknowledged after severe pollution episodes occurred in Europe and North America before the 1960s. In these areas, pollutant levels have decreased. During the last 15 years, however, consistent results, mainly from epidemiological studies, have provided evidence that current air pollutant levels have been associated with adverse long- and short-term health effects, including an increase in mortality. These effects have been better studied for ambient particle concentrations but there is also substantial evidence concerning gaseous pollutants such as ozone, NO₂ and CO. Attempts to estimate the impact of air pollution effects on health in terms of the attributable number of events indicate that the ubiquitous nature of the exposure results in a considerable public health burden from relatively weak relative risks.

Introduction

Anthropogenic air pollution (i.e. that superimposed on the background of natural pollution originating from plants, radiological decomposition, forest fires, volcanic eruptions, etc.) has existed since people learned how to use fire, but has increased rapidly with industrialization.

The well known and severe air pollution episodes in Europe and North America before 1960 provided indisputable evidence that those high levels of air pollution can have very important adverse health effects, including a significant increase in mortality. Since then, legal and other corrective measures have contributed to a reduction in air pollutant concentrations, especially of black smoke (an index of ambient particles) and sulphur dioxide (SO₂), to moderate or low levels in many, though not all, the areas traditionally affected by air pollution. Until the mid 1980s, it was generally thought that ambient pollution levels in Europe did not threaten human health. However, results from epidemiological studies during the last 15 years have consistently shown that moderate and low concentrations of traditional pollutants such as ambient particles can have both short- and long-term effects on health. Furthermore, in Europe and elsewhere, a change in the emission sources (with vehicles increasingly becoming the most important source in many areas) has
contributed to changes in the air pollution mixture, which is now characterized by high concentrations of nitrogen oxides and photochemical oxidants. Today we are less concerned with very severe air pollution episodes but much more with the consequences of acute and chronic air pollution exposure for excess respiratory and cardiovascular morbidity and mortality.

Clean air is considered to be a basic requirement for human health and well-being. Individual and population exposure to air pollution is caused by both indoor and outdoor sources. Although the components of indoor and outdoor pollution may be the same, and the exposure-response relationship is not affected by the source of a specific pollutant, outdoor and indoor sources can usefully be treated separately as they are determined by different factors and require different management policies. The focus in this chapter is on outdoor (ambient) air pollution; indoor air pollution is discussed in Chapter 11. At the same time, it needs to be noted that, whilst ambient air pollution exposure occurs outdoors, it also penetrates indoors, at a rate which depends on the nature of a particular pollutant. The involuntary and ubiquitous nature of the exposure results in a considerable public health burden of relatively weak adverse health effects.

The air pollutants routinely measured by most organized monitoring systems include various indicators of ambient particle concentrations and gases. Addressing the problem by pollutant is in many ways inadequate since, in the real world, individuals are exposed to mixtures of pollutants which may act in combination or synergistically. The study of mixtures of air pollutants is, however, extremely complex and as yet in its infancy. This chapter will therefore focus on particles and gases, which are most relevant for health according to current scientific knowledge.

**Ambient particles**

**Measurement, sources, distribution and relevant components of the particle mix**

Ambient particles are a mixture with various physical and chemical characteristics. Relevant, interrelated, physical characteristics of particles are size, surface and number. Possibly relevant chemical characteristics include the content of transition metals, crustal material, polycyclic aromatic hydrocarbons, carbonaceous material, sulphates and nitrates. Their concentrations may thus be measured using a wide range of different indices. The traditional ambient particle indicator in Europe has been Black Smoke (BS), measured by reflectometry, representing black particles of aerodynamic diameter <4 µm. The reflectometry units are typically transformed to mass using a calibration curve (the OECD curve).
Widespread monitoring has also been made of total particle mass (TSP) concentration. This is dominated by large particles outside the respirable range, thought today not to be so relevant for health. The US EPA in 1979 defined PM$_{10}$ (particles with diameter <10 µm) as the ambient particle indicator to be used for regulatory purposes and in 2000 added PM$_{2.5}$ (those with diameter <2.5 µm). The airborne particle mix in each location has different chemical and physical characteristics and depends on the range of sources and their proportional contribution to the mix.

Particles derived from combustion sources (vehicles, power plants, etc.) are generally smaller whilst those coming from abrasion (road dust, wind blown soil) are often larger. Until recently, all regulations have been based on the particle mass per unit volume. Nevertheless, the number of particles (and surface area) to mass ratio increases with decreasing size, and it seems that number of particles may also be relevant to health effects. The particle mix is composed of primary particles (which are emitted) and secondary particles, such as sulphates and nitrates, which are formed in the atmosphere.

Smaller particles tend to be remarkably homogeneously spread over large areas, penetrate effectively indoors and consist to a larger extent of primary and secondary combustion products (containing elemental carbon and PAHs, sulphates and nitrates).

Although there are some results indicating that particular components of the particle mix are responsible for specific health outcomes, the existing evidence is still limited (see below).

**Current guidelines and regulations for ambient particles**

The current WHO air quality guidelines for Europe accept that available information does not allow a judgment of concentrations below which no effects are to be expected. Thus, only concentration–response tables for acute health effects are provided, based on studies mainly using PM$_{10}$ and a few using PM$_{2.5}$ as the particle indicator, and relative risks of long-term effects. No guideline values are recommended and risk managers are referred to the risk estimates provided.

The European Union adopted a general framework Directive for air pollution in 1996 and a daughter directive, including ambient particulate matter regulations in 1999. The standards adopted can be summarized as follows:

- for the 24 h levels, 50 µg/m$^3$ of PM$_{10}$ should not be exceeded more than 35 times per year by 2005 and more than seven times per year by 2010;
- for the annual levels, 40 and 20 µg/m$^3$ should not be exceeded by the years 2005 and 2010, respectively.
There is a planned review of this regulation currently on-going which should result in a decision about any need for revision during 2003.

The US EPA has adopted standards for PM$_{10}$ (not to exceed 150 µg/m$^3$ on a 24-h basis and 50 µg/m$^3$ on an annual basis) complemented by standards for PM$_{2.5}$ (not to exceed 65 µg/m$^3$ on a 24-h basis and 15 µg/m$^3$ on annual basis). These are also currently under the process of a review based on new scientific evidence$^{11}$.

In European cities, the mean annual levels of PM$_{10}$ in the 1990s ranged between 14 and approximately 65 µg/m$^3$, whilst black smoke levels ranged between 10 and 65 µg/m$^3$. In several cities, the level of 50 µg/m$^3$ is exceeded for more than 35 days per year$^{12}$.

**Health effects of ambient particle concentrations**

**Short-term (acute) effects**

The short-term effects of particles have been the main focus for study, especially in time-series studies, in several locations throughout the world. Acute effects are well established for total non-accidental, respiratory, cardiopulmonary and cardiac daily mortality, as well as respiratory hospital admissions$^{2}$. There is also evidence of acute effects on respiratory function, lower respiratory symptoms and increased medication use by asthmatic subjects$^{2}$.

Typically, effect estimates are given as an increase in the health outcome associated with a 10 µg/m$^3$ increase in particle concentrations. There is, however, heterogeneity in the effect estimates reported from different studies. In the WHO guidelines, based on studies until 1994, an increase of 0.74% (95% CI 0.62–0.86%) is reported for the daily total number of deaths and 0.80% (95% CI 0.48–1.12%) for the daily hospital respiratory admissions. More recently, two large multi-city studies, the European APHEA (Air Pollution and Health: a European Approach)$^{13}$, and the US NMMAPS (National Mortality, Morbidity and Air Pollution Study)$^{14}$, have provided estimates based on 29 and 20 cities, respectively. The APHEA estimate for the daily total number of deaths is 0.6% (95% CI 0.4–0.8%) and the NMMMAPS estimate 0.5% (95% CI 0.1–0.9%). Later estimates from NMMAPS were 0.4% based on 90 cities$^{15}$. After problems were discovered with the software used in the original analyses, these estimates were recalculated, using different modelling methods$^{16}$. This gave a revised estimate of 0.2% (still statistically significant) for the 90 cities in NMMAPS. The optimal model to be used to control for confounding effects is still not clear. The US EPA has organized a workshop where several sensitivity analyses have been presented and a report published$^{17}$. It appears that the above reported estimates cover the extremes of likely effects. For hospital admissions, the reported increase
in COPD and asthma admissions for the elderly from the APHEA study\textsuperscript{18} is 1.0\% (95\% CI 0.4–1.5\%) and from the NMMAPS study\textsuperscript{15} 1.5\% (95\% CI 1.0–1.9\%).

It is clear that the above health effects concern to a larger extent the more sensitive population subgroups, but the specific characteristics of these subgroups have not been exactly identified. There is evidence that the socially deprived, the elderly and persons with pre-existing respiratory or cardiac disease or diabetes are more susceptible to the health effects of air pollution\textsuperscript{19–21}. It is also apparent that the acute effects of air pollution do not represent only short-term harvesting: analyses using distributed lag models have indicated that the effects persist over a longer period of time (>1.5 month) and the extent of mortality displacement may be considerable, depending on the cause of death\textsuperscript{22,23}.

**Long-term effects**

Long-term effects of chronic exposure to ambient particle concentrations have been studied less. The results and calculations of attributable risks and years of life-lost have largely been based on two US cohort studies\textsuperscript{24,25}. Relative risk estimates for total mortality reported from Dockery et al\textsuperscript{24}, per 10 $\mu$g/m$^3$ in long-term average pollutant concentration, were 1.10 for PM$_{10}$, 1.14 for PM$_{2.5}$ and 1.33 for sulphates. Corresponding estimates from Pope et al\textsuperscript{25} were 1.07 for PM$_{2.5}$ and 1.08 for sulphates. Based on these studies, it has been calculated that the expected reduction in life expectancy from air pollution exposure is in the order of a few years\textsuperscript{26}. Recently, Pope published a further analysis of the ACS data and evidence from a European cohort study has provided consistent results\textsuperscript{27,28}. An estimate for three countries (Austria, France and Switzerland) using the effects reported from the US cohort studies concluded that about 6\% of the annual total mortality may be attributed to air pollution exposure\textsuperscript{29}, whilst in the WHO ‘Global Burden of Disease’ project about 1,000,000 premature deaths are attributed to high PM concentrations worldwide\textsuperscript{30}.

**Ozone**

**Measurement, sources and distribution**

Ozone is one of a range of photochemical oxidants which are formed as secondary pollutants by the action of solar radiation in the presence of primary pollutants, mainly nitrogen oxides and volatile organic compounds\textsuperscript{2}. Tropospheric ozone pollution should be distinguished from the problem of stratospheric ozone depletion, which is linked to global warming and risks of UV radiation. Because of its generation procedure, tropospheric ozone is a more important problem in the summertime and...
in areas with more prolonged sunshine. In the presence of precursor primary pollutants (especially NO), ozone is ‘scavenged’. As a result, low concentrations tend to occur in busy city centres, where NO concentrations are high, whilst higher concentrations are observed downwind in city suburbs to which ozone is transported but where NO and other precursor concentrations are relatively low. Thus the spatial distribution of ozone and resulting personal exposure patterns differ from those of other pollutants. Ozone measurements are often expressed as ppb or µg/m³ (1 ppb = 2 µg/m³ at 20°C).

**Regulations**

The WHO guidelines for ozone give a level of 120 µg/m³ for an 8-h average². The US EPA regulations¹¹ comprise an 8-h standard of 157 µg/m³ and a 1-h level of 235 µg/m³. The EU regulation for ozone for the protection of human health, still under consideration, is 120 µg/m³ for an 8-h average not to be exceeded for more than 20 days per year by the year 2010³¹. In several European cities, the 90th percentile of ozone 1-h concentrations currently exceeds 120 µg/m³ and the maximum³ reaches more than 200–300 µg/m³.

**Health effects**

Ozone, as a potent oxidant, may react with a variety of biomolecules⁴, potentially causing both short- and long-term effects. Its effects have been assessed in controlled exposure experiments as well as epidemiological studies. Short-term effects are better established. They include an increase in the daily total number of deaths, especially for the warm season, an increase in hospital respiratory admissions, increased respiratory symptoms, pulmonary function changes, increased airway responsiveness and airway inflammation. In the NMMAPS Study, a 0.5% increase in mortality associated with 20 µg/m³ (10 ppb) in the daily O₃ concentrations is reported during summertime¹⁵. The corresponding estimate from the APHEA project is a 2.9% increase in mortality associated with a 50 µg/m³ increase in daily ozone³². In a study from Montreal, Goldberg *et al* estimated a 3.3% increase in daily deaths in the warm season, associated with an increase of 21.3 µg/m³ in 3-day ozone concentration³³.

Experimental studies have mainly focused on acute exposures of up to a few hours. These show functional decrements in healthy exercising adults at concentrations around 160 µg/m³, whilst there are more severe effects at concentrations of 500 µg/m³ or more. A number of field studies done in children and young individuals indicate that pulmonary function decrements can occur at levels of 120–240 µg/m³. After repeated
prolonged exposure, pulmonary function shows adaptation but there is evidence that inflammation continues. There is also evidence for association of short-term peaks in O₃ exposures and lung epithelial damage. It must be noted that individual responsiveness to O₃ exposure varies substantially for reasons which remain largely unexplained.

For long-term effects, the evidence is less consistent. There are a few studies indicating that long-term ozone exposure may be a risk factor for asthma incidence, lung function growth, and lung cancer incidence and mortality. In these studies, it is not entirely clear that the ozone effects are not confounded by particle levels. Furthermore, the ACS cohort study found no indication of an association between long-term ozone exposure and either lung-cancer or total mortality.

**Nitrogen dioxide (NO₂)**

*Measurement, sources and distribution*

Nitrogen dioxide is mainly produced as a result of emissions from vehicles and is thus considered a good indicator of ambient, traffic-generated air pollution. Power plants and fossil-fuel burning industries also contribute to NO₂ pollution. There are also significant indoor sources of NO₂, such as gas stoves, and indoor NO₂ levels may dominate the total personal exposure to NO₂. However, NO₂ typically forms part of a complex pollutant mixture which is different in indoor from outdoor air.

During high temperature combustion, nitric oxide (NO), NO₂ and other nitrogen oxides (NOₓ) are generated. Part of the NO is converted to NO₂ through oxidation reactions which involve oxygen and ozone. NO₂, in the presence of sunlight, participates with hydrocarbons and oxygen in the formation of ozone and other secondary photochemical oxidants and is therefore an important precursor of O₃ formation. NO₂ also reacts with aerosols to form secondary (often acidic) particles.

NO₂ is measured routinely by monitoring networks and is expressed either as µg/m³ or ppb (1 ppb = 1.913 µg/m³ at 20°C).

*Regulations*

WHO guidelines provide a 1-h limit of 200 µg/m³ and an annual limit of 40 µg/m³. The US EPA only provides for an annual standard of 100 µg/m³. The EU legislation on NO₂ provides one short-term limit value at 200 µg/m³ for 1 h and an annual level at 40 µg/m³, not to be exceeded after 2010.
In European cities, the median of 24-h NO\textsubscript{2} concentrations currently ranges from about 30 to about 90 µg/m\textsuperscript{3} and the 90th percentile from about 40 to about 140 µg/m\textsuperscript{3}. The concentrations tend to be higher in cities with higher traffic density and in southern European cities\textsuperscript{13}.

**Health effects**

Healthy subjects experience reductions in pulmonary function and increased airway reactivity only at levels of NO\textsubscript{2} exposure much higher (>1500 mg/m\textsuperscript{3}) than those measured outdoors\textsuperscript{2,4}. Some people, however, are susceptible to effects at much lower concentrations.

It seems that the most sensitive subjects are asthmatics, though individual asthmatic subjects differ in their sensitivity to NO\textsubscript{2} exposure. In experimental studies with mild asthmatics, hyper-responsiveness and lung function decrements have been reported at NO\textsubscript{2} concentrations as low as 550 µg/m\textsuperscript{3}, though responders cannot be defined \textit{a priori}\textsuperscript{2,4}. Subjects with more severe asthma may respond differently.

Epidemiological studies have mainly focused on indoor exposures\textsuperscript{43} (see also Chapter 11). From these, there is evidence of increased respiratory symptoms and illness with increased long-term average indoor NO\textsubscript{2} concentration\textsuperscript{43,44}. The few studies which were conducted evaluating outdoor exposures\textsuperscript{45} showed increasing illness incidence with increasing NO\textsubscript{2} concentrations, but the causal association with NO\textsubscript{2} was not entirely clear. It should be noted that even small changes in susceptibility to respiratory viruses may have important public health significance, mainly because of widespread indoor exposure.

Some epidemiological studies have investigated short-term effects of NO\textsubscript{3} on mortality and hospital admissions\textsuperscript{32,46,47}. In some of these studies, significant (but weak) effects of NO\textsubscript{2} have been found. The effects tend to be reduced, however, in multi-pollutant models with inclusion of particles or carbon monoxide in the model, so it is not completely clear whether effects can reliably be attributed to NO\textsubscript{2}. NO\textsubscript{2} has also been found to modify the effect of particles: in the APHEA study, the increase in mortality due to particles was higher in cities where the long-term NO\textsubscript{2} concentrations were higher\textsuperscript{13}. This was interpreted as an indication that a greater proportion of particles originated from traffic in places with higher NO\textsubscript{2} levels. One cohort study has evaluated the long-term effects of NO\textsubscript{2}, though only as a general indicator of traffic pollution\textsuperscript{28}.

There are also experimental studies investigating changes of host defence against infection. Animal studies have suggested that effects on alveolar macrophage antimicrobial function can occur at NO\textsubscript{2} concentrations of 1000 µg/m\textsuperscript{3} or higher. This may explain the increased infectivity found in some epidemiological studies. A few clinical studies of controlled
exposure and subsequent infection in vitro of alveolar macrophage cells have indicated effects on host defence mechanisms of some healthy individuals. The importance of NO₂ for health and the need for regulation thus comes less from its direct effects on health than its role as an O₃ precursor and a contributor to the formation of secondary particles.

**Sulphur dioxide (SO₂)**

**Measurement, sources, and distribution**

In the earlier part of the 20th century very high concentrations of SO₂, together with particles, were measured in many urban areas. Because of their close interdependence (both were derived primarily from coal combustion) the effects of SO₂ and particles were often considered together. Since the 1970s, SO₂ concentrations in both Europe and the USA have declined as a result of changing fuel quality and fuel use. However, in large cities outside those areas (e.g. in China), where coal is still used for domestic cooking and heating, high concentrations are still observed. Because of its historic importance, monitoring of SO₂ has been extensive and there is a large and long-term database of 24-h SO₂ measurements in Europe. SO₂ concentrations are expressed in ppb or µg/m³ (1 ppb = 2.704 µg/m³ at 20°C).

**Regulations**

WHO provides a guideline of 125 µg/m³ for 24-h SO₂ exposure, 500 µg/m³ for 10 min and an annual average of 50 µg/m³, independent of the presence of particles. The US EPA gives a 3-h average standard of 1300 µg/m³, a 24-h average of 365 µg/m³ and an annual standard of 80 µg/m³. The EU has limit values for 1 h of 350 µg/m³ not to be exceeded by 2005, 125 µg/m³ for 24 h and an annual average of 20 µg/m³ for the protection of ecosystems with no margin of tolerance. The median levels of 24-h SO₂ are typically below 50 µg/m³ in European cities but there are occasional values of 125 µg/m³ on a 24-h basis, mainly in the cities of central-eastern Europe.

**Health effects**

Older experimental studies established very short-term responses to high levels of SO₂ which included decreases in lung function, and increases in
specific airway resistance and respiratory symptoms\textsuperscript{2}. Asthmatics are the most sensitive group, although individuals vary in their responsiveness.

Because of their close association, short-term epidemiological studies in the past were unable to distinguish between the effects of SO\textsubscript{2} and particles. Recent studies, however, consistently demonstrate effects on mortality (total, respiratory and cardiovascular)\textsuperscript{46,48} and hospital respiratory and cardiovascular admissions\textsuperscript{49,50}, in cities with SO\textsubscript{2} levels below the WHO guidelines. This finding is considered by some investigators to be inexplicable at such low levels of SO\textsubscript{2} and merits further investigation. Although the effect of SO\textsubscript{2} appears to be independent of particles in multipollutant models, it may in reality be associated with sulphates and be an indicator of specific particle characteristics.

As far as long-term exposures are concerned, results from cohort studies\textsuperscript{24,25} which evaluated SO\textsubscript{2} indicate that health effects are predominantly a result of exposure to ambient particles.

**Carbon monoxide (CO)**

*Molar, sources, and distribution*

Carbon monoxide is mainly produced by incomplete combustion of carbonaceous fuels such as gasoline and natural gas. Outdoors it is mainly emitted from vehicles. Its concentration is relatively high in traffic canyons and may be very high in road tunnels, multi-storey car parks and other such microenvironments. Also CO concentrations inside vehicles may be higher than outdoors, while a range of indoor sources exist, such as ETS and gas appliances\textsuperscript{2}. It has been shown that individual exposure to CO in non-smokers mainly happens during motor vehicle travel\textsuperscript{4}.

CO is routinely measured by monitoring networks and is usually expressed in mg/m\textsuperscript{3} or ppm (1 ppm = 1.165 mg/m\textsuperscript{3} at 20°C).

*Regulations*

WHO air quality guidelines give a guideline of 100 mg/m\textsuperscript{3} for 15-min exposure, 60 mg/m\textsuperscript{3} for 30-min, 30 mg/m\textsuperscript{3} for 1-h and 10 mg/m\textsuperscript{3} for 8-h exposure. There is no long-term average guideline. The US EPA have adopted a standard of 10 mg/m\textsuperscript{3} as an 8-h and 40 mg/m\textsuperscript{3} as a 1-h average\textsuperscript{11}, while the EU\textsuperscript{51} proposes an 8-h limit value of 10 mg/m\textsuperscript{3}, not to be exceeded by 2005. The WHO air quality guidelines are set to prevent levels of COH\textsubscript{b} (carboxyhaemoglobin) in the blood exceeding 2.5%.
Health effects

The toxic effects of CO are largely attributed to its high affinity with haemoglobin and myoglobin. Its affinity to haemoglobin is 200–250 times that for oxygen. Approximately 80–90% of absorbed CO binds with haemoglobin to form carboxyhaemoglobin (COHb). High exposures to CO cause acute poisoning, but such exposures are not encountered in outdoor urban settings. Unlike other gaseous pollutants presented above, CO appears to have no toxic effect on the lung but its health effects are manifested through the interference with oxygen transport. Continuous exposure to levels less than 10 mg/m³ should not cause COHb levels >2% in normal non-smokers. For continuous exposures to CO concentrations up to 200 ppm at sea level, the COHb% at equilibrium can be approximated as COHb% = COppm × 0.16. In practice, it is difficult to predict the percentage COHb because of the large spatial and temporal variation in CO exposure.

In controlled human exposure studies in patients with coronary artery disease, COHb levels between 2 and 6% have been associated with cardiovascular endpoints such as shortening of time to onset of angina. A limited number of recent epidemiological studies have provided evidence on the association of CO exposure to cardiac arrhythmia, hospital admissions for heart disease and mortality.

Conclusions

In summary, current levels of air pollution in Europe have considerable adverse health effects. These have been better studied for ambient particle concentrations, which appear to have both long- and short-term effects including an increase in mortality. It appears that the health effects of particles mainly concern sensitive population subgroups such as the elderly or those with chronic respiratory illness.

The short-term effects of ozone exposure on health are also well documented. With regard to other pollutants, there is some evidence of NO₂ and CO effects. NO₂, in addition, is important as a precursor to other pollutants and as a traffic pollution indicator. The levels of SO₂ have decreased in Europe and, although this pollutant is consistently associated with health endpoints, it may be acting as a surrogate for a specific mixture of other pollutants.

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