

Exposure

Sources and air concentrations

Airborne particulate matter (PM) is a very diverse material in terms of its physical and chemical properties, and many sources contribute to its atmospheric concentrations. Airborne particles are typically very small, ranging in size from a few nanometers up to 100 μm or more. While all particles in this range can be found in the air, only particles in the range of 0.1–2 μm can remain airborne for long periods (10 days or more). Particles less than about 10 μm , the PM_{10} fraction, are the most important from a health point of view, as such particles reach the thoracic parts of the respiratory tract to a large extent.

Airborne particles can be either directly emitted (primary particles) or formed in the air by chemical reactions or the condensation of gases (secondary particles). Mechanically generated airborne particles are normally larger than 2.5 μm (coarse particles), while the particles formed from gas conversions are smaller than 2.5 μm (fine particles). Due to their different size and formation processes, fine and coarse particles have substantially different properties (chemical composition, atmospheric half-time, temporal and spatial variability).

The annual Swedish emission of primary particles (coarse and fine) is estimated to be about 50 000–100 000 t. Wood combustion for heating is probably the major source, but emission estimates are uncertain. Heavy-duty diesel vehicles, the combustion of heavy oil for energy production, machines, and industrial processes are other important sources. Resuspension of road dust is probably also important; however, no reliable estimates of its contribution are available on a national level.

Regular monitoring of PM_{10} in a few major cities in southern Sweden since the beginning of the 1990s has shown that the average concentration at roof level is around 10–20 $\mu\text{g}/\text{m}^3$. Levels in rural areas are in the lower end of this range. The comparatively small difference between roof-top urban levels and rural levels results from the strong influence of long-range particle transport on the concentrations. The 98th percentile of the daily mean values ranges from about 30 to 50 $\mu\text{g}/\text{m}^3$, and the maximum daily mean concentrations are in the approximate range of 50–100 $\mu\text{g}/\text{m}^3$. At street level, the mean concentrations range from 20 to 40 $\mu\text{g}/\text{m}^3$, and the 98th percentile of the daily means varies from 50 to 100 $\mu\text{g}/\text{m}^3$. The maximum daily mean concentra-

tions are in the range of 100 to 150 $\mu\text{g}/\text{m}^3$, and hourly mean concentrations can exceed 300 $\mu\text{g}/\text{m}^3$. The highest concentrations are measured in spring, probably because of the resuspension of road dust due to the build-up of particles on the road surface during sanding and salting, as well as because of road wear by studded tires in the winter season.

No major changes in concentration are anticipated during the next few decades. There are indications that reduced emissions due to better combustion technology for vehicles and wood boilers will be counteracted by an increase in the share of diesel cars and also by an increase in the use of wood for heating. Moreover, the contribution from the particles transported long-range is estimated to remain about the same as now.

Deposition and clearance

Particle deposition in the airways depends on particle size, density, and shape. Particles of soluble material can take up water in the airways and grow considerably. Deposition is also dependent on respiration pattern, including mouth or nose breathing. Deposition in the alveolar region is highest for particles of 20–30 nm, about 50%.

Recent experiments indicate substantial retained fractions of particles after 24 hours in small ciliated airways (bronchioli), and the clearance of these fractions appears to be rather independent of mucociliary transport. For persons with chronic bronchitis, clearance by coughing is an important mechanism in the larger airways of the lung, in addition to mucociliary transport, but its importance in small ciliated airways is uncertain.

The mechanical clearance of particles from the alveolar region in humans is extremely slow, with a half-time of about 5 years for the majority of the particles. This slow clearance should be relevant for the carbon skeleton of ambient particles. However, particles of many materials typically considered insoluble in water, such as many metal oxides, can be cleared at a much faster rate because they are dissolved in the acid milieu in the phagolysosomes of the alveolar macrophages. Particles deposited in the alveolar region can be transported to the regional lymph nodes, especially toxic particles, such as quartz particles, ultrafine particles, and also rather large inert particles when the inhaled amount is extremely large. In all of these situations there may be a considerable number of particles outside alveolar macrophages.

Health effects

Short-term effects

Experimental studies. Most experimental studies have dealt with sulfuric acid aerosols and persons with asthma, who are more sensitive than healthy subjects to these particles with respect to lung function. In the investigations on ventilatory function, the study design and methods of measuring lung function have been similar. Still, the results have differed remarkably. Significant changes in young asthmatics have, for example, been observed already at $70 \mu\text{g}/\text{m}^3$, whereas concentrations of $1000 \mu\text{g}/\text{m}^3$ or higher have been necessary to induce significant changes in asthmatics in other studies. An explanation for the different results may be that the groups of asthmatics differed in bronchial reactivity. In combined exposure of sulfuric acid aerosols and ozone (O_3), there was no indication of any major synergistic effect. Furthermore, short-time exposure to carbon black particles ($200 \mu\text{g}/\text{m}^3$) and sulfuric acid particles ($100 \mu\text{g}/\text{m}^3$) among healthy subjects and asthmatics did not induce any significant effect on lung function.

The results of the clearance studies seem more consistent than those based on lung function tests. Apparently, there is an effect of sulfuric acid particles on mucociliary clearance at least down to $100 \mu\text{g}/\text{m}^3$ in short-term exposures. The effect seems to increase with duration of exposure. In contrast to the results regarding ventilatory function, asthmatics do not seem more sensitive to exposure to sulfuric acid particles than healthy subjects do.

Healthy subjects exposed to filtered or unfiltered diesel exhaust have shown only small differences in effects. The filtered exhaust had about half as many particles as the unfiltered exhaust (1.4×10^6 and 2.6×10^6 particles/ cm^3 , respectively), but the carbon dioxide concentration was similar (1.7 and 1.9 ppm). In a later study 4.3×10^6 particles/ cm^3 was reported to correspond to $300 \mu\text{g}/\text{m}^3$. There was an increase in airway resistance (R_{aw}) of around 15% for both exposures. In the bronchial portion of the lavage fluid, the number of macrophages was significantly increased only after the exposure to the unfiltered diesel exhaust, whereas the neutrophils increased by a factor of 3–4 after both exposures. The phagocytic activity of alveolar macrophages was significantly reduced after both exposures. In these studies, it was difficult to assess whether the effects were caused by particles or by gases.

In another study with realistic but complex exposures, volunteers with mild asthma were exposed to the atmosphere in a road tunnel for 30 minutes during the rush hour. When the subjects inhaled pollen antigen 4 hours after the end of the exposure, the SR_{aw} and thoracic gas volume (TGV) were significantly increased

when compared with the results of the control exposure, and more asthma symptoms were seen later in the evening after the tunnel exposure. The asthma symptoms correlated both with the concentrations of nitrogen dioxide (NO_2) and particulate matter with diameters of $<2.5 \mu\text{m}$ ($\text{PM}_{2.5}$), but the relationship appeared to be stronger for NO_2 . The late-phase reaction tended to be higher for those with $\text{PM}_{2.5}$ exposure above $100 \mu\text{g}/\text{m}^3$.

There are very limited human data on whether the number, surface area, or mass of particles is the most appropriate way to measure dose. Healthy subjects inhaling cholinergic aerosols with mass median diameters of 3 or $7 \mu\text{m}$ required a three to four times higher mass for the large particles than for the small particles in the tracheobronchial tract to induce the same effect on R_{aw} and forced expiratory capacity in 1 second ($\text{FEV}_{1.0}$). This result may be relevant also for at least some particles in ambient air, as another study indicated a strong correlation between the effects of cholinergic aerosols and the effects of sulfuric acid aerosols on asthmatic subjects.

Epidemiology. A large number of studies has consistently observed an association between mortality and the levels of particulate air pollution on the previous day or days. Different gravimetric measures, as well as reflectance or visibility measures, have been used with similar results. The measured or estimated daily mean PM_{10} levels ranged from about 30 to $80 \mu\text{g}/\text{m}^3$ during the observation periods in most of the studies. It has lately been suggested that the smaller particulate fractions (eg, $\text{PM}_{2.5}$ or even smaller) are primarily responsible for the health effects observed. The possibility that particles are a surrogate for other pollutants cannot be completely dismissed. However, the association was consistently observed in locations with differing levels of other pollutants. The effect corresponds to around a 0.5–1% increase in mortality for a $10 \mu\text{g}/\text{m}^3$ increase in PM_{10} , and it appears to be stronger for respiratory deaths and cardiovascular deaths. Associations were observed at particulate concentrations well below $100 \mu\text{g}/\text{m}^3$, and some studies even indicate weaker relationships at higher levels. Furthermore, several studies have reported stronger effects in the summer (when PM_{10} levels are usually lower).

The studies on hospital admissions and emergency room visits also provide evidence of adverse health effects resulting from short-term exposure to particles. Increases in the daily morbidity range from about 0.5% to 3% per $10 \mu\text{g}/\text{m}^3$ of PM_{10} in most studies. An effect on many respiratory conditions, such as chronic obstructive pulmonary disease and pneumonia, has been found, as well as an effect also on cardiovascular diseases in some studies. The results regarding asthma admissions show a larger variability, which may be partly due to a smaller sample size, but hospital visits for asthma,

particularly of children, were rather consistently associated with particulate air pollution levels, with increases of roughly 1% to 4% per 10 $\mu\text{g}/\text{m}^3$ increase in the PM_{10} . The results from recent European studies of hospital admissions, indicating excess risks of about 0.4–0.9% per 10 $\mu\text{g}/\text{m}^3$ of PM_{10} for different disorders in different subgroups, appear to be lower than previous findings from the United States and elsewhere.

Particulate air pollution has been shown to be related to both respiratory symptoms and lung function in healthy persons. For the most part children have been studied, often in the age range of 5–15 years. The lung function decrements have been small (ie, corresponding to only about 0.1–0.3% per 10 $\mu\text{g}/\text{m}^3$ increase in PM_{10}). In addition they have often been more strongly related to longer averaging or lag times than to previous-day levels, and, therefore, the question of a possibility of persistent effects is raised. Symptoms of the lower respiratory tract, such as cough and wheeze, have been the most consistently related to particulate exposure, with excess relative risks (RR) of about 2–8% per 10 $\mu\text{g}/\text{m}^3$ increase in the PM_{10} level. For asthmatics, a somewhat stronger effect has often been observed for pulmonary function but not necessarily for symptoms. Extra asthma medication, generally bronchodilator use, has also been associated with particulate exposure, and it may modify the observed effects on symptoms and lung function.

Population-based studies suggest an association between restrictions in activity, leading to work and leisure-time loss, and weekly average particulate air pollution levels. Preterm delivery and low birthweight has also been associated with particulate air pollution during the week and 3 months before delivery, respectively. A relation between sudden infant death syndrome and particulate air pollution has also been suggested, but the data are not conclusive.

Long-term effects

Animal experiments. The review of animal experiments has primarily focused on diesel exhaust particles and ultrafine particles. Rats have primarily been studied for pathological and histological effects in the lung after exposure to diesel exhaust particles. The findings include chronic inflammatory changes involving proliferation and hyperplasia of the alveolar epithelium and type 2 cells, thickening of the alveolar septa, wall fibrosis, and emphysema, as well as activation of inflammatory cells and the release of cytokines and mediators. A comparison of diesel exhaust particles and carbon black in animal inhalation studies has shown that a reduction in lung function and an accumulation of macrophages appears in parallel. This finding suggests that the toxic effect of diesel exhaust particles is in part coupled to the carbon

core. The toxicity of diesel exhaust particles could in part also be mediated via the production of oxygen radicals and the release of different inflammatory mediators.

Animal experiments show that aggregates of ultrafine particles are more toxic than aggregates of fine particles. When aggregates of ultrafine and fine particles have been installed via the trachea or inhaled, the ultrafine particles have induced much stronger inflammatory reactions. The relationship between dose and the alveolar retention half-time of test particles could be well described by one curve for both fine and ultrafine particles when the dose was expressed by the surface area of the particles. This finding suggests that the surface area may be a better measure of the dose than the mass, at least for some health effects.

Diesel exhaust particles introduced by different routes, intraperitoneally, intranasally or intratracheally, may act as an adjuvant to pollen and hence increase the sensitization response. This action has been observed in both human and animal studies (mostly in mice). For example, immunoglobulin (Ig) E production in response to an allergen has been enhanced by diesel exhaust particles. Furthermore, diesel exhaust particles may act as a carrier of pollen allergens and thereby increase the deposition of pollen in the lower airways.

Epidemiology. Large cross-sectional studies of geographic variations in mortality and air pollution in the United States provided an initial impetus for research on the health effects of particles, but they could not answer questions regarding short-term versus long-term effects. The lack of individual data also makes these studies vulnerable to confounding. Several cross-sectional studies of symptoms suggest that chronic bronchitis, cough, and related symptoms are associated with particulate air pollution, whereas the data regarding asthma or allergy are less consistent. From the cross-sectional studies on pulmonary function, there is some evidence for a long-term effect of particulate air pollution. Two major cohort studies from the United States strengthen the conclusion that long-term particulate exposure is associated with cardiopulmonary mortality. These studies controlled for major risk factors, including smoking habits, using information obtained at entry to the cohort. Over the range of $\text{PM}_{2.5}$ levels from the least to the most polluted cities the studies estimated increases in total mortality of 26% per 18.6 $\mu\text{g}/\text{m}^3$ and 17% per 24.5 $\mu\text{g}/\text{m}^3$, respectively. These figures would correspond to an excess total mortality of about 10% for every 10 $\mu\text{g}/\text{m}^3$ increase. A third cohort study from the United States, focusing on Seventh Day Adventists, found an association between PM_{10} levels and cardiopulmonary mortality among men but not among women. Unfortunately, no data in relation to $\text{PM}_{2.5}$ levels were available.

Evaluation

Exposure to particles in the ambient air has been associated with several adverse health effects. This assessment focuses on effects other than cancer. A recent review evaluated the evidence on particles in the ambient air and lung cancer (1). It was concluded that the observed excess risk of 20–40% for lung cancer in areas with high particulate levels did not appear inconsistent with extrapolations based on occupational data, primarily including workers exposed to diesel exhaust particulate. This finding provides a further impetus for restricting exposure to airborne particulate.

Experimental evidence from asthmatics shows that acute effects on lung function may occur already at levels of 70 µg/m³ of sulfuric acid aerosols. Exposure in a road tunnel at PM_{2.5} levels above 100 µg/m³ was associated with enhanced asthma symptoms after exposure to pollen. However, the specific role of PM_{2.5} is unclear because of concomitant exposure to other factors, such as nitrogen oxides (NO_x).

Animal experiments provide no clear evidence on possible mechanisms behind the acute effects on respiratory symptoms, hospital admissions, and mortality in association with comparatively low levels of airborne particulate in epidemiologic studies. There is limited evidence from experimental studies that the surface area, and maybe even the number, of particles is more relevant than the mass for observed health effects. Long-term inhalation exposure to high levels of diesel exhaust particulate and fine particulate gives rise to inflammatory reactions in the respiratory tract of experimental animals. Some evidence indicates that diesel exhaust particulate may enhance allergic sensitization.

Quantitative risk assessment

The epidemiologic evidence published during the last decade clearly points to a relation between short-term exposure to particulate air pollution and adverse health effects well below current air quality guidelines in many countries. Unfortunately, only limited support has been provided by experimental studies, and, therefore, there is a lack of understanding of the mechanisms behind the effects, such as those on mortality. There are, however, experimental data indicating that ultrafine particles induce stronger inflammatory reactions than fine particles at the same mass. Considerable uncertainty still exists regarding which characteristics of the particles are important for the observed effects. It is not unlikely that particles originating from different sources, such as diesel vehicles and wood burning, may differ in toxicity. Recent epidemiologic evidence suggests that the fine fraction (PM_{2.5} or less) is especially harmful. However, quantitative assessments of exposure-response relation-

ships regarding acute effects will be based on PM₁₀, as information on PM_{2.5} is not available in most studies.

Measurements of PM₁₀ in ambient air in Sweden are limited, and, therefore, there are uncertainties as to the quantitative risk assessment. Episodes of increased 24-hour levels of particulate depend primarily on meteorological phenomena, such as the transport of polluted air from Europe and inversion during the winter season. Only a few urban areas measure PM₁₀ regularly, and it is therefore difficult to generalize for the whole country. In southern and middle Sweden the highest 24-hour levels generally range from 20 to 60 µg/m³, and the winter half-year means are from 12 to 15 µg/m³ (primarily based on roof-top measurements in Stockholm, Göteborg, and Malmö). The particulate levels thus increase roughly by 8–45 µg/m³ above average during an episode with increased particulate levels (average about 25 µg/m³ for all measurement stations during heating periods in 1993–1994 and 1994–1995). In general, up to 5 such episodes occur yearly in Sweden. The influence by transport from surrounding countries decreases with latitude, while the importance of inversion episodes increases. It may thus be relevant to generalize the measured values also to northern Sweden.

Table 1 summarizes the evidence on short-term exposure to airborne particulate and some health effects. In an attempt to avoid extrapolation linearly down to the low background levels of Sweden, the estimates have been based on a typical 3-day air pollution episode in which the PM₁₀ level increased by 25 µg/m³. According to the data in the table, roughly 10–30 excess deaths, 50–300 hospital admissions and emergency room visits for respiratory and cardiovascular conditions, and 5000–20 000 person-days of respiratory symptom exacerbations would occur in Sweden if the whole population experienced such an air pollution episode. It is likely that mainly people with particular susceptibility would be affected.

The public health impact of short-term associations between particulate levels and mortality remains

Table 1. Estimated acute health effects following exposure to a 3-day episode of PM₁₀ levels increased by 25 µg/m³ in a population of 1 million. (PM₁₀ = particles less than about 10 µm in diameter)

Health effect	Excess risk (% per 10 µg/m ³ PM ₁₀)	Back- ground rate (per 10 ⁶)	Number of subjects (per 10 ⁶) ^a
Respiratory symptoms (person-days)	2–8	10 000	500–2 000
Hospital admissions & emergency room visits for respiratory and cardiovascular conditions	0.5–3	400	5–30
Excess mortality	0.5–1	100	1–3

^a Excess risk per 25 µg/m³ PM₁₀ multiplied by background rate.

unclear. If the effects primarily involve patients who are terminally ill, the life shortening may be minimal. A few cohort studies indicate an increased mortality also in relation to long-term exposure. The observed effects correspond to an increase of about 10% for every 10 $\mu\text{g}/\text{m}^3$ increase in the $\text{PM}_{2.5}$ level in the two studies presenting data on this particulate measure, or roughly 1100 deaths a year per 1 million subjects. A possible effect on average life expectancy on the order of 1 to 1.5 years lost has been estimated from these data. Cross-sectional studies on respiratory symptoms and lung function provide further support for an effect by particulate air pollution, but these data are unsuitable for use in the assessment of effects resulting from long-term exposure. In view of the limited evidence on the long-term effects of particulate air pollution, no quantitative risk assessment has been performed. Furthermore, relevant information on population exposure to particulate in Sweden is lacking.

Proposed health-based guideline

Short-term variations in PM exposure are associated with adverse health effects even at very low levels of exposure. However, the available evidence does not allow derivation of a threshold below which no effects occur. Associations have been observed in studies where the 24-hour average or estimated PM_{10} level was from 30 to 80 $\mu\text{g}/\text{m}^3$. The evidence is the most limited in the

lower part of the interval, but it would seem appropriate that the long-term goal should lie near the lower end of this range. Thus a health-based guideline for PM_{10} is proposed at 30 $\mu\text{g}/\text{m}^3$ as the 24-hour average. It is probable that certain people are particularly susceptible to airborne particulate, such as asthmatic children and adults. These groups comprise fairly large parts of the population, and, therefore, the public health importance of any effects is great. Recent evidence suggests that the fine fraction ($\text{PM}_{2.5}$ or less) may be especially harmful, but the available information is too limited for a guideline based on this measure.

The available evidence on the health effects related to long-term exposure to airborne particulate is limited. However, epidemiologic findings suggest serious effects well below current standards. The yearly average levels of $\text{PM}_{2.5}$ ranged down to 10 $\mu\text{g}/\text{m}^3$ in the metropolitan areas under study, and it may be reasonable to use this value as a basis for a guideline. It would correspond to a PM_{10} level of about 15 $\mu\text{g}/\text{m}^3$.

References

1. Camner P, editor. Particles in the ambient air as a risk factor for lung cancer. Stockholm: Swedish Environmental Protection Agency, 1997. Report 4804.