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Review

Quantifying human exposure to air pollution—Moving from static monitoring to spatio-temporally resolved personal exposure assessment

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HIGHLIGHTS

► We review and discuss recent developments and advances of research into personal exposure to air pollution.
► We emphasise the importance of personal exposure studies to accurately assess human health risks.
► We discuss potential and shortcomings of methods and tools with a focus on how their development influences study design.
► We propose a novel conceptual model for integrated health impact assessment of human exposure to air pollutants.
► We present a conceptual model taking into account latest technological capabilities and socio-economic context.

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ABSTRACT

Quantifying human exposure to air pollutants is a challenging task. Ambient concentrations of air pollutants at potentially harmful levels are ubiquitous in urban areas and subject to high spatial and temporal variability. At the same time, every individual has unique activity-patterns. Exposure results from multifaceted relationships and interactions between environmental and human systems, adding complexity to the assessment process.

Traditionally, approaches to quantify human exposure have relied on pollutant concentrations from fixed air quality network sites and static population distributions. New developments in sensor technology now enable us to monitor personal exposure to air pollutants directly while people are moving through their activity spaces and varying concentration fields.

The literature review on which this paper is based on reflects recent developments in the assessment of human exposure to air pollution. This includes the discussion of methodologies and concepts, and the elaboration of approaches and study designs applied in the field. We identify shortcomings of current approaches and discuss future research needs. We close by proposing a novel conceptual model for the integrated assessment of human exposure to air pollutants taking into account latest technological capabilities and contextual information.

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1. Introduction

Human exposure to environmental pathogens and specifically air pollutants is a highly topical issue. Clean air to breathe is a basic requirement of life and the quality of air both outdoors and indoors is a crucial determinant of health (WHO, 2010). Air quality is affected by pollutants such as nitrogen oxides (NO_x), particulate matter (PM), carbon monoxide (CO) and ground level ozone (O_3).

Substantial growth in individual transport activities and energy consumption reflect growing affluence and contribute considerably to high and, in some cases, increasing ambient levels of air pollutant concentrations. Urban areas with high population densities are especially affected.

Air pollutants are ubiquitous and a certain level of exposure is inevitable, whether a person is indoors or outdoors. For risk and impact assessments of air pollution effects and the design of control policies, such as the UK National Air Quality Strategy (NAQS) or national Air Quality Standard regulations (Scottish Statutory Instrument, 2010) as well as indoor air quality information (Parliamentary Office of Science and Technology, 2010), it is necessary to accurately quantify everyday human exposure to air pollution. Traditionally, personal, environmental exposure has not been directly assessed for individuals, but rather by estimating population-wide exposure via networks of fixed monitoring sites deriving annual ambient average concentrations and spatial interpolation of the results. However technological advances have produced sophisticated monitoring devices carried or worn by a person during their regular daily routine allowing for personal exposure to be monitored explicitly. Time-geography accounting for the movement of people and their individual activity-space is a crucial determinant of personal exposure in this context. The following quote from the founding father of time-geography, Torsten Hägerstrand, reflects this well:

> "*Existence in society implies people are constantly in motion. Virtually every individual possesses his own unique field of movement, with his residence in the centre and with places of work, shops, places of recreation, residences of intimate friends, and other similar locales serving as nodal points.*" (Hägerstrand, 1967, p. 8)

In this paper the focus is on methods and concepts for monitoring the movement of individuals and their everyday exposure to environmental air pollution in space and time. Following the introduction of methods and concepts for exposure assessment in general, recent papers investigating personal exposure are assessed. Methods, concepts and technologies as well as study design described in these papers are discussed in the subsequent sections. We identify shortcomings and development potentials in this research area. Finally, we derive recommendations for future research needs and introduce a novel conceptual model for the assessment of human exposure to air pollution.

2. Background and scope of the review

Human exposure to a pollutant has been defined as occurring when "*a person comes into contact with the pollutant*" (Ott, 1982, p. 186). Exposure assessment is "*… the process of estimating or measuring magnitude, frequency and duration of exposure to an agent…*" (Zartarian et al., 2007, p. 58). Ideally, it is a complementary concept describing sources, pathways, routes as well as the uncertainties in the assessment. Personal exposure assessment is evolving quickly and latest advances in technology enable the tracking of individuals while simultaneously measuring pollutant concentrations. In this section, methods applied in exposure assessment and for time-activity analyses are reviewed, and their implementation in research is discussed. It is beyond the scope of this paper to give a complete account of exposure science and human exposure research; hence the reader is referred to two recent books (Lazaridis and Colbeck, 2010; Ott et al., 2007) and several articles (Ashmore and Dimitroulopoulou, 2009; Hertel et al., 2001a; Monn, 2001) covering the emergence, state and methods of this research area and its subtopics more comprehensively. Moreover this paper concentrates on research in industrialised countries and their specific exposure situations. Time-activity patterns in developing countries are different, as well as emission sources and lifestyle and hence the methods applicable (e.g. Allen-Piccolo et al., 2009; Branis, 2010; Colbeck and Nasir, 2010; Freeman and Saenz de Tejada, 2002).

The assessment of exposure to air pollutant concentrations in space and time is not trivial as it is affected by many determinants and governed by complex relationships and interactions between environmental and human systems. For risk and health impact assessment (HIA), different conceptual models have been developed reflecting these relationships. The modified *Driving forces–Pressures–State–Exposure–Effect–Action* (mDPSEEA) model (Morris et al., 2006; Steinle et al., 2011) for instance represents an impact pathway analysis, structuring and mapping the complex interactions between environmental and socio-economic factors. The "modified" in mDPSEEA addresses the explicit recognition of context, i.e. socio-economic, demographic and environmental factors, as modifiers for potential exposure and effect. Context can thus account for aspects affecting the susceptibility to and severity of an effect due to the same or similar exposure in different receptors.

Air pollutants are ever-present and comprise a range of substances interacting, reacting and creating many heterogeneous pollutant mixes. It is impossible to identify any individual air pollutant as a sole causal agent of an adverse health effect (Branis, 2010; Goldberg, 2007). Environmental, meteorological and microclimatic influences, which are changing dynamically, add to the complexity as well as people moving in space and time, showing individual behavioural patterns (McKone et al., 2008). This means personal exposure is a function of concentration and time (Nuckols et al., 2004). As a consequence, individuals can be exposed in any environment to a large variety of pollutants and pollutant mixes (Branis, 2010; Goldberg, 2007).

Exposure to air pollutants has traditionally been assessed based on data from fixed-site air quality monitoring networks. Such network sites usually provide a large quantity of data for a wide range of pollutants, albeit for one point in space. Applying interpolation techniques, spatial maps of air pollutant concentrations are derived, typically for annual average concentrations. With this derived pollution surface, pollutant concentrations can be spatially related to a population or a specific subpopulation such as asthma patients, children or pregnant women (Harrison et al., 2002; Nethery et al., 2008a, 2008b). Allocating a population to a monitoring site is most suitable for large population studies regarding outdoor air (Chow et al., 2002), but is unavoidably affected by assumptions implicit in the application of this indirect method compared to real exposure scenarios (Cattaneo et al., 2010; Hertel et al., 2001a). Exposure assessment based on averaged measurements artificially diffuses pollution and operates on aggregated demographic data, which is problematic for personal exposure assessment as it does not provide a representative measure of an individual's personal exposure (Rodes et al., 1991). Moreover using such fixed-site data as exposure estimates ignores the impact of individual mobility patterns, especially time spent away from home (Setton et al., 2011).

Suitable alternatives to using data from fixed site monitoring are spatio-temporally explicit modelling, and/or personal monitoring.