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An approach to assess the Particulate Matter exposure for the population living around a cement plant: modelling indoor air and particle deposition in the respiratory tract

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ABSTRACT

In this paper we studied the exposure to three size fractions of outdoor particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) collected in an area influenced by a cement plant. For that purpose, three groups of population were evaluated (children, adults and retired) in two seasons (summer and winter). Outdoor measured PM concentrations, as well as physiological parameters and activity patterns of the three groups of population were used as input data in two different models. The first one was an indoor air quality model, used to elucidate indoor PM concentrations in different microenvironments. The second one was a dosimetry model, used to evaluate the internal exposure and the distribution of the different PM fractions in the respiratory tract. Results from the indoor air quality model showed that special attention must be paid to the finest particles, since they penetrate indoors in a greater degree. Highest pulmonary doses for the three PM sizes were reported for retired people, being this a result of the high amount of time in outdoor environments exercising lightly. For children, the exposure was mainly influenced by the time they also spend outdoors, but in this case due to heavy intensity activities. It was noticed that deposition of fine particles was more significant in the pulmonary regions of children and retired people in comparison with adults, which has implications in the expected adverse health effects for those vulnerable groups of population.

1. Introduction

Particulate matter (PM) is a complex mixture of extremely small particles and liquid droplets suspended in the atmosphere originated from a wide range of sources (such as traffic, industry, energy production or domestic combustion). Consequently, its composition and size is widely variable in space and time. Nowadays, PM is a concern because its inhalation is related with many adverse health effects (such as cardiovascular and pulmonary diseases), being estimated that this pollutant is responsible for around 2.1 million of premature deaths per year globally (Fantke et al., 2015; Kelly and Fussell, 2012; Kim et al., 2015).

The two more influent parameters in the damage potential of PM are its chemical composition and size. Common constituents of PM include sulphates, nitrates, ammonium, and other inorganic ions (such as ions of sodium, potassium, calcium, magnesium, and chloride), organic and elemental carbon, crustal material, particle-bound water and metals (including cadmium, copper, nickel, vanadium, and zinc). Furthermore, biological components such as allergens and microbial compounds are found in PM (WHO, 2013). Regarding PM size, literature discriminates between particles with a diameter of less than 10 µm (PM_{10}), and particles with a diameter smaller than 2.5 µm ($PM_{2.5}$). The fraction between PM_{10} and $PM_{2.5}$ is usually known as “coarse particles” ($PM_{10\text{-}2.5}$), while $PM_{2.5}$

Abbreviations: ARA, Applied Research Associates; BF, breathing frequency; DF, deposition fraction; FRC, functional residual volume; HRT, human respiratory tract; ICRP, International Commission on Radiological Protection; IEC, Statistical Institute of Catalonia; INE, Spanish Statistical Office; INSEE, French Institute of Statistics and Economy; ME, microenvironment; MPPD, multiple path particle dosimetry; P, pulmonary; PM, particulate matter; T, time; TB, tracheobronchial; TV, tidal volume; US EPA, United States Environmental Protection Agency; URT, upper respiratory tract; WHO, World Health Organization

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is often called “fine PM”. $PM_{2.5}$ also comprises ultrafine particles, which are those having a diameter of less than 0.1 μm. In most locations in Europe, $PM_{2.5}$ constitutes 50–70% of PM_{10} (WHO, 2013). Size plays a key role on determining the part of the respiratory tract where particles deposit and, therefore, their potential of being harmful. Smaller particles, especially ultra-fines, penetrate into the interstitium and blood stream, being more hazardous (Hoek et al., 2008).

In order to control PM levels and protect the health of the population, outdoor concentrations of PM_{10} and $PM_{2.5}$ are widely studied, especially in areas with heavy traffic, or with other significant sources, such as cement or power plants (Cheng et al., 2010; Marcon et al., 2014; Patton et al., 2014; Querol et al., 2014; Rovira et al., 2014; Wilkinson et al., 2013). In addition, ambient monitoring networks have been established all over Europe and the USA by national institutions and local councils. They are equipped with on-line monitors providing continuous data with sufficient time resolution (half-hourly values) (Monn, 2001). However, the monitoring of particles smaller than 2.5 μm is still very scarce. Although outdoor levels of PM_{10} and $PM_{2.5}$ are usually used to estimate the human risks due to PM exposure, in developed countries population spend more than 80% of their time indoors (Hänninen et al., 2013). Furthermore, the different breathing patterns associated to the different activities performed both in and out doors are not taken into account when assessing human exposure. Therefore, risks due to PM exposure may be miscalculated.

Since data regarding indoor aerosol particles are not usually available, indoor aerosol models may be used as an alternative to estimate the amount of outdoor particles that penetrate indoors. Concerning the inhalation pattern issue, dosimetry models could be very useful to calculate the deposition of different PM sizes along the pulmonary region according to diverse breathing rates. Although some papers have addressed the simulation of indoor PM concentrations (McGrath et al., 2014; Sarigiannis et al., 2014) and some others the deposition in the human respiratory tract (Li et al., 2015; Patterson et al., 2014; Sarigiannis et al., 2015), studies joining the results from both kind of models are still sparse (Hussein et al., 2015).

The objective of this study was to evaluate the human PM exposure, in an industrial area where a cement plant is operating in Barcelona (Spain), as well as to assess the dose retained in the different parts of the human respiratory tract. To do that, outdoor concentrations of three PM fractions (10, 2.5, and 1 μm) were used as input in an indoor air quality model to calculate PM levels in indoor microenvironments. Furthermore, a dosimetry model was used to estimate the internal exposure and the distribution of the different PM fractions in the respiratory tract of three groups of population (children, adults and retired) in order to evaluate their potential hazard according to different patterns of exposure and conditions.

2. Methodology

2.1. Site description and PM outdoor concentrations

The studied area is located in the north of the metropolitan area of Barcelona (Catalonia, Spain). Different PM sources are operating in the area, such as some industries and an important organic waste-treatment facility. In addition, the neighborhood is crossed by two highways with heavy traffic. However, in terms of sources of PM, the greatest attention is focused on the cement plant due to its proximity to nuclei of population. This plant has been operating in the area since 1917, and as a consequence of the substantial development of the town in recent decades, the distance from the facility to the dwellings has dramatically decreased to 300 m, meaning that some inhabitants are potentially being exposed to the emissions from the facility. Hence, not only residents but also local authorities are concerned about the potential health risks and environmental impact of the cement plant emissions (Rovira et al., 2011).

In order to know the composition of outdoor PM, and have a preliminary idea of the cement plant contribution to ambient PM, a previous study was performed in the area (Sánchez-Soberón et al., 2015). In that study, levels of PM_{10}, $PM_{2.5}$ and PM_1 were measured in a school placed 300 m away from the cement plant during different seasons. This point was the only one selected in the evaluation since, according to previous studies performed in the area, highest concentrations of PM were registered there (Rovira et al., 2011). Those 24 h-PM outdoor concentrations (shown in Table 2) were used in the present study as input to estimate indoor concentrations of PMs, and, therefore, assess the human exposure. Although we understand that the cement facility is not the only source of outdoor PM, outdoor PM could be used as an oversized approximation for cement emissions.

2.2. Exposure scenarios: Microenvironments (ME) and time patterns

To evaluate the real human exposure it is important to know how people spend their time, which means knowledge regarding the contexts, circumstances, and durations of the exposures. A microenvironment (ME) is a generic location which may be assumed to have homogenous conditions (Monn, 2001). Exposures are then estimated using the concentrations, time spent, and activities performed in different MEs. In this study, we assumed three different microenvironments: home, workplace, and outdoors. Home and workplace were considered as indoor activities. Two seasons namely winter and summer were also considered. Time-activity profiles have been shown to be influenced by factors such as employment status and age, since these factors affect the relative proportion of time individuals spend indoors and outdoors (Schweizer et al., 2007). Regarding time activity profiles, the study was conducted to three population groups: children, adult employees, and retired person, all of them male (Table 1). Activity profiles for adults and retired were adapted from reports about time use (IEC, 2012; INSEE, 2010), while for children they were taken from (Cohen Hubal et al., 2000).

2.3. Indoor PM estimation: IAQX model

The indoor concentrations were calculated using model for Indoor Particulate Matter (PM.exe) of US EPA’s Indoor Air Quality simulation Tool Kit, IAQX v1.1 (US EPA, 2000a). This model was chosen according to its high accuracy, tested by the EPA by comparing indoor simulations and measures (US EPA, 2000b). Detail description of this generic indoor PM model can be found in Nazaroff and Cass (1989). The model takes into consideration: infiltration of ambient PM, interzone air movement, indoor sources, and deposition. Mean outdoor concentrations of $PM_{10\text{-}2.5}$, $PM_{2.5\text{-}1,}$ and PM_1 of two seasons (summer and winter) were used as constant input, while initial indoor concentrations were considered 0. Table 2 shows the values of the parameters considered for the simulations. Only one indoor air zone was considered since studies on air exchange rates have shown that generally air is well mixed in houses and minor differences are found between different rooms (Wallace et al., 2002). Different ventilation conditions were considered to simulate the PM levels in the indoor ME in winter and summer since amount of time that the windows are opened and the use of ventilation systems have been demonstrated to strongly influence the air exchange rates (Abt et al., 2000; Chen and Zhao, 2011; Korhonen et al., 2000; Wang et al., 2015). Home