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Deposition of aerosol particles from a subway microenvironment in the human respiratory tract

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ABSTRACT

Conventional subway systems are characterized by high particulate matter (PM) concentrations. To relate PM exposure to adverse health effects it is important to determine the dose of the inhaled particles in the human respiratory tract (HRT). Therefore, the total and regional doses of particles for a healthy adult male using the dosimetry model ExDoM in the subway system were estimated. The overall dose was determined using the average exposure $PM_{2.5}$ concentrations obtained from an extensive campaign in the Barcelona subway system, including measurements on the platforms and inside the trains. Despite the lower $PM_{2.5}$ concentrations inside the trains with respect to those on station platforms, the highest dose was observed inside the trains due to longer exposure time, evidencing the importance of the exposure period in the estimation of the particle dose. Overall, during a subway commuting travel, roughly 80% of the inhaled mass of subway $PM_{2.5}$ was deposited in the HRT. The highest amount of the inhaled particles was deposited in the extrathoracic region (68%), whereas the deposition was much smaller in the tracheobronchial tree (4%) and alveolar–interstitial region (10%). Individual's daily exposure to $PM_{2.5}$ and dose were estimated, considering a typical time-activity pattern of an adult male who lives in Barcelona and commutes by subway. While a subject typically spends approx. 3% of the day in the subway system, this microenvironment may account for up to 47% of the total $PM_{2.5}$ daily dose. These results might be similarly high for other commuting modes due to the reported high PM exposure levels. The dose is mainly dependent on the particle size and exposure concentrations.
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1. Introduction

Urban population is daily exposed to air particulate pollution from a range of sources, including the ambient environment and three main microenvironments: home, workplace and commuting. In fact, the exposure to airborne particles depends on the lifestyle of each individual and the different microenvironments frequented (Buonanno, Fuoco & Stabile, 2011; Buonanno, Marks & Morawska, 2013). Epidemiological and toxicological studies have shown associations between

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particulate matter (PM) and adverse health effects (e.g. Dominici et al., 2006; Katsouyanni et al., 2001; Pope & Dockery, 2006; Russell & Brunekreef, 2009; Schikowski et al., 2007; Valavanidis, Fiotakis & Vlachogianni, 2008). Although the large majority of these studies relate health effects to PM exposure (the inhaled concentration), the negative outcomes are mainly caused by the subsequent deposition of PM in the respiratory tract during breathing (Salma, Balásházy, Winkler-Heil, Hofmann & Záray, 2002). Hence, in order to understand the mechanisms behind the health responses, it is crucial to determine the respiratory tract deposition fraction (DF) of aerosol particles, which is their probability to deposit, and the dose (amount of inhaled particles deposited) (Löndahl et al., 2009). For aerosols this dose can be given as number, surface area or mass of the deposited particles. The dose of particles in the human respiratory tract (HRT) depends on a number of factors, including PM exposure concentrations, physicochemical characteristics of PM, exposure duration, and exposed subject characteristics, such as age, gender, state of health, lung morphology, and breathing parameters (Broday & Agnon, 2007; Glytsos, Ondráček, Džumbová, Kopanakis & Lazaridis, 2010; Heyder, 2004; Hofmann, 2011; Lazaridis, Broday, Hov & Georgopoulos, 2001; Patterson, Zhang, Zheng & Zhu, 2014). However, most of the studies on the health impact of aerosol inhalation link the observed health effects with day-averaged concentrations from fixed ambient air quality monitoring stations, rather than personal exposure to particles at the indoor and outdoor places where the individual may be active (Aleksandropoulou, Mitsakou, Housiadas & Lazaridis, 2008).

Inhaled particles are carried with the tidal air through the respiratory system. However, when travelling along an airway, particles will be exposed to different physical mechanisms forcing them to displace off the streamlines of the inhaled air volume and eventually depositing on the surrounding airway surfaces. The most important mechanisms acting upon the inhaled particles are diffusion (Brownian motion), inertial impaction, electrostatic charging, and sedimentation (gravitational settling) (Hofmann, 2011; Hussain, Madl & Khan, 2011; Löndahl et al., 2014).

The deposited dose of atmospheric aerosols in the human respiratory tract is measured by monitoring the inhaled and exhaled particle concentrations (e.g. Löndahl et al., 2008; Montoya et al., 2004; Morawska, Hofmann, Hitchins-Loveday, Swanson & Mengersen, 2005). This provides an empirical estimation for the total deposition pattern of aerosol particles in the respiratory system. Due to experimental limitations, the regional dose in the respiratory system (extrathoracic, tracheobronchial, and alveolar–interstitial regions) cannot be determined experimentally and is typically estimated by means of mathematical models. Several dosimetry models have been developed over the years (Aleksandropoulou & Lazaridis, 2013; Asgharian, 2004; Georgopoulos & Lioy, 2006; Heyder & Rudolf, 1984; ICRP, 1994; Klepeis, 2006; Koblinger & Hofmann, 1990; Lazaridis et al., 2001; Mitsakou, Mitrakos, Neofytou & Housiadas, 2007; Rudolf, Köbrich & Stahlhofen, 1990; Sturm, 2007; Yeh & Schum, 1980). These models for both total and regional deposition have been compared to experimental studies, with a reasonable correlation being obtained between model predictions and experimental measurements (Asgharian & Price, 2007; Löndahl et al., 2008; Stuart, 1984).

Several studies on PM exposure in different commuting modes along complementary routes have stated that all commuting modes (passenger cars, bus, subway, motorbike, cycling and pedestrian) are characterized by high PM exposure levels due to the fact that commuters are close to mobile emission sources. Moreover, in this assessment studies it is very important to account for the breathing rates and journey times (e.g. de Nazelle et al., 2012; Gulliver & Briggs, 2004). Many people living in metropolitan areas worldwide commute using underground subway transportation. Several studies have investigated the air quality in underground subway systems (see Martins et al., 2015a and references therein), and most of them reported elevated pollution levels in terms of PM in comparison to the outdoor ambient air. The PM in this microenvironment is mostly generated internally by the motion of the trains and movement of passengers, but can also origin from the inflow of outside air through the ventilation system, which promotes the mixing and resuspension of PM (e.g. Querol et al., 2012). Despite the relatively short amount of time spent in the subway on a daily basis, or commuting in a general way, PM exposure levels in such microenvironment are of concern given the relatively high PM concentrations. Michaels and Kleinman (2000) reported that peak exposures of 1 h or less, just over the typical time spent in a transport environment, may be extremely relevant in terms of health effects. In addition, the exposure to PM in the subway system has been associated with adverse health effects (Bachoual et al., 2007; Bigert et al., 2008; Seaton et al., 2005). However there is an uncertain and limited nature of the evidence for subway metalliferous PM toxicity (Moreno et al., 2015 and references therein), as for example part of subway particles bioreactivity has been associated to the glass fibre filters in the extracted samples (Karlsson, Ljungman, Lindbom & Möller, 2006), and no increased lung cancer risk has been found amongst subway train drivers (Gustavsson, Bigert & Pollán, 2008).

To the authors' knowledge, there are no studies on the deposition of subway PM in the human respiratory tract. Therefore, the main objectives of this study were to (i) determine the $PM_{2.5}$ exposure of subway commuters, (ii) calculate the total and regional doses in the respiratory tract based on the $PM_{2.5}$ exposure during subway commutes, as a function of the time spent on the platforms and inside the trains, and (iii) estimate the overall daily $PM_{2.5}$ dose, considering a typical time-activity pattern. The exposure and dose assessment was performed using aerosol measurements in the Barcelona subway system and in the urban background of Barcelona (Spain), with limitations for the remaining indoor microenvironments considered, as explained later in results and conclusions. In this study, the $PM_{2.5}$ dose in the HRT was estimated applying the dosimetry model Exposure Dose Model (ExDoM) (Aleksandropoulou & Lazaridis, 2013).

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