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Review article

Airborne particles in indoor environment of homes, schools, offices and aged care facilities: The main routes of exposure

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ABSTRACT

It has been shown that the exposure to airborne particulate matter is one of the most significant environmental risks people face. Since indoor environment is where people spend the majority of time, in order to protect against this risk, the origin of the particles needs to be understood: do they come from indoor, outdoor sources or both? Further, this question needs to be answered separately for each of the PM mass/number size fractions, as they originate from different sources. Numerous studies have been conducted for specific indoor environments or under specific setting. Here our aim was to go beyond the specifics of individual studies, and to explore, based on pooled data from the literature, whether there are generalizable trends in routes of exposure at homes, schools and day cares, offices and aged care facilities. To do this, we quantified the overall 24 h and occupancy weighted means of PM_{10}, $PM_{2.5}$ and PN - particle number concentration. Based on this, we developed a summary of the indoor versus outdoor origin of indoor particles and compared the means to the WHO guidelines (for PM_{10} and $PM_{2.5}$) and to the typical levels reported for urban environments (PN). We showed that the main origins of particle metrics differ from one type of indoor environment to another. For homes, outdoor air is the main origin of PM_{10} and $PM_{2.5}$ but PN originate from indoor sources; for schools and day cares, outdoor air is the source of PN while PM_{10} and $PM_{2.5}$ have indoor sources; and for offices, outdoor air is the source of all three particle size fractions. While each individual building is different, leading to differences in exposure and ideally necessitating its own assessment (which is very rarely done), our findings point to the existence of generalizable trends for the main types of indoor environments where people spend time, and therefore to the type of prevention measures which need to be considered in general for these environments.

1. Introduction

Exposure to airborne particulate matter (PM) is one of the most significant environmental risks people face. Recent 'Global Burden of Disease' (GBD) assessments placed exposure to $PM_{2.5}$ (mass concentration of particulate matter with aerodynamic diameter $< 2.5\ \mu m$) among the top ten risks leading to worldwide lower life expectancy and/or lives with disease (Forouzanfar et al., 2015). Most of the PM exposure occurs indoors, because this is where people spend a large fraction of their lives.

Indoor particles are a mix of ambient particles that have infiltrated indoors, particles emitted indoors, and particles formed indoors through reactions of gas-phase precursors originating from both indoor and outdoor sources, as schematically presented in Fig. 1. Ambient

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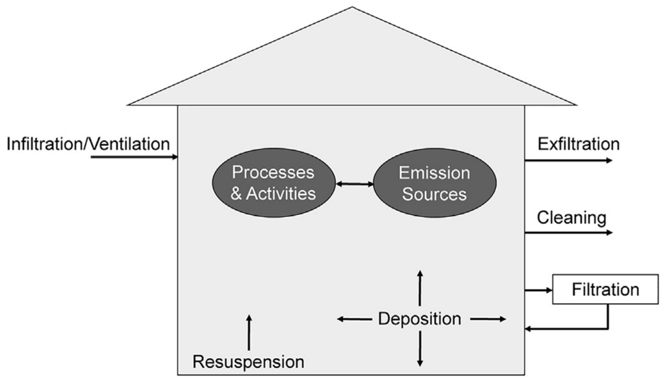

Fig. 1. Schematic diagram of the key factors influencing indoor air particle concentrations, adapted from Thatcher and Layton (1995).

(atmospheric) aerosols in urban environment originate predominantly from fossil fuel burning, automobile emissions, resuspension, or chemical and thermodynamic processes e.g. Belis et al. (2013), but also from long range transport. In an indoor environment, activities such as cooking or indoor combustion, e.g. Wallace (2006); smoking, e.g. Wallace (1996) and Waring and Siegel (2007); vaping, e.g. Schripp et al. (2013); secondary formation processes, e.g. Waring (2014); and dust resuspension, are the most significant sources of aerosols. Because of these different sources, airborne particles span a range of diameters from a few nanometers to tens of micrometers. Equivalent diameter d_p (e.g. µm, nm) is the classical descriptor of particle size in aerosol science, based on which particle transport, dynamics, and fate can be described (Nazaroff, 2004).

Exchange of air between indoors and outdoors plays a crucial role in indoor air pollution control. An air exchange rate (AER) [h^{-1}] is a measure of the volume added to or removed from a space divided by the volume of the space ASHRAE (2013). AERs parameterize air exchange mechanisms due to the individual or combined effects of infiltration through the building envelope and mechanical or natural ventilation (ASHRAE, 2013). Outdoor-air exchange introduce ambient aerosols indoors (El Orch et al., 2014; Johnson et al., 2016; Riley et al., 2002) and dilute any existing indoor aerosols, as well as any SVOCs that are precursors to aerosol formation indoors (Weschler and Shields, 2000; Weschler and Shields, 2003; Youssefi and Waring, 2014). Whichever of the three outdoor-air exchange mechanisms dominates, it strongly impacts the magnitude of the overall ambient aerosol source contribution. That is, the natural ventilation airflows move through large openings almost without aerosol loss, though infiltration and mechanical ventilation flows move through cracks in the building envelope or through filters, respectively, so the outdoor aerosol source contribution is lessened.

Many different facets of particulate matter are potentially of significance to health, including their physical properties such as size and its distribution, shape or surface area, as well as chemical composition and microbiology. Particle characteristics depend on the sources from which they originated and on the post emission processes involving the particles, and therefore the composition and toxicity of indoor particles is very complex, with similarities but also differences to outdoor aerosols.

The theory of basic processes driving aerosol dynamics is reasonably well established and has mathematical description. Numerous experimental studies quantified the relevant parameters of indoor environments and indoor air. Various types of modelling approaches exist, including those based on balance equations, physico-chemistry, computational fluid dynamics (CFD), Monte Carlo modelling, or combinations of these approaches, and they have been employed in many research projects to gain insight into the nature of indoor aerosol dynamics (Holmberg and Li, 1998; Hussein and Kulmala, 2008; Hussein et al., 2015; Loth, 2000; Nazaroff and Weschler, 2004; Rackes and Waring, 2013).

Despite this large body of knowledge, the complexity of the processes taking place in or affecting indoor environment makes drawing conclusions about general significance of various factors or processes, a very challenging task. In particular, *one of the key questions is the origin of the particles, whether they come from indoor or outdoor sources*, as very different prevention measures need to be put in place in each of these two cases. And finally, *are the concentrations encountered in various indoor environments, a health risk?* In the absence of answers to these questions, the effects of exposure to indoor air pollution cannot be quantified, nor can indoor air pollution be effectively managed, since no clear recommendations can be given to legislators or building owners, whether public or private.

The aim of this work was to provide a general overview, based on literature published, of: 1) the origin – indoor or outdoor – of different particle size fractions for selected key indoor environments; and (2) the significance of this knowledge for exposure control and management of indoor air quality. Particle size fractions considered were $PM_{2.5}$, PM_{10} (mass concentration of particulate matter with aerodynamic diameter < 2.5 µm and < 10 µm, respectively) and UFP (ultrafine particles, < 0.1 µm), measured typically as particle number concentration. The focus of this work was on homes, schools and day cares, offices and age care facilities, which are of significance as the most typical indoor environments where people spend the majority of their time. Following a comprehensive literature review, comparative analysis of the available data was conducted to elucidate the role of the key factors and processes affecting airborne particles in the above indoor microenvironments. Not included in the review were sources of and factors specific to: bioaerosols, cigarette smoke and e-cigarettes or indoor biomass burning, as these are very specific types of aerosols/sources, each a topic for a separate review.

2. Materials and methods

2.1. Literature search

Literature search was conducted to identify studies, which investigated both indoor and outdoor concentrations of various particle metrics in the indoor environments of interest. Many of such studies were identified by our earlier work Morawska et al. (2013), with several more published since then.

Studies were selected for inclusion based on whether they reported a mean and standard deviation in any of these environments. Another inclusion criterion was the presence of residents, studies conducted in empty test buildings were excluded, as well as studies where the participant were given restrictions in their daily habits (e g not allowed to cook).

2.2. Data analysis

Data from measurement periods of 24 h or a multiple thereof (e.g. 48 h, 168 h) were analysed in this section as “24 h” averages. For data which were recorded during the occupancy hours at schools, day care centres and in offices, these have been analysed as “Occupancy” averages. Due to very limited amount of reported data on occupancy time concentrations in homes (which from exposure assessment point of view seem to be the most relevant in any microenvironment) analysis of home environments was conducted for 24 h averages and their multiple thereof. For homes only data from publications reporting simultaneous and continuous measurements of both indoor and outdoor concentrations were included. Excluded were studies where smoking occurred, performed in unoccupied homes i.e. no residents and no indoor sources and studies assessing specific indoor sources in laboratory conditions. Due to lower amount publications on schools, day cares centres and offices as well as the fact that indoor/outdoor ratios were not calculated, the studies have not been restricted to those reporting both

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