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HUMAN EXPOSURE TO OUTDOOR AIR POLLUTION

(IUPAC Technical Report)

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Human exposure to outdoor air pollution

(IUPAC Technical Report)

Abstract: Human exposure to outdoor air pollution is believed to cause severe health effects, especially in urban areas where pollution levels often are high, because of the poor dispersion conditions and high density of pollution sources. Many factors influence human health, and a good assessment of human air pollution exposure is, therefore, crucial for a proper determination of possible links between air pollution and health effects. Assessment of human exposure is, however, not straightforward, and this is the background for the present paper, which recommends how to carry out such assessments. Assessment of human exposure to air pollution may be carried out by use of:

- categorical classification,
- application of biomarkers,
- analysis of air pollution data from routine monitoring networks,
- personal portable exposure monitors, or
- application of mathematical air pollution exposure models.

The categorical classification is a crude indirect method based on indicators of exposure such as type of residence, type of job, presence of indoor sources, etc. Categorical classification is generally inadequate for application in air pollution epidemiology. Biomarkers can be a strong instrument in assessment of health effects and provide information about air pollution exposure and dose. Use of biomarkers is, therefore, particularly useful when applied in combination with exposure assessment through one of the methods 3 to 5. The main focus of this paper is on these three methods for determination of human air pollution exposure. The optimal solution is clearly a combination of methods 2 to 5, but the available resources often set a limit to how far the assessment is carried out, and the choice of strategy will, therefore, often be very important for the outcome of the final study. This paper describes how these approaches may be applied and outlines advantages and disadvantages of the approaches used individually and in combination. Furthermore, some examples of specific applications in Denmark and the Netherlands are given for illustration.

1. INTRODUCTION

It is well known that air pollution at high concentrations in some cases has led to acute health effects on human beings. The classic example is the severe London smog (smoke and fog) episode in 1952 where the mortality rate in the city increased dramatically [1]. In such extreme cases a link between high pollution concentrations (in this case, sulfur dioxide and soot mainly emitted by domestic heating) and human health effects is evident, but even when the link is less clear, air pollution may have considerable health impacts. It has been estimated that 30 to 40% of Europeans live in cities where they are exposed to air pollution concentrations at or above the guidelines of the World Health Organization (WHO) and the European Union (EU) [2,3]. Various studies have indicated that long- as well as short-term exposure to elevated pollution concentrations may have an impact on human health. Studies of long-term exposure to air pollution (especially particulates) suggest an increased risk of chronic respiratory illness (e.g., see refs. 4–11) and of developing various types of cancer (e.g., see refs. 12–14).

Other studies on short-term exposure to high pollution concentrations have suggested higher prevalence of bronchitis, asthma, and other symptoms (e.g., see ref. 14). For both chronic and acute health effects, the elderly, children, and those suffering from respiratory or heart conditions seem to be most at risk. Recent European studies on the externalities of electricity generation and transportation (ExternE) and green accounting exercise (GARP) indicated that health impacts from air pollution is the single most important damage category in Europe [16]. An apparently high-end assessment of the WHO datasets [17] found that 6% of deaths in Austria, France, and Switzerland can be associated with exposure to particle pollution. Long-term exposure to air pollution from traffic has been estimated to cause approximately 20 000 annual premature deaths in Austria, France, and Switzerland [18]. This number is more than the double the total annual number of deaths due to traffic accidents in these three counties (in total, approximately 10 000 per year in the three countries). Even though mortality dominates the damage costs, a significant part of the costs are due to morbidity [19]. The study for Austria, France, and Switzerland indicated that 300 000 cases of bronchitis among children can be associated with air pollution, together with 15 000 hospital admissions for heart diseases. Furthermore, calculations in the study showed that air pollution in the three countries causes 395 000 and 162 000 asthma incidences among adults and children, respectively. Health effects and loss of well-being due to air pollution exposure have been estimated to have an annual cost of 27 billion EUR for the three countries studied [20].

Health effects of air pollution is the result of a chain of events, which include release of pollution, atmospheric transport, dispersion and transformation over contact and uptake of pollution before the health effects take place (Fig. 1). The conditions for these events vary considerably and have to be accounted for, in order to ensure a proper assessment.

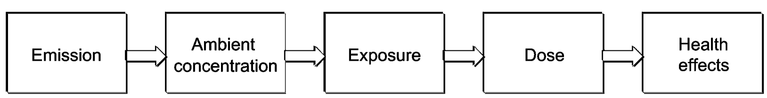

Fig. 1 Human health effects of air pollution are the result of a chain of events going from the release of pollutants leading to an ambient atmospheric concentration, over the personal exposure, uptake, and resulting internal dose to the subsequent health effects.

Most of the world's population is situated in cities of varying sizes. Naturally, people living in large cities are, in general, exposed to higher pollution concentrations than those living in small villages. One notable exception is ozone, which is generally found in lower concentrations in urban areas compared with rural sites. During the last decades, because of legislation concerning emissions from power plants and industry, together with a steady growth in road traffic, the emission from traffic has become one of the major sources of air pollution, i.e., in large European cities [21,22]. Traffic exhaust gases contain pollutants such as nitrogen oxides [NO_x defined as the sum of nitrogen monoxide (NO) and nitrogen dioxide (NO_2)], hydrocarbons, carbon monoxide (CO), and particles. When emitted in urban streets with poor dispersion conditions (e.g., inside street canyons) substantial air pollution concentrations can be reached, especially at low wind speeds (e.g., see refs. 23,24).

Another important source of air pollution is residential heating. In particular, when domestic heating dominates over district heating, as is the case in some third world and Eastern European countries, sulfur and soot emissions are still contributing considerably to local pollution.

Studies of human exposure to air pollution have a number of different uses. It is important to choose the right strategy for the study in order to obtain the optimal accuracy of the exposure estimates. Examples of uses of exposure studies are:

- impact assessment on population exposure, for example, in connection with various types of management such as traffic and city planning;

- comparison of the exposure of different specific population groups, for example, in connection with epidemiological studies;
- estimation of the average or peak exposures of the population in connection with, for example, health assessment;
- validation of exposure estimates, for example, in connection with development of model tools for broader use;
- identification of the most important sources of pollution exposure, for example, in connection with emissions reduction strategies; and
- being used as a tool in connection with identification of possible associations between exposure and health effects.

Accurate estimates of human exposure are essential for a realistic assessment of the possible risk of various health effects. Such estimates have often been based on measurements in ambient air obtained from fixed-site monitors. However, because of the large local variations in pollution concentrations these estimates are often associated with high uncertainties. Geostatistical techniques such as kriging have, in some cases, been used to interpolate ambient data from an irregularly spaced set of point measurements for epidemiological studies (e.g., the one by Mulholland *et al.* [25]). However, these techniques have not typically been constrained by physiochemical models and hence may not generate physically consistent spatial fields especially in complex dispersion environments of urban areas, but also for example of very reactive gases such as ozone. Better estimates are generally needed using more accurate methods in the form of direct exposure measurements or application of exposure models (Figs. 2 and 3). This is the main focus of the present paper. Exposure to indoor pollution (e.g., refs. 26,27) and tobacco smoking (e.g., see ref. 28) are very important in assessment of total human exposure since people generally spent more time indoor than outdoor. The relationships between indoor and outdoor pollutant concentrations are only briefly treated in this paper. In this context we will focus only on the impact of outdoor releases on indoor concentrations. Occupational air pollution exposure obtained by the use of the so-called logbook method is described in the IUPAC Technical Report by Olesen *et al.* [29].

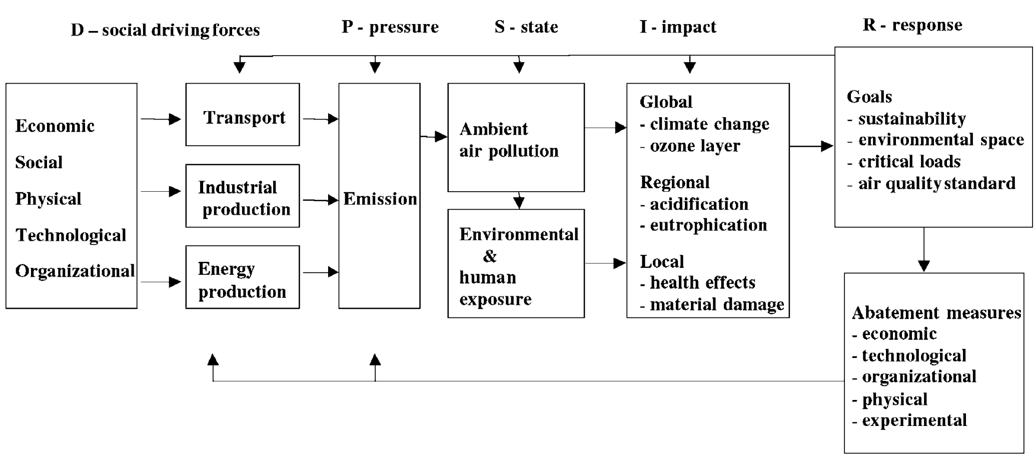

Fig. 2 A schematic illustration of the chain in air pollution impact assessment applying the DPSIR concept developed by the National Institute of Public Health and the Environment (RIVM) in the later 1980s. DPSIR is a conceptual model used to describe and analyze environmental problems. Social driving (D) forces such as transport and industry lead to environmental pressures (P) that degrade the state (S) of the environment that has an impact (I) on human health or the environment which makes the society carry out a response (R) through various actions. In this sketch the focus is on the air pollution problems, but the concept may also be applied to other environmental problems.

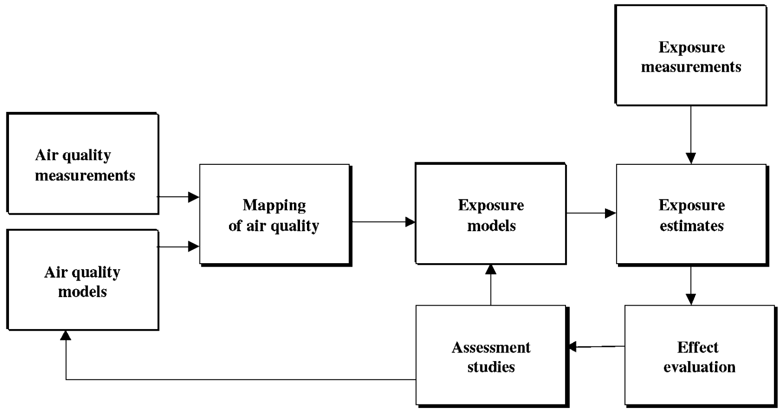

Fig. 3 Another schematic illustration of the chain in air pollution impact assessment, but in this case with focus on the tools for carrying out the assessment studies. Air quality measurements and air quality models may be applied for mapping pollution concentrations. The obtained air pollution concentrations may be used in exposure models for estimating human exposure, but direct exposure measurements may also be applied for obtaining information on human exposure. Using the exposure data in epidemiological studies or applying determined effect functions, the impact on the population may be estimated. Changing input parameters in human exposure may carry out assessment studies and/or air pollution models, and the possible changes in impact on the population may be determined.

2. DEFINITIONS: CONCENTRATION, EXPOSURE, AND DOSE

Before going into a discussion of assessment of air pollution exposure, it is useful to define some of the central terms of which some are defined in the "IUPAC Glossary for Chemists of Terms used in Toxicology" [30]. However, we will make a few minor modifications to these definitions for the present paper. The modifications are described in the following section in order to obtain a very clear separation between concentration, exposure, and dose in the following discussions. (Some of the definitions used here are taken from refs. 32,33.)

2.1 Concentrations and mixing ratios

The local abundance of a pollutant in ambient air may be expressed as concentration or mixing ratio. The *concentration* of a specific pollutant is defined as mass (e.g, microgram and nanogram, denoted mg and ng, respectively) or amount (mole) of material per volume of air. For mass concentration this can be expressed mathematically as $\rho = M/V$, where ρ is the mass concentration, M is the mass of substance, and V is the volume of air; similarly for amount concentration.

Mass mixing ratio is defined as mass of substance per mass of air (for example, μg/g often expressed in units parts per million, ppm). *Amount mixing ratio* (commonly, and hereinafter, *mixing ratio*; often denoted *mole fraction*) is defined as moles of substance per mole of air (often expressed in units parts per billion, ppb, or nmol/mol). Concentrations of particles may furthermore be expressed in number per volume of air. It should be noted that Duffus *et al.* [31] does not distinguish between concentration and mixing ratio, whereas we make a clear separation between the two in the following.

2.2 Human exposure

Human exposure refers to an individual's contact with (note: contact not uptake) a pollutant concentration. Therefore, it is important to make a distinction between concentration and exposure; concentration is a physical characteristic of the environment at a certain place and time, whereas exposure describes the interaction between the environment and a living subject [34]. The pollution pathways may be external (e.g., skin contact) or internal (e.g., consumed or respired, which is usually the principal pathway for uptake when air pollution is considered). The term total exposure refers to a person's contact with pollution from all sources and by all pathways, which means any kind of exposure to a given type of pollution (here restricted to air pollution exposure). For personal exposure to take place two events need to occur simultaneously; pollution concentration at a particular time and place must be nonzero and the person must be present in that same place and at that time [35,36]. Exposure has the dimension of (mass) × (time) / (volume) or (concentration) × (time), for example, with unit µg d m^{-3}.

Exposure studies can be carried out with the aim of obtaining estimates of the exposure of the individual (personal exposure) or for a larger population group (population exposure). The exposure can be obtained from direct measurements on individuals, either a total population or selected persons, or it may be determined from model calculations.

Duffus *et al.* [31] defines exposure as; concentration, amount or intensity of a particular environmental agent that reaches the target population, organism, organ tissue or cell, usually expressed in numerical terms of substance concentration, duration, and frequency (for chemical agents and microorganisms) or intensity (for physical agents such as radiation). This definition is useful, but organ, tissue, and cell exposure should have been defined as a dose rather than as an exposure. We will, therefore, make this distinction in the following.

2.3 Integrated exposure

Exposure may be determined by direct or indirect methods. Direct methods are measurements made by personal portable exposure monitors or measurements of biological markers. In indirect methods, the exposure is determined by combining information about concentrations at locations with information about the time spent in specific environments.

In applying the indirect methods, the concept of defining *microenvironments* is a common and practical tool in exposure assessment. A microenvironment is defined as a three-dimensional space where the pollution concentration at some specified time is spatially uniform or has constant statistical properties [34]. The microenvironment can be the interior of a car, inside a house, or urban, suburban, and rural areas, etc. Integrated exposure (sometimes incorrectly referred to as dose), is the exposure that a specific person experiences over a given period of time. Using the indirect method and introducing the concept of microenvironments, the *integrated exposure* can be expressed as:

$$E_i = \sum_j^J C_j t_{ij} \tag{1}$$

where E_i is the total exposure for person i over the specified period of time, C_j is the pollutant concentration in microenvironment j, t_{ij} is the residence time of the person i in microenvironment j, and J is the total number of microenvironments. The total exposure is, therefore, the sum of exposures during a given time and has thus the same dimension as exposure in general: (mass) × (time) / (volume) or (concentration) × (time), for example, with unit µg d m^{-3}.

Usually, exposure scales with the number of people exposed. However, there may be cases where it can be meaningful to integrate the exposure over a given population. In the case where n persons are exposed to the same concentration for the same time, the exposure is in this case n times that for one person and, for example, with the unit (concentration) × (time). The resulting population exposure can then be used, for example, to relate number of hospital admissions to exposure.

A constraint for using the indirect methods (eq. 1) is that the residence time of the person (termed the time–activity pattern) needs to be known together with the pollution concentrations in each of the microenvironments at the time when the person is present.

2.4 Dose

The distinction between exposure and dose is important in impact assessment studies; *dose* is the mass of pollution that crosses one of the body's boundaries and reaches the target tissue [34]. This definition is in accordance with the definition of Duffus *et al.* [31]; total amount of a substance administered to, taken, or absorbed by an organism. If a person breathes in a volume of air containing pollution and then breathes it out again, the dose is the mass of pollution retained in the body. Dose and integrated exposure are thus identical only for conditions where the body boundary does not represent a barrier for the uptake, for example, in the case of exposure to gamma radiation. When the uptake of pollutants takes place mainly in the respiratory system, there is a systematic difference between exposure and dose. For example, consider four persons in a room at a given pollution concentration: a dead person, a child, and two adults, one sitting and one running round the room. Although all four experience the same exposures, the dead person does not receive any dose and the child receives a high dose since it has small lungs and needs high respiration frequency. Considering the two adults, the physically active adult will receive a higher dose than the adult at rest, because of the difference in the frequency of respiration. Another example is the findings of Van Wijnen *et al.* [37], that show that car drivers have a higher exposure to certain pollutants than bicyclists in Amsterdam. However, because of the higher rate of respiration, the bicyclists had, in some cases, higher doses than the car drivers.

In some cases, two types of dose are defined: intake dose and absorbed dose [32]. This distinction is made to account for compounds that mainly pass through the body without being absorbed. Since this paper does not consider the possible health effects of the dose, we will refer only to intake dose and refrain from discussion of the absorption processes in the body.

Dose may be integrated over a given population, but as is evident from the above example of the four persons there may be great differences over a population even if each individual would be in contact with the same concentrations of pollution.

Health effects may, for example, appear when a given critical or maximum tolerable dose is exceeded and is then the result of the series of events shown in Fig. 1. Whether there is a health effect will, however, depend on three different aspects of the exposure (and subsequent dose). This situation is discussed in the next section.

3. COMPONENTS AND TYPES OF EXPOSURE

Three different aspects are important in connection with estimation of human exposure to pollution [34]:

- Magnitude: what is the pollutant concentration?
- Duration: how long is an individual in contact with the pollution (exposed)?
- Frequency: how often does the exposure to a certain concentration appear?

It is useful to distinguish between long- and short-term exposure because of the differences in health effects. For some compounds there may be a health effect of the long-term exposure due to accumulation in the body (i.e., for compounds such as lead and benzene), whereas the short-term, high exposure may show little effect on human beings unless extremely high concentrations are reached. In this case, the integrated exposure will provide the needed information for estimating the accumulated amount of material in the body. However, for other compounds health effects will only be observed when certain threshold values are exceeded. For some compounds these thresholds need to be exceeded for a certain period of time before effects are observed, and for these compounds it is not sufficient to determine the integrated exposure. In this case, the pollution exposure has to be determined as the total period of time exposed to concentrations above the threshold value, or as the product of concentration and time for the period in which the exposure was above the threshold value. This second concept is the basis for the proposed revised ozone and particulate matter (PM) standards in the United States.

Measuring an individual's exposure to a given pollutant may be a relatively straightforward procedure. However, in a public health perspective the aggregated exposure of a certain population group (such as a community or, for example, an occupational cohort) is of interest. Obtaining this kind of information is a much more complex task, mainly because of the large number of people that need to be studied in order to ensure a representative sample and to obtain statistical power. One of the advantages of obtaining exposure data for a number of individuals in a specific group is that it is more straightforward to link exposure to health effects and to determine exposure–response relationships. However, the most common approach is the indirect method of combining pollution concentrations observed at various microenvironments (often, data from fixed monitoring sites are used to represent some of these) with data logs and diaries about the time spent in specific environments (e.g., see ref. 38). The problem of relating fixed-site monitoring data to population exposure has been discussed in the literature [39–41]. There are several assumptions implicit in the application of the indirect method (eq. 1):

- The concentration in the specific microenvironment is assumed constant or having a well-determined variation during the time the person is present there. This is often a crude but necessary assumption.
- The presence of a certain concentration in the microenvironment and the presence of the person are assumed to be independent events, which, of course, is not always the case.
- The number of microenvironments is limited to a tractably small number, disregarding or simplifying the variations within each microenvironment.
- Often, the procedure for exposure estimation is based on hourly or even diurnal mean values, disregarding higher frequency acute effects of shorter-term peak exposures.
- Indoor concentrations are often estimated from outdoor concentrations using fixed indoor/outdoor ratios (e.g., see refs. 42–44) which may in reality vary highly from place to place. Furthermore, indoor sources will in some cases contribute more to indoor concentrations than outdoor sources. These two factors are crucial since people in industrialized regions in general spend 80 to 90% of their time indoors [45,46] (see also Section 4.5).

All of these above assumptions need to be taken into account when the exposure estimates are used for the evaluation of possible health effects. Furthermore, when indirect methods are applied, it should be considered whether the available concentration measures are obtained at a relevant height and representative for the given environment. Often, monitoring in streets is performed at a height of 2.5 to 3 m, which is above the heads of the pedestrians. At the pavements in urban streets the concentrations are typically rather homogeneously distributed at the lowest 3 m, but there may be cases where this is not so, especially when short averages are considered.

4. AIR POLLUTION MONITORING

As already stated, air pollution exposure can be obtained from direct monitoring on a (specific) person or indirectly by monitoring (or calculating) pollutant concentrations at various environments. A personal monitor can be a small, lightweight device, for example, a diffusion tube, a badge, or a filter with a battery-operated pump, which can be carried or worn by the person during the normal daily routine. Personal portable monitors make it possible to measure exposure directly for each of the individuals in smaller selected population groups (or cohorts). By combining monitoring data with personal diaries or logbooks, it is possible to identify areas where the highest concentrations occur and sometimes even to identify (the nature of) the emission sources. Furthermore, this type of data is crucial for developing and testing exposure models.

4.1 Personal monitoring

For a number of pollutants, small portable personal exposure monitors sensitive enough for measuring ambient concentrations are now available, and undoubtedly more will be available in the near future. These monitors can be divided into two types:

- integrated samplers that collect pollutants over a specific period of time and then returned to the laboratory for analysis, and
- continuous monitors that use a self-contained analytical system to measure on location.

Both systems may be passive as well as active monitors. The active monitors use a pump and a power source to move air through a collector or sensor, whereas passive monitors use diffusion to bring the pollutant in contact with the sensor or collector. Today, passive diffusion samplers are available for compounds such as: carbon monoxide (CO) [40]; nitrogen dioxide (NO_2) [47,48]; nitrogen oxides (NO_x) [49]; ozone (O_3) [50]; and benzene [51,52]. Brown [53] has given a review of many of the techniques for monitoring NO_2, sulfur dioxide (SO_2), and benzene.

Active monitors are also available for a variety of compounds including particulate matter [54,55].

Most of the *personal portable monitors* used today are integrated samplers. Passive diffusion tubes and badges have proved especially useful, since they are inexpensive and easy to operate. By choosing a subgroup from a given population group via a random selection, it is possible to obtain a picture of the exposure profile of the entire group. This makes it possible to perform investigations on relatively large population groups. The disadvantage of the passive personal monitor is clearly the time resolution, and with this type of monitor it is therefore difficult to identify spatial and temporal variation in exposure and hence to infer specific sources.

4.2 Monitoring networks

For indirect estimation of exposure, the *monitoring networks* for ambient air pollution serve as important sources of information about pollution concentrations and their trends, mainly at fixed sites. These networks are established with the purpose of:

- providing warnings in connection with pollution episodes;
- estimating contributions from various sources;
- in some cases also for conducting process studies; and
- especially for following trends in pollution concentrations.

For use in air pollution exposure studies careful considerations are needed since these stations represent the conditions for the local site, and at nearby sites the conditions may be significantly different.

The urban monitoring network consists typically of street stations where compounds mainly emitted by local traffic and, to some extent, local industry [traditional compounds such as NO, NO_x, CO, SO_2, soot, and total suspended particulate matter (TSP)] are measured. More detailed analysis is often also performed for different metals in the particle phase. At a growing number of stations particle measurements are reported as particulate matter in the fraction under 10 µm in diameter (PM_{10}). It is anticipated that $PM_{2.5}$ (particle size less than 2.5 µm) soon will become a standard parameter in urban monitoring networks; a number of studies have indicated a relation between health effects and the fine fraction particle concentrations [56,57]. A recent study has shown that coarse particle concentrations are not associated with increased mortality [58]. It has been hypothesized that health effects of particles may be associated with the number concentrations rather than the mass of particles. Seaton [59] states that the smallest particles are the most dangerous because they can penetrate all the way to the alveoli and further to blood circulation. Another possibility is that surface properties of the particle (e.g., see ref. 60) or the particle composition such as, for example, the contents of polycyclic aromatic hydrocarbons (PAHs) should be given more attention. Rombout *et al.* [61] conclude, however, that with the current level of uncertainty regarding health effects of particles, it is not yet possible to indicate if a different indicator for PM is preferable.

The sources of particles are generally different for the typically observed three particle modes: coarse, fine, and ultrafine particles (e.g., see the study of Keywood *et al.* [62]). The actions required ensuring the reductions in concentrations are therefore also different. Future guidelines may be changed from mass-based limit values to limit value based on particle number concentrations. This means that the main focus may be on ultrafine particles in the size range below about 100 nm. Any standard on number concentration would need a specification of lower limit to the diameter range, as a function of number vs. diameter usually rises with lower diameter, at least down to 20 nm and sometimes well below. Other compounds that are about to become commonly monitored are different kinds of hydrocarbons such as benzene, toluene, and xylenes. In addition to the urban stations at "hot spot" sites in streets with heavy traffic, the networks in many cities are now supplemented with urban background stations placed in parks and backyards or (preferably) at roof top level. Besides providing valuable information about the current pollution concentrations, they may also serve as important tools for studies of the governing chemical and physical process as well as for model evaluation. Data from urban background stations may serve as input for street pollution models [23], but these data are also representative for the air in the ventilation of most urban buildings, where ventilation systems are usually placed on the backyard side of the building. Stations outside the city, far away from built-up areas, may additionally provide information on rural background concentrations of air pollution.

Easily measurable "indicator" components allow estimation of concentrations of other compounds for which monitoring is less straightforward or highly expensive. Therefore, even though a compound may not be harmful itself, it may turn out to be very useful as a compound in the monitoring program, when it is used as an indicator for other and more harmful pollutants. An example is the use of black smoke data to estimate B(a)P concentrations [63]. The relation between the pollutant and its indicator needs naturally to be checked on a regular basis. This check can be carried out by operating the more expensive measurements on a single station or alternatively over shorter periods during selected campaigns.

4.3 Scouting, scanning, and monitoring

During recent years new measuring techniques have become available, especially a number of new optical methods have been developed for continuous monitoring. These techniques make it possible to measure a considerable number of compounds with high time resolution. With such new and better automatic measuring techniques available, it is important to define criteria for selecting compounds that should be measured. A process called *scouting, scanning, and monitoring* has recently been introduced to support the graded application of different measuring regimes (see discussion by F. de Leeuw [64]). These measuring activities are:

- Scouting: the performance of field campaigns with a limited number of exploring measurements in source areas and receptor areas.
- Scanning: the performance of systematic measurements of air quality at zone, agglomeration, or country levels.
- Monitoring: routine measurements performed on multi-annual and large area (e.g., country) basis.

Scouting can indicate which compounds may be present at a given site. When these detected compounds are hazardous, or their presence might indicate that other more serious species are present, *scanning* is performed. Scanning involves analyzing a variety of compounds with the aim of discovering which compounds may be present at harmful concentrations, and which should be measured on a routine basis under the *monitoring* networks. The procedure will identify which compounds are associated with human health risk at current concentrations.

4.4 Air quality directives

The new European Community Council Directive on Air Quality Assessment and Management, often referred to as the *Framework Directive* (FWD), aims at better quality and uniformity of air quality monitoring [65]. The aims and objectives are to:

- establish objectives for improving ambient air quality in the EU using a set of exposure/dose limits where harmful effects to the environment as a whole and to human health are minimized,
- assess the ambient air quality in Member States in a uniform manner,
- make available information on ambient air quality to the public, and
- maintain good ambient air quality and improve poor ambient air quality.

In order to "assess the ambient air quality in Member States in a uniform manner" the network will be designed in similar ways in all Members States. The FWD "daughter" directives have been adopted or are under preparation for the following pollutants: SO_2, NO_2, particles (PM_{10} and $PM_{2.5}$), lead, O_3, benzene, and CO [65,66]. The limit values are based on lowest-observed-adverse-effect levels (LOAEL), and are mainly based on WHO's recommendations published in 1997. The target dates for compliance, which is the time when all member states must comply with the limit values, will be based on economic and technical possibilities.

The directives will define the monitoring strategy for every pollutant. Ideally, the monitoring stations should be located in order to be representative for the exposure of the population. However, it is realized that it is necessary to supplement the measurements with other assessment tools, for example, air quality models. The extent of the monitoring will depend on the concentration of the pollution. In zones where the limit values are likely to be exceeded, well-defined monitoring must be carried out. In zones with lower pollution concentrations so-called indicative measurements (or scouting) can be carried out, or measurements supplemented with model estimates. In zones with the lowest concentrations simpler estimates can be made, based on emission inventories, simple model estimates, etc.

4.5 Outdoor and indoor exposure

An obvious disadvantage of using the direct method based on fixed-site monitors or models for outdoor pollutant concentrations in exposure estimation, is the already mentioned fact that people spend a significant part of their time indoors. Some knowledge about indoor concentrations is, therefore, vital in assessing exposure [26]. For some pollutants a relatively simple relation between indoor and outdoor concentrations may be obtained from experimental data. Such simple relationships were determined in a study on particulate matter inside and outside seven homes in Birmingham [28]. The study showed indoor/outdoor relations for $PM_{1.1}$, and PM_{10} of 0.8 and 1.0, respectively. However, for some pollutants and at certain conditions, indoor sources may dominate over outdoor sources and thereby determine the indoor pollution concentrations. A number of studies have found that for some pollutants indoor concentrations were frequently higher than outdoor concentrations (e.g., see refs. 42,67). For these cases, special surveys need to be carried out. The ratio between indoor and outdoor pollution has also been investigated in other studies (e.g., see refs. 68,69). It seems that simple ratios can be applied, if the aim is to estimate average population exposure. However, for more detailed studies of the distribution of the cohorts' exposure or for exposure of individuals, more specific investigations of indoor sources may be needed.

5. AIR POLLUTION MODELING

Models may serve as very useful tools for indirect estimation of human exposure. As already stated, it is not possible to perform monitoring in all the various environments that the population meets. Lifetime exposure cannot be measured directly, and for this kind of study modeling is the only option.

Furthermore, data from air quality models can supplement the monitoring data for performing mapping of pollution concentrations in the various microenvironments in which monitoring is not performed. For model tools to be useful in exposure studies, they need to be well tested and they need to describe the dominating physical and chemical processes in the atmosphere at the given location [70]. Further, it is important that when comparative studies are performed harmonized model tools are applied, so that differences because of model parameterizations can be avoided. For point source models such harmonization work is already initiated (e.g., see refs. 71,72), and similar work will follow for other model types such as, for example, street pollution models and transport-chemistry models on regional and long-range transport scales.

Since a significant part of exposure of the population in many cities is caused by emissions from traffic in urban streets, *street pollution models* serve as important tools in exposure assessment. Examples of such models are STREET [73], CPBM [74], OSPM [75], and CAR [76]. In the following section, we give a few examples of how the OSPM has been applied for exposure studies in Denmark and how the CAR model has been applied in the Netherlands.

5.1 Exposure modeling in Denmark

Bus drivers and letter carriers can be exposed to high concentrations of air pollution from traffic during their working days. Monitoring this exposure on workers in their working environment demands considerable resources, and, therefore, there is a need for comprehensive model tools for estimating pollution exposure for use in epidemiological studies. In a resent Danish study—the *Bus Driver project*—nitrogen dioxide (NO_2) measurements were performed by passive diffusion samplers inside a bus, outside a bus, on a letter carrier, and on the bicycle of the letter carrier during a three-weeks campaign in Copenhagen, Denmark [77]. Sampling was performed for the entire working day of the bus driver and for the total mail route for the letter carrier. Calculations with the Operational Street Pollution Model (OSPM) were performed for 22 selected street sections along the bus route and the mail route of the letter carrier. Applying information from bus schedules and diaries, the average exposure of the bus and the letter carrier's bicycle was obtained. The measurements showed that the NO_2 concentrations inside and outside the bus were practically identical. Similarly, the NO_2 concentrations on the letter carrier and the bicycle were similar. The OSPM was able to reproduce the measurements well (Figs. 4 and 5), and the study, therefore, showed that this type of model could serve as a useful tool for exposure assessment in occupational epidemiological studies of bus drivers in urban areas.

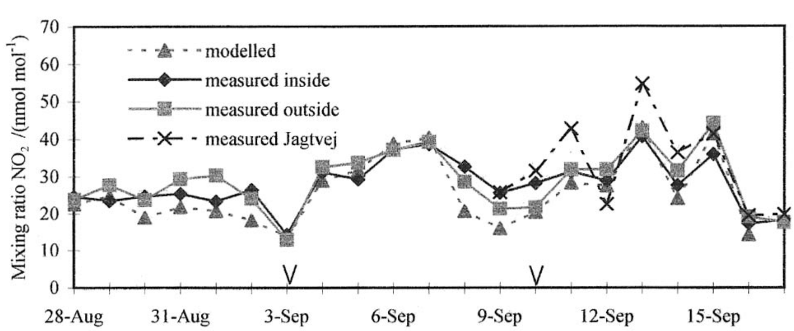

Fig. 4 Average nitrogen dioxide mixing ratios over a whole working day of the Copenhagen bus driver for the campaign period 28 August–17 September 1995. The figure shows measurements for the entire working day of the bus drivers obtained inside and outside the bus, and results obtained from OSPM calculations representing the average concentrations along the bus route. Average concentrations for the working hours at the monitoring station Jagtvej (one of the streets on the bus route) are shown as well. Arrows on the time axis indicate Sundays [77].

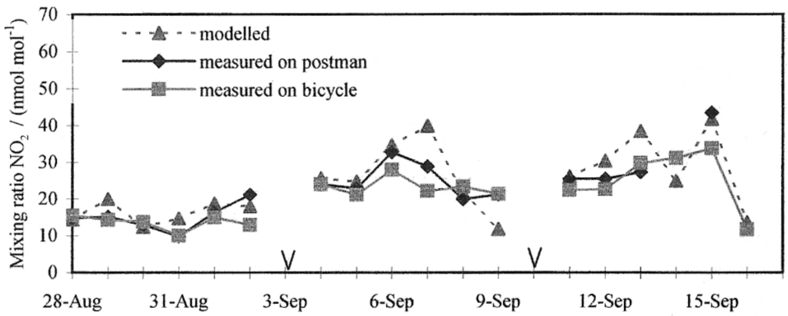

Fig. 5 Average nitrogen dioxide mixing ratios during the mail route of the Copenhagen letter carrier for the campaign period 28 August–17 September 1995. The figure shows measurements sampled for the time spent on the mail route on the letter carrier and on his bicycle and results obtained from OSPM calculations representing the average concentration along the mail route. Arrows on the time axis indicate Sundays (when no post is delivered) [77].

In the described study of Hertel *et al.* [77], information concerning the configuration of the streets (street orientation, street width, height of buildings along the street, etc.) was manually obtained on location, and information about traffic was obtained from the local municipality. Another study also based on calculations with the OSPM was the Danish *Children cancer study* [78–80]. The possible association between exposure to traffic air pollution and development of childhood cancer in Danish children was investigated. Exposure at the front door at the address was taken as an indicator of the personal exposure of the child. Input data for the OSPM calculations were obtained from a questionnaire sent to the local authorities. The information in the questionnaires was digitized, and a program was developed for interpretation and subsequent generation of input files for the model [81,82]. The system was evaluated against a series of NO_2 and benzene measurements obtained from 200 addresses. A reasonably good agreement was obtained (Fig. 6), and the system was subsequently applied to nearly 20 000 addresses of Danish children in the period 1960 to 1991 [79].

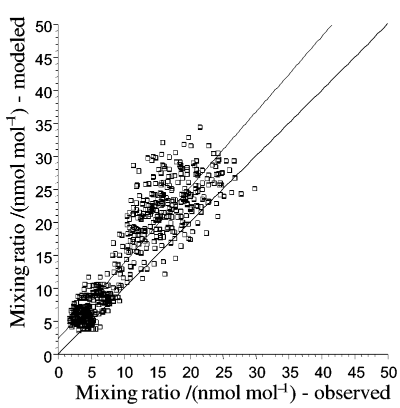

Fig. 6 Comparison of about 1200 observed and calculated monthly mean NO_2 mixing ratios at the address (front door) of 200 Danish children (100 in Copenhagen and 100 in rural areas). Data are identical to the ones presented in Raaschou-Nielsen *et al.* [80].

5.2 Exposure modeling in the Netherlands

In the Netherlands the Calculation of Air Pollution from Road Traffic model (CAR) has been developed [83] as a tool for evaluation of possible street location where air quality standards may be exceeded. CAR is a simple, parameterized, and easy-to-use model, which runs on a personal computer. In the Netherlands, the model supports provincial and municipal authorities in the implementation of air quality decrees under the Air Pollution Act. The CAR model predicts annual mean concentrations and 98-percentile values of components emitted by traffic such as nitrogen dioxide (NO_2), carbon monoxide (CO), lead, and benzene.

By analysis of measured concentrations in streets and an extensive program of wind tunnel experiments the relation between emissions and concentrations was investigated for a large number of configurations, which differs with respect to distances to the road axis, dimensions and shapes of streets, the vicinity and dimensions of buildings, effects of trees on wind velocity, etc. Based on these studies parameters with the largest influence on the concentrations were selected. After the development the model has been validated by means of an intensive measuring program in different traffic situations and street configurations. At present, there is a yearly calibration of model parameters based on the measurements of 13 urban monitoring stations.

In the CAR model, computations are performed by calculation of:

- The local street emission from speed-class-dependent emission factors for light- and heavy-duty cars, the traffic density (number of cars per day), and the fraction of heavy duty traffic in the street.
- The street-specific concentration from the traffic emissions and the street-type-specific dispersion parameter, which was empirically determined, based on the wind tunnel experiments. The value of this dispersion parameter depends on the selected street type and distance to the road axis.
- Street-level air quality by adding a city background concentration (e.g., the upwind concentration measured in a more rural area).

The air quality at street level can be determined by means of the CAR model in combination with maps showing traffic intensities. In the Netherlands the CAR model is used for a yearly survey of air quality in Dutch cities. It is also used as an evaluation tool in the assessment of traffic management plans. An example of an application of the model is given in Fig. 7 presenting the total length of roads in Dutch cities where air quality limit values are exceeded over the period 1988–1995. In general, the results indicate that the air quality along city streets is improving. As a result of the introduction of the 3-way catalyst and unleaded petrol the limit values of lead (0.5 $\mu g/m^3$ as yearly averaged) is no longer

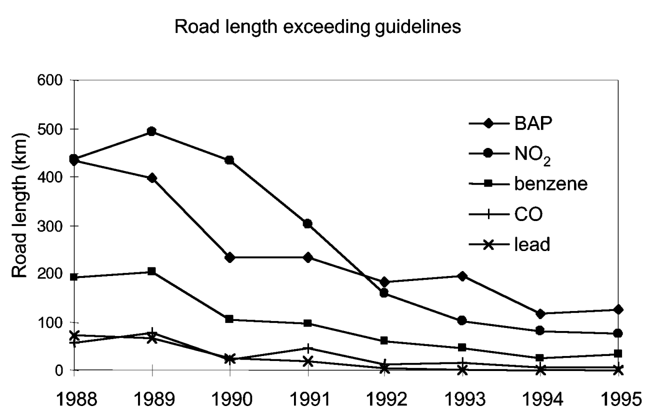

Fig. 7 Total length of roads in Dutch cities where national air quality limit values are exceeded, during the period 1988–1995 [84].

exceeded after 1993. The exceedances of CO limit value (98-percentile of 6 mg/m^3) are reduced to a few kilometers. Similar but less strong reductions are found for the other pollutants. In recent years, exceedances of B(a)P limit value (1 ng/m^3 as yearly averaged) outnumbers the exceedances of other pollutants. As the number of diesel cars is still increasing, exceedances of the B(a)P limit values are not likely to diminish in the coming years.

A recent extension of the CAR model is the CARSMOG model [85], which calculates hourly concentrations of traffic-related pollutants for standard streets in all major Dutch cities. CARSMOG calculates concentrations in "standard" streets using a normalized, annually averaged street contribution, the distribution of traffic emissions over the hours of the day, days of the week and month of the year, and the fluctuating traffic pattern obtained from a comparison between measured and modeled street concentrations for operational street stations. The model can be a valuable tool for municipal authorities for controlling air quality in their cities. Both CAR and CARSMOG models can easily be applied in cities in other countries, provided that (a limited number of) monitoring stations are operational for validation and calibration of the models.

5.2 Use of GIS in street pollution modeling

In these years, geographical information systems (GIS) are being integrated into many monitoring programs, not only for presentation purposes, but also as useful tools in producing mappings of air pollution concentrations in urban areas, etc. The dispersion of pollution in urban areas is highly influenced by the presence of buildings, and, therefore, a detailed description of the specific street configuration is needed in order to model the concentrations from the traffic in a given street (e.g., see ref. 23). Street configuration data may be obtained manually or from questionnaires filled out by local authorities (e.g., see ref. 82). However, automatic map interpretation programs may also be designed to provide the street configuration of a given street or even a specific address, which can then serve as a useful tool in exposure modeling. An example of such a system is the Danish AirGIS system that is now applied for exposure assessment ([86–88]). This system is based on data from national administrative databases: the Central Personal Database (CPR), the Central Business Database (CVS), the Building and Residence Database (BBR), the National Address Database, and local traffic and road databases. An example of results obtained with the AirGIS system is shown in Fig. 8. GIS-based systems are finding increasing use in assessment of air pollution levels and exposure (e.g., see refs. 89,90).

5.3 Inverse modeling

Essential for the application of dispersion models is reliable input data concerning emissions. However, in many cases the emission factors for the different vehicle categories are not well known. In this case, inverse modeling can be performed. This process involves a backward calculation procedure, using street pollution models and air quality measurements from a fixed-site street and urban background monitor, meteorological data, and traffic counts, to estimate the actual emission factors for the specific car fleet (e.g., see ref. 91). The obtained emission factors can then be used for calculations in other streets for which monitoring data are not available.

5.4 Exposure models

In some cases, models have been developed specifically for exposure modeling. These can either be physical models based on the microenvironment approach or statistical models that relate exposure to selected and easily determined parameters. Stochastic components may, furthermore, be added to the physical models in order to reflect the variability, for example, in pollutant concentrations in a given microenvironment. Examples of exposure models based on the microenvironment approach are:

Fig. 8 Number of people living at a given address, annual mean benzene concentrations (1996) computed with the AirGIS model, and a simple exposure index given by number of people multiplied by the annual mean concentration [86].

- The Simulation of Human Air Pollution Exposures (SHAPE) uses Monte Carlo techniques to vary data for concentrations and time–activity pattern within certain ranges [46].
- The Air Pollution Exposure Model (AirPEx) is based on concentrations obtained from monitoring stations and 24-h diurnal time–activity pattern obtained from a study of 5000 individuals [92].
- The American National Air Quality Standards Exposure Model (NEM) relates personal exposure to concentrations and time spent in a number of microenvironments. NEM was designed to determine the effects of air quality standards on population exposure [34].

6. TIME–ACTIVITY PATTERN

Time–activity pattern of the population, of course, to a large extent governs the exposure to air pollution. This has already been discussed in the previous sections and may be illustrated in many ways. One example is given in Fig. 9, which shows the diurnal variation in the fraction of sports activities taking place together with the diurnal variation in ozone concentrations.

Time–activity pattern of the population are usually not available. One of the simplest ways to perform human exposure investigations is, of course, to relate exposure to outdoor pollutant concentrations at the front door, which may be the only feasible approach in many retrospective studies (e.g., see ref. 79). However, other types of studies offer the opportunity to measure personal exposure and at the same time collect information about time–activity patterns. In Hagen *et al.* [94], 5800 persons in a northern region of Norway were requested to fill in a diary concerning their activities and well-being during a campaign period in which a number of air pollution measurements were performed simultaneously. The information concerning their time pattern in different activities was later used as input for an air pollution exposure model. In the Netherlands a similar survey on time–activity pattern has been performed for 5000 individuals [92].

In most cases only sparse information about the time budgets, activity pattern and commuting behavior of the population are available. For example, information about the time in the most critical microenvironments with respect to pollution, can seldom be obtained. It is especially important to investigate whether sensitive groups such as elderly people, children, and people with different illnesses have time–activity patterns that differ significantly from the general population. There may also be large regional differences and differences over respective age groups. This suggests that for long-term

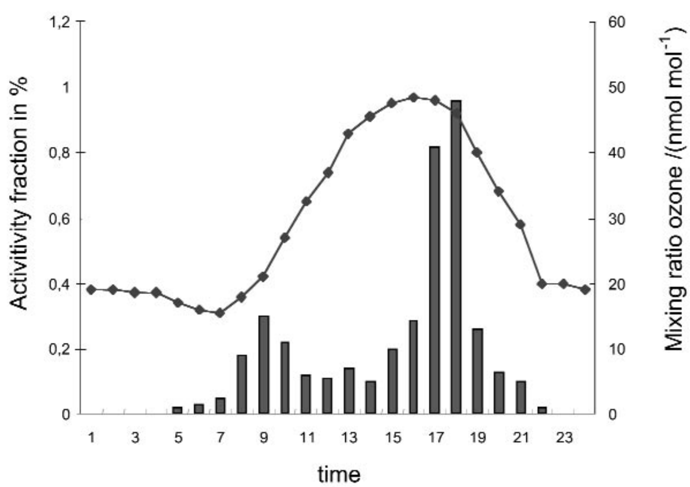

Fig. 9 The diurnal variation in the fraction of sports activities and mixing ratio of ozone [93].

exposure studies a different time–activity pattern should be applied over the lifetime of a person. Furthermore, the a person's residence changes many times during his/her lifetime. Swedish studies indicate that for the Swedish population as a single group, there is an average of about six residential address changes during a lifetime [95], but the number seems to be higher, i.e., in North America [96].

A review of time–activity patterns in exposure assessment is given in Ackermann-Liebrich *et al.* [97]. The information needed in such studies include location of the activity, the period or time when the activity took place (e.g., time of day, phase in life), and the duration of the activity. The information that can be obtained from these kinds of investigations can be divided into two categories:

- data collected by national level institutes such as a national bureau of statistics, building registers, etc. (data such as age, occupation, socio-economic status, location of houses, working places, etc.), and
- information collected as a specific part of air pollution epidemiological studies (e.g., from questionnaires).

A diary (or logbook) can be supplemented by an automatic device that is activated each time the person in the experiment has made an entry in the diary. Thereby, the time is automatically stored. A totally different concept from using a diary is an electronic time–activity monitor or data logger (e.g., see the overview in Jantunen [98]). Such devices may automatically detect whether the person is outdoors or indoors, etc. This kind of device has rarely been used in studies to date, but may be a useful tool in the future as the technology becomes more advanced. Related technology to adopt in future systems are likely to include the global positioning system (GPS) receiver, based on satellite information, that can compute the location at any time with a high precision.

Fig. 10 Example of GPS data logging during an air pollution exposure study in Denmark. Positions are plotted as black dots for every 6 s. Data are obtained from a GPS in a backpack, and an adjustment is performed by use of a corrector that makes use of information from FM radio-masts with known positions (differential GPS).

In an ongoing Danish research program a GPS system was applied to track study subjects during an exposure campaign. The battery-driven GPS was carried in a backpack together with a $PM_{2.5}$ cyclone and a pump. The GPS data were corrected to obtain higher precision by use of information about position of Danish radio-masts by a device developed by the National Survey and Cadastra Denmark (Spot-FM). After correction, data were stored on a Palm-top mini-PC for later analysis in the laboratory. Figure 10 is an example of data from this system where the positions are plotted on a map with building images. The largest problem with this type of equipment is the weight of the battery packs, which tends to alter the daily routine of the study subjects.

An important issue regarding time–activity patterns for exposure studies is to reach consensus on which parameters are needed. Data may be obtained from more or less automatic devices or from questionnaires. However, it is important that the right information is obtained, stored, and made available in a useful form; for example, the design of questionnaires for determination of time–activity patterns is not an easy task from this perspective.

7. BIOLOGICAL MARKERS

This kind of investigation involves analyses of bodily material (e.g., urine, saliva, blood, exhaled breath, faeces, hair, nails, etc.) in which the concentration of a pollutant, or the metabolite of a pollutant, is determined. Biomarkers may provide information about the dose that has been received and taken up by the body, or they may provide information about effects (e.g., oxidative damage to cells). A recommendation for conducting biomarker measurements of volatile organic compounds was given by Heinrich-Ramm *et al.* [99]. Another overview was given in Rolle-Kampczyk *et al.* [100].

Biological monitoring has three major advantages over environmental monitoring for estimating health risks [34]:

- Only pollutants that cross the boundary and enter the body are included.
- Biological markers are more directly related to the biological processes from which health consequences arise.
- Biological monitoring can serve as a basis for total risk estimates from multiple chemicals. It takes into account all exposures from all routes.

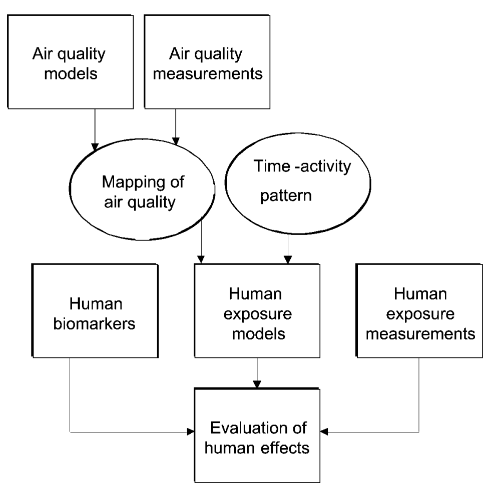

Fig. 11 Human biomarkers should be used in connection with exposure data obtained from measurements and modeling.

The greatest disadvantage is that specific markers are known for only a few compounds, which allow a specific (selective) inference to the air pollution exposure components. A mixture of pollutants often will give different response in biomarkers (and in health effects) than the presence of a single pollutant. Therefore, there is a great need for specific laboratory studies under controlled conditions in order to interpret the results from field studies. Exposure studies should investigate simultaneously the internal dose and external (close to human) exposure. This supports the statement that exposure measurements and biological markers should be used to supplement each other (Fig. 11). Caution should be taken in the interpretation, when analyses of biomarkers are made and the results are compared with exposure data and estimated dose. Because of the various cleaning processes in the body, material is steadily removed from the target organs, continuously changing the concentration in the organ.

8. DISCUSSION AND RECOMMENDATIONS

Studies of human exposure may serve various purposes. It is crucial that the right strategy is chosen for the specific study in order to obtain the optimal accuracy of the exposure estimates. Several approaches or methods can be applied for determination of human exposure to outdoor air pollution:

1. categorical classification based on indicators of exposure (e.g., type of residence, type of job, indoor sources to exposure, etc.);
2. application of biological markers of pollutant exposure (e.g., analysis of urine and blood samples for PAH metabolites, etc.);
3. extrapolation of monitoring data over wider areas (an entire urban area, etc.) to represent the exposure of a certain population;
4. monitoring individual exposure of an entire cohort or a selected subgroup of a population/cohort using portable devices;
5. determination and application of statistical models that relate exposure to selected and easily determined parameters; and
6. application of the indirect method based on the microenvironment approach and using monitoring data and well-tested air quality models.

Method 1 can only be used for very crude estimates and is considered inadequate for application in air pollution epidemiology [1]. Categorical classification has, therefore, not been treated explicitly in this paper.

Method 2 is application of biological markers (or biomarkers) for exposure or dose evaluation. These markers are direct measures of the concentration of a pollutant or its metabolite in bodily material (e.g., urine or blood). The various cleaning processes in the body steadily remove the pollutant and its metabolites from the bodily material. This has to be accounted for in the interpretation of the data. Biomarkers provide very useful information, but it is recommended that these markers be applied in combination with monitoring of personal exposure (method 4).

Method 3 can only be recommended for very crude estimates. The variability in pollution concentrations within, for example, an urban area will, for many compounds, be very large, even when longer averages are considered. Kriging procedures have, in some cases, been applied in order to interpolate ambient data from an irregularly spaced set of points for epidemiological studies, but these have typically not been constrained by physiochemistry and may, hence, provide physically inconsistent fields, especially for very reactive gases.

Method 4 can provide very useful information for epidemiological cohort and cross-sectional studies. For specific population groups (or cohorts) personal exposure monitoring may thus provide the needed information. For a larger cohort, a random selection of a subgroup may provide information that can be extrapolated to the total cohort. New monitoring techniques (active as well as passive) have made it possible to perform personal monitoring for an increasing number of compounds. The new techniques need to be carefully validated against well-documented monitoring techniques. The disadvantage is that impact assessment of emission reduction strategies, etc. cannot be carried out.

This disadvantage also applies to method 5, which is restricted not only to a specific group, but also to specific environmental conditions. Impact assessment of emissions reduction strategies can thus only be carried out when method 6 is applied. In some case-control studies, it is not possible to use personal exposure monitoring for determination of the exposure. In this case, methods 5 and 6 are usually the only options for estimation of exposure.

Method 6 (the indirect method) demands a rather detailed study of the most representative microenvironments and detailed time–activity pattern of the population.

For population exposure of larger cohorts, method 4 with random selection of a subgroup of the cohort may still be applied. However, this may depend on what is technically and economically possible in the specific study. For long-term exposure, it will often be necessary to use indirect methods (methods 5 and 6) for estimating human exposure. Furthermore, it cannot be expected that measurements on larger cohorts will be carried out on regular basis. Therefore, when the aim is to follow the development in human exposure, indirect methods to estimate exposures will often be the only feasible approach. Combinations of monitoring at fixed-site locations and use of model tools are useful for obtaining concentrations at the various outdoor microenvironments. However, there is still a strong need for more information about the concentrations and variations in concentrations in various microenvironments. In some cases, these are highly uncertain.

Most people in the industrialized world live in cities where local sources (especially traffic) contribute significantly to the pollution concentrations (with ozone as an exception—ozone concentrations are generally lower in urban areas compared with rural sites). The presence of buildings has a major impact on the local pollution concentrations in cities. For estimation of urban street pollution concentrations, local street configuration data are needed. The use of GIS may serve as a tool for automatic generation of such data for large numbers of streets in given urban areas based on present technical digital maps and databases whenever these are available. Indirect methods build into GIS systems will turn out to be very strong tools in future exposure assessment studies.

For exposure modeling there is still a great need for more detailed databases concerning time–activity patterns of the different populations, combined with exposure data. Questionnaire investigations combined with the various available statistical data from national bureaus need to be compiled into time–activity databases for use in exposure studies. Personal exposure studies can serve as essential tools for validation of population exposure estimates. Diaries and logbooks carried out in connection with such studies should serve as information for general time–activity pattern. Furthermore, information about the ratio between indoor and outdoor pollution can be crucial for certain pollutants.

Impact and scenario studies where the effects of different strategies for reduction of emissions are investigated in terms of their potential impact on human exposure can only be carried out by means of the indirect method, and only by application of physiochemical models (method 6). Detailed parameterization allows one to construct scenario studies and carry out sector-by-sector studies. Such parameterizations require accuracy, which in turn requires innovative approaches in sampling and analysis. For practical use, in the near future, investigations need to be based on well-tested models that describe the dominating physical and chemical processes governing the pollutant concentrations at the various microenvironments. Careful sensitivity and validation tests and, in the case of comparative studies, model harmonization are also obvious tools in this work.

The identification of the most important sources to human exposure may be compiled from personal exposure measurements with high time resolution combined with detailed diaries/logbooks. For measuring techniques with long sampling time, statistical methods may be applied for identification of the most important sources. Other types of studies can be measurements at specific sources and use of receptor modeling on detailed data from fixed-site monitoring stations. The last two approaches may be used to identify sources of outdoor concentrations in specific areas.

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LIST OF ACRONYMS

The most important acronyms are listed in alphabetic order.

Acronym	*Explanation*
AirGIS	Air pollution exposure modeling system: a GIS-based model system developed at NERI in Denmark
AirPEx	Air Pollution Exposure model: an exposure model developed by RIVM in the Netherlands
B(a)P	benzo[a]pyrene: one of the hazardous hydrocarbons
BBR	Building and Residence Database: a Danish acronym for a Danish database
CAR	Calculation of Air pollution from Road traffic: a street pollution model developed by TNO and RIVM in the Netherlands
CARSMOG	extended version of the CAR model
CO	carbon monoxide
CPBM	Canyon Plume Box Model: a street pollution model developed in Germany
CPR	Central Personal Database: a Danish acronym for a Danish database
CVR	Central Business Database: a Danish acronym for a Danish database
DG-XII	Directorate General-XII, under the European Commission
DPSIR	driving forces, pressures, state, impact, and response: a conceptual model developed by RIVM in the Netherlands
EEA	European Environment Agency
EC	European Commission
FWD	Frame Work Directive: the European Community Directive on Air Quality Assessment and Management
ExternE	Externalities of Energy: a European project
GARP	Green Accounting Research Project: a European project
GIS	geographical information system
GPS	global positioning system: a satellite-based positioning system
LOAEL	lowest-observed-adverse-effect level
NEM	American National Air Quality Standards Exposure Model
NERI	Danish National Environmental Research Institute
NO	nitrogen monoxide
NO_x	sum of nitrogen monoxide and nitrogen dioxide
NO_2	nitrogen dioxide
OSPM	Operational Street Pollution Model: a street pollution model developed at NERI in Denmark
O_3	ozone
PAH	polycyclic aromatic hydrocarbons
PM	particulate matter
PM_x	particulate matter under x µm, for example, PM_{10} and $PM_{2.5}$
RIVM	Dutch National Institute of Public Health and the Environment (Dutch acronym)
SATURN	Studying Atmospheric Pollution in Urban Areas: a EUROTRAC program
SHAPE	Simulation of Human Air Pollution Exposures: an exposure model developed in the United States

SO_2	sulfur dioxide
STREET	Street pollution model developed in the United States
TSP	total suspended particulate matter
UNEP	United Nations Environment Program
WHO	World Health Organization

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