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

Francisco Sánchez-Soberón [a], Montse Mari [a], Vikas Kumar [a], Joaquim Rovira [a,b], Martí Nadal[b] and Marta Schuhmacher [a,b*]

[a] *Environmental Engineering Laboratory, Departament d'Enginyeria Quimica, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Catalonia, Spain*

[b] *Laboratory of Toxicology and Environmental Health, School of Medicine, IISPV, Universitat Rovira i Virgili, Sant Llorenç 21, 43201 Reus, Catalonia, Spain*

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* Corresponding author. Tel.: +34 977 55 96 21; fax: +34 977 55 96 53. E-mail address: marta.schuhmacher@urv.cat (M. Schuhmacher).
Environmental Engineering Laboratory, Departament d'Enginyeria Quimica, Universitat Rovira i Virgili, Av. Països Catalans 26, 43007 Tarragona, Spain.

Abstract

We evaluated the exposure to $PM_{10-2.5}$, $PM_{2.5-1}$, and PM_1 on people living in an area directly impacted by a cement plant. Human exposure was evaluated in three groups of population (children, adults and retired people). Outdoor concentrations were used to estimate their infiltration in different indoor microenvironments. In turn, a dosimetry model was used to evaluate the internal exposure and the distribution of the different PM fractions in the respiratory tract. The modelling showed that special attention must be paid to the finest particles which were found to be the ones that infiltrate indoors in a higher degree. In addition, the dosimetry model showed how patterns of activity and physiological parameters affect the mass of particles deposited and the regions of the human respiratory tract affected by the different particle fractions. The highest deposited doses for the three PM sizes were noted for retired people, being the main contribution 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.

Key words

Cement
Fine particulate matter
Indoor and outdoor exposure
Human respiratory tract model

Highlights

- PM deposition in the respiratory tract was evaluated for three population groups.
- Activity patterns and different microenvironments were used in our calculation.
- Outdoor activities are the main contributors to PM deposited mass.
- Children experienced the highest deposition dose in the pulmonary region.
- Retired registered the highest deposited mass in the respiratory tract as a whole.

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) and therefore its composition and size is widely variable in space and time. The indicators commonly used to describe PM refer to the mass concentration of particles with a diameter of less than 10 µm (PM_{10}) and of particles with a diameter of less 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 $PM_{2.5}$, often called "fine PM", also comprises ultrafine particles 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). Regarding composition, common constituents of PM include sulfates, nitrates, ammonium, other inorganic ions such as ions of sodium, potassium, calcium, magnesium, and chloride, organic, and elemental carbon, crustal material, particle-bound water, metals (including cadmium, copper, nickel, vanadium, and zinc), and polycyclic aromatic hydrocarbons (PAH). In addition, biological components such as allergens and microbial compounds are found in PM (WHO, 2013).

In order to control PM levels and protect the health of the population, ambient outdoor concentrations of PM_{10} and $PM_{2.5}$ fractions 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. Outdoor ambient levels of PM_{10} and $PM_{2.5}$ are usually used to estimate the human risks due to PM exposure. However, in developed countries population spend more than 80% of their time indoors (Hänninen et al., 2013). 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.

The inhalation of PM is associated with many adverse health effects on the population; in particular there is evidence of the effects on cardiovascular disease and respiratory disease or premature mortality. It is estimated that globally, around 2.1 million of deaths each year are caused by fine particulate matter (Kim et al., 2015). Apart from PM levels, health effects caused by PM depend on its physical and chemical properties. 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, specially ultrafine particles (those with a diameter smaller than 100 nm) penetrate into the interstitium and into the blood stream and consequently they are more hazardous (Hoek et al., 2008). Dosimetry models take into account particle sizes to calculate the deposition of inhaled particles in different parts of the respiratory system using theoretically derived efficiencies for deposition by diffusion, sedimentation, and impaction within the airways, as well as particle clearance in the lung following the deposition. Therefore, dosimetry models have been proposed to be integrated in PM risk assessment protocols.

Since 1917, a cement plant has been operating in a town located in the metropolitan area of Barcelona (Catalonia, Spain). The area where the cement plant is located includes a number of different industries, and the town is crossed by two highways with heavy traffic. An important organic waste-treatment facility is currently running in that same zone. However, the greatest attention is focused on the cement plant due to its proximity to nuclei of population. 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).

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 to model their infiltration in different indoor microenvironments. In turn, a dosimetry model was used to estimate the internal exposure and the distribution of the different PM fractions in the respiratory tract in order to evaluate their potential hazard according to different patterns of exposure and conditions.

Methodology

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: Indoors (at home), workplace, and outdoors. 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).

Outdoor PM Data

Outdoor exposure was evaluated considering the ambient $PM_{10-2.5}$, $PM_{2.5-1}$, and PM_1 levels which were measured in a previous study (Sánchez-Soberón et al., 2015). Two different seasonal periods, winter (December 2013) and summer (July 2014) were evaluated. The sampling was carried out in a school placed at 300 m from the cement plant. Methodology was previously described in Sánchez-Soberón et al. (2015). Those 24h-PM outdoor concentrations (shown in Table 2) were also used as input to estimate indoor concentrations of PMs.

Indoor PM estimation: IAQX model

The ambient 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

(EPA, 2000). 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_{10-1}, $PM_{2.5-1}$, 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 air exchange rates of 0.44 h^{-1} for winter and 1.30 h^{-1} for summer were taken from the comprehensive study of Wallace et al. (2002) monitored for a year under normal living conditions with more than 4500 measurements. Very limited information is available regarding ventilation rates in Spanish office workplaces (Dimitroulopoulou and Bartzis, 2014). Ventilation rate from workplace, 1.00 h^{-1}, was taken from the study by Orosa and Baaliña (2008) who evaluated 25 bank office buildings. Regarding indoor deposition rates, which are size dependent, have been estimated in many studies for different PM fractions. Results show substantial variability in the methods used and the type of particles examined (Wallace et al., 2002). In addition, other factors influence deposition, including near surface air flows, incomplete mixing of room air, and turbulence (Wallace et al., 2002). Infiltration factor, which is also size dependent, represents the equilibrium fraction of ambient particles that penetrates indoors and remains suspended. PM infiltration factors measured by different researchers also show great variability, since their measurement conditions are quite different as it was reviewed by Chen and Zhao (2011). They reported values ranging from 0.2 to 0.5 for PM_{10} and from 0.5 to 0.8 for $PM_{2.5}$. (Chen and Zhao, 2011). According to those values, we assumed infiltration factors of 0.80, 0.60, and 0.35 for PM_1, $PM_{2.5-1}$ and $PM_{10-2.5}$, respectively. Since the main objective of the work was to evaluate the exposure to particles in an industrial area with a cement plant, no indoor sources were considered. Neither re-suspension and chemical reaction/dynamics were considered.

Multiple Path Particle Dosimetry model (MPPD 2.11)

The patterns of deposition after inhalation were estimated for the different sizes of PM in each region of the respiratory tract (head, tracheobronchial, and pulmonary) by Multiple Path Particle Dosimetry model (MPPD) developed by the Chemical Industry Institute of Toxicology (CIIT, USA). The MPPD version 2.11 includes age-specific lung models. The model was previously described by Winter-Sorkina and Cassee (2002). Input parameters cover: 1) PM characteristics (size distribution, shape, and density), 2) Activity patterns, and 3) Exposed subject characteristics (age, height, and body weight of the subjects) as well as respiratory physiological parameters (such as tidal volume (TV), breathing frequency (BF), functional residual volume (FRC)). Particles were considered spherical (shape factor of 1) in the calculations. Although the density of particles is also variable depending on their composition, we assumed particles having a density of 1 g/cm^3 as it has been done in other studies with no site specific data (Hussein et al., 2015). Table 1 shows the activity patterns as well as physiological input parameters for the simulation of the deposition fraction of children, adults, and retired person. Mean body weights and heights for adults and retired were taken from INE (2012) while for children they were obtained from Carrascosa et al. (2008). Some physiological inputs were considered as age and activity dependent. Breathing frequencies for working adult, retired person, and children were obtained from ICRP (1994) and USEPA (2011). Default model values for Upper Respiratory Tract (URT) volumes were used. FRC for working adult and retired were calculated using following equation presented by Stocks and Quanjer (1995):

$$FRC\ (in\ liter) = 2.34 \times Height + 0.001 \times Age - 1.09$$

Deposited doses are function of ambient concentrations (indoor and outdoor), the deposition fractions (DF), the amount of time (T) spent in each activity during the day (classified as: sleeping, sitting, exercising lightly, and exercising heavily according to the different time patterns), as well as the breathing frequency (BF) and tidal volume (TV) for the different aforementioned activities. The following equation was used to evaluate the deposited dose (Yeh and Schum, 1980):

Deposited dose (µg) = DF x ambient conc. (µg/m³) x TV (m³/breath) x BF (breath/min) x T (min)

Results and discussion

Indoor concentrations

The results of the simulated indoor concentrations of $PM_{10\text{-}2.5}$, $PM_{2.5\text{-}1}$ and PM_1 in the homes and workplaces defined by assumptions in Table 2 are presented in Fig. 1. As previously mentioned, for the simulations, mean outdoor concentrations were taken from a monitoring exercise in the case study area for two seasonal periods (winter and summer)(Sánchez-Soberón et al., 2015). Since it was assumed that initially indoor concentrations were zero, results of the simulation show how indoor concentrations increase until they reach a steady state value. For the three PM fractions, notable seasonal differences could be observed in home concentrations. These differences were directly related to the measured outdoor concentrations which were higher in winter ($PM_{10\text{-}2.5}$: 19 µg/g, $PM_{2.5\text{-}1}$: 1 µg/g, and PM_1: 31 µg/g), with the exception of $PM_{2.5\text{-}1}$, than in summer ($PM_{10\text{-}2.5}$: 1 µg/g, $PM_{2.5\text{-}1}$: 7 µg/g, and PM_1: 13 µg/g) (Sánchez-Soberón et al., 2015). Air exchange rate, which accounts for the airflows that can occur across buildings (leakage, natural ventilation, and mechanical ventilation), is considered one of the most important parameters to explain the indoor-outdoor PM relationship (Hussein et al., 2015). Although we assumed higher air exchange rates for summer, considering that windows are opened for more time in summer than in winter (Wallace et al., 2002), the estimated indoor $PM_{10\text{-}2.5}$ and PM_1 levels were still higher in winter, in line with the higher outdoor concentrations found. Regarding workplaces, winter concentrations were higher than that at home according to the higher air flow rates representative of an office (Orosa and Baaliña, 2008). Since the ventilation rate in an office remains almost constant over the year, PM levels in summer were lower than in winter, in consonance with the lower outdoor PM concentrations reported in summer.

With regard to the different PM sizes, PM_1 showed the highest concentrations in all the considered scenarios according not only to the higher outdoor concentrations, but also to the higher infiltration factors, since the smaller particles are those that mostly remain suspended once they penetrate indoors from outdoors. This is explained by their lower deposition rates and higher penetration factors in comparison with those of fine and coarse particles (Monn, 2001). In summer, the pattern indoors was $PM_1 > PM_{2.5\text{-}1} > PM_{10\text{-}2.5}$

in both home and workplace. At home, PM levels were only slightly higher than that estimated in workplace according to the ventilation rates. In winter, in both environments the distribution was $PM_1>PM_{10-2.5}>PM_{2.5-1}$ in consonance with the outdoor concentrations.

In our study to assess indoor exposure we only considered the infiltration of outdoor particles since our purpose was to assess the PM exposure in an area affected by a cement plant. However, particles are also originated from indoor sources (Ferro et al., 2004). Major indoor sources include combustion events (such as cooking, tobacco smoking, candle, and incense burning) and the use of gas and electric appliances as well as resuspension activities such as walking, dusting, and vacuum. Some studies point out that in homes major indoor sources of $PM_{2.5}$, and even more of PM_1, are originated outdoor (Hassanvand et al., 2014). Other studies, such as that by McGrath et al. (2014) show how indoor concentrations are highly modified by indoor activities. They reported mean $PM_{2.5}$ concentrations of 7.3 $\mu g/m^3$ in an indoor environment with no emission sources that were increased to 296 $\mu g/m^3$ when smoking 6 cigarettes, 289 $\mu g/m^3$ due to a frying event and 326 $\mu g/m^3$ as a result of burning an incense stick. Nevertheless, indoor sources are extremely variable according the human activities developed and their strength is still largely unknown since emission rates for the same process may be very different (Hussein et al., 2015).

Deposited fractions of PM in the HRT

The average deposition fractions (DF) of $PM_{10-2.5}$, $PM_{2.5-1}$, and PM_1 in the head/throat (Head), pulmonary/tracheobronchial (TB), and pulmonary/alveolar (P) regions of the human respiratory system for children, adults, and retired during 24 hours are presented in Table 3. For each of the cohorts different DF were obtained for each of the considered activities. Deposition fractions were estimated according specific input parameters for Tidal volume (TV), functional residual volume (FRC), and breathing frequency (BF)) for each age and activity throughout the day (Table 1). No differences were found between summer and winter DFs, meaning that this parameter does not depend on the PM concentrations. The head region was the part of the respiratory tract where higher percentages of deposition were found for all particle sizes and all age groups. The highest deposition rates in the head region were noticed for the coarse particles. These values are in agreement with other studies where among all sizes, the coarse particles show the highest DFs in the head of the respiratory system (Behera et al., 2015; Sarigiannis et al., 2015; Winter-Sorkina and Cassee, 2002). That is explained by a combination of sedimentation and the impaction of particles onto the larynx and airway bifurcations (Behera et al., 2015). The DFs of coarse particles in the head region were higher for adults than for children. On the other hand, coarse particles DFs in the pulmonary TB region were significantly higher for children than for adults. This results are in agreement with those found by Winter-Sorkina and Cassee (2002). Regarding $PM_{2.5-1,}$ the highest deposition rates were also found in the head, being maximum in adults followed by retired and children. With respect to TB region, the percentage of $PM_{2.5-1}$ deposited fraction was significantly higher for children than for adults and retired, especially due to the characteristic heavy intensity activities of children (values of DFs were 0.340, 0.021 and 0.021, for children adults and retired, respectively). $PM_{2.5-1}$ DFs in P region were higher for children for all the activities. Regarding $PM_{1,}$ DFs were very similar for adults, children and retired, with slight variations for the different activities. The pattern of deposition for PM_1 was the same as for $PM_{2.5-1,}$ in case of adults and retired, being the DFs higher in P than in TB regions. For children PM_1 DFs were smaller than for adults and retired for all the activities and regions of the respiratory tract. Differences in DFs among different age groups and respiratory regions found in the present study agree with the previously exposed by Watson et al. (1988). Higher ventilation rate per body weight in children, and differences in clearance patterns depending on the respiratory region could lead to a variable dose distribution from the childhood to the old age.

Data regarding different DFs according to different activities is sparse. Saber and Heydari (2012) calculated the DF for different particle sizes and breathing velocities in the head and the first three generations of branches in the tracheobronchial region. Their results showed that the bigger breathing intensity the higher deposition fraction in every respiratory region regardless of particle size. We found this same trend, but only in the head region, registering higher DFs in TB for sleeping or sitting activities. In our model of respiratory tract, TB region comprises 16 generations of branches. This greater number of bifurcations could lead to a higher deposition of particles by sedimentation under lower ventilation rates (Sarigiannis et al., 2015). It was not possible to compare our results of DF in the lung with those obtained by Saber and Heydari (2012), since they did not consider the deposition in the pulmonary region. Salma et al. (2015) studied the deposition of PM_1 in the respiratory tract of women within different environments and activities. They also observed that sleeping and sitting activities reached their maximum DFs in the head region. But unlike our study, light and heavy exercise experienced their maximum deposition fraction values in the pulmonary region. These results could be explained because oral breathing was taken into account under light and heavy exercise conditions, leading to a smaller deposition in the upper part of the respiratory tract. As in our study, DF was more affected by the type of activity (breathing frequency) than by locations (microenvironments). Hussein et al. (2015) also took into account time activity patterns to calculate the deposited doses of fine and ultrafine particles in the respiratory tract of adults exposed to indoor and outdoor environments. However, in that study the different DFs according to the activities were not discussed. In most studies deposition fractions are calculated by using the characteristics of the respiratory system of an average human adult with single values for tidal volume and breathing frequency (Ham et al., 2011). In other cases, deposition factors have been calculated with specific values for different groups of age for tidal volume, breathing frequency, functional residual volume and volume of the upper respiratory tract, but all those parameters are considered constant for the different activities (Sarigiannis et al., 2015; Winter-Sorkina and Cassee, 2002). The overall results show that the most sensible parameters that define the part of the tract where particles deposit are the particle size and the breathing rate. Therefore the consideration of different breathing rates according to pattern activities enhances the particle deposition assessment.

Deposited doses of PM in the HTR

Fig. 2 shows the PM mass deposited in the different parts of the respiratory system (head/throat (Head), pulmonary/tracheobronchial (TB), and pulmonary/alveolar (P)) for children, adults, and retired people in the two periods (winter and summer) assessed. Notable differences could be noticed between summer and winter periods which were in accordance with the different outdoor PM concentrations measured in the area of study in both periods and subsequently used to evaluate indoor concentrations. The accumulated doses of the three sizes of PM evaluated were mainly found in the head/throat part of the respiratory tract, being the amounts higher for the retired people followed by adults and children, respectively. The higher deposited doses of $PM_{10-2.5}$ in the head part of retired people were related to the high contribution (78%) of the light outdoor activities since they spend a high amount of time experiencing a high breathing rate in outdoor environments (in comparison with adults, that showed similar deposition fractions for the same activities and equal TV). For all three cohorts more than 80% of the $PM_{10-2.5}$ deposited dose in the head region were due to outdoor activities. In the case of children, this percentage increases till 90%, being in this case 80% of the dose attributable to heavy intensity activities. It has to be highlighted that as it can be observed in Fig. 2 children were found as the group with the highest $PM_{10-2.5}$ dose deposited in the TB pulmonary region (being deposition winter values 16.8, 1.2, and 1.4 μg/day for children, adults, and retired, respectively). These means that deposited concentrations of $PM_{10-2.5}$ in TB region were nearly 15 and 12 times higher for children than for adults and retired, respectively. Regarding the amount of $PM_{2.5-1}$ deposited, it was higher in the P than in the TB area for the three groups evaluated. In the P region, children were the group with the highest amount of $PM_{2.5-1}$ deposited. As regards $PM_{2.5-1}$, deposited in TB region was almost the same for adults, retired, and children. With respect to PM_1, similar accumulated values were noticed in the TB and P regions for adults, retired, and children, respectively.

Conclusions

Human health risk may be enhanced by a better knowledge of the total exposure. Integration of outdoor and indoor microenvironments concentrations and activity patterns can help to improve the information about real exposure. This approach however implies the availability of the reliable data for specific case studies. In this study, we implemented an indoor ambient model and a dosimetry model to evaluate the exposure to $PM_{10-2.5}$, $PM_{2.5-1}$ and PM_1 for the population living in the surroundings of a cement plant in Barcelona (Spain). The results of the IAQX model showed that PM_1 was the fraction with the highest indoor levels, at home and workplace, as a result of their higher infiltration factors and lower deposition rates. The indoor PM concentrations were in consonance with the outdoor concentrations, as well as the infiltration factors, which are higher in summer when windows are opened a higher percentage of time. It should be taken into account that we did not consider any emission from indoor sources which some studies point out that may be significant in some cases due to the activities of the inhabitants of the house, however they are still difficult to quantify. The results of the MPPD2.11 dosimetry model showed the different behaviour of the particles of different size in the human respiratory tract. Results showed that the activity pattern and physiological parameters have high impact on the deposited particles concentration in the human respiratory tract and the areas affected depending on their size. Age also play important factor in the deposited dose as for all the three particle sizes, retired people have recorded higher doses. This fact was notably related to the activity pattern of retired people which spend significant amount of time in the light outdoor activities. For children, the exposure was mainly influenced by the time they spend outdoor doing heavy exercises. Results show that fine particles ($PM_{2.5-1}$ and PM_1) were more accumulated in the pulmonary regions (P and TB) of retired people and children which are more vulnerable groups of population. Particularly children are considered a risk group to environmental pollution since their immune system and lungs are not fully developed while old people are also more susceptible to respiratory disorders.

The model here presented showed to be suitable to evaluate the PM exposure and deposited doses in the different parts of the lung considering specific data for different exposure groups. However, for the two evaluated periods, high variability was found in the deposited PM doses in the different parts of the lung as result of the PM different outdoor PM concentrations considered. Ambient PM concentrations are very variable according to daily circumstances such as sources and meteorological conditions. Therefore, an extensive PM monitoring campaign in the area under study will be carried out. This will give us more accurately results that will help us model validation and less uncertainty about the actual risk to the population.

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Table 1. Activity patterns and physiological/morphological parameters for children, adults and retired.

	Age (years)	Activity	Time (hours)	Height (cm)	BW (kg)	BF (breaths/min)	TV (ml)	FRC (ml)	UTR (ml)
Child	10	Sleeping	9.6	139.5	36	17	304	1484	25
		Sitting	11.5			19	333		
		Light indoor	0.4			32	583		
		Light outdoor	0.5			32	583		
		Heavy	2.0			45	752		
Adult	45	Sleeping	8.1	175	69.7	12	625	3455	50
		Sitting	10.4			12	750		
		Light indoor	2.8			20	1250		
		Light outdoor	2.3			20	1250		
		Heavy	0.4			26	1920		
Retired	75	Sleeping	8.6	175	69.2	12	625	3705	50
		Sitting	7.8			12	750		
		Light indoor	3.7			20	1250		
		Light outdoor	3.7			20	1250		
		Heavy	0.2			26	1920		

Table 2. Input parameters in the IAQX simulations.

Parameter	**Value**	**Reference**
Building		
Number of air zone	1	
Volume (m^3)	$90m^2$ x $2.5m=225m^3$	
Do we consider deposition?	Yes	
Ventilation		
Air exchange rate (h^{-1})	Winter: 0.44; Summer: 1.30 Working: 1.00	(Wallace et al., 2002) (Orosa and Baaliña, 2008)
PM properties		
Number of size group	PM_1, $PM_{2.5-1}$, $PM_{10-2.5}$	
Deposition rate (h^{-1})	0.8, 1, 2.5	(Wallace et al., 2002)
Outdoor sources		
Infiltration factor (IF) size (dimensionless)	0.80, 0.60, 0.35	(Chen and Zhao, 2011)
Ambient particle concentration ($\mu g/m^3$)	Winter: PM_1: 31; $PM_{2.5-1}$: 1; $PM_{10-2.5}$:19 Summer: PM_1: 13; $PM_{2.5-1}$: 7; $PM_{10-2.5}$: 1	(Sánchez-Soberón et al., 2015)

Table 3. Deposition fractions for the different PM size fractions for child, adults and retired. Average values are calculated having into account the time spent in each activity on a daily basis.

	Child			Adult employee			Retired		
PM_1	**Head**	**TB**	**P**	**Head**	**TB**	**P**	**Head**	**TB**	**P**
Sleeping	0.107	0.042	0.018	0.137	0.053	0.085	0.108	0.062	0.099
Sitting	0.125	0.042	0.024	0.158	0.051	0.101	0.126	0.058	0.118
Light indoor	0.288	0.036	0.042	0.347	0.038	0.076	0.367	0.038	0.068
Light outdoor	0.288	0.036	0.042	0.347	0.038	0.075	0.367	0.038	0.067
Heavy	0.433	0.034	0.035	0.535	0.036	0.046	0.526	0.036	0.046
Average	**0.150**	**0.041**	**0.023**	**0.198**	**0.049**	**0.089**	**0.197**	**0.053**	**0.095**
$PM_{2.5-1}$									
Sleeping	0.281	0.056	0.367	0.469	0.086	0.166	0.386	0.112	0.192
Sitting	0.292	0.056	0.357	0.509	0.075	0.185	0.430	0.097	0.216
Light indoor	0.354	0.132	0.226	0.773	0.032	0.103	0.793	0.030	0.091
Light outdoor	0.354	0.132	0.226	0.774	0.032	0.102	0.794	0.030	0.089
Heavy	0.362	0.340	0.094	0.894	0.021	0.046	0.891	0.021	0.048
Average	**0.296**	**0.083**	**0.334**	**0.559**	**0.069**	**0.159**	**0.530**	**0.081**	**0.167**
$PM_{10-2.5}$									
Sleeping	0.641	0.268	0.041	0.917	0.034	0.006	0.898	0.053	0.005
Sitting	0.667	0.270	0.022	0.924	0.027	0.007	0.909	0.041	0.006
Light indoor	0.796	0.192	0	0.949	0.008	0.001	0.951	0.007	0.001
Light outdoor	0.796	0.192	0	0.949	0.008	0.001	0.951	0.007	0.001
Heavy	0.855	0.139	0	0.955	0.004	0	0.955	0.004	0
Average	**0.677**	**0.255**	**0.027**	**0.927**	**0.025**	**0.005**	**0.918**	**0.034**	**0.004**

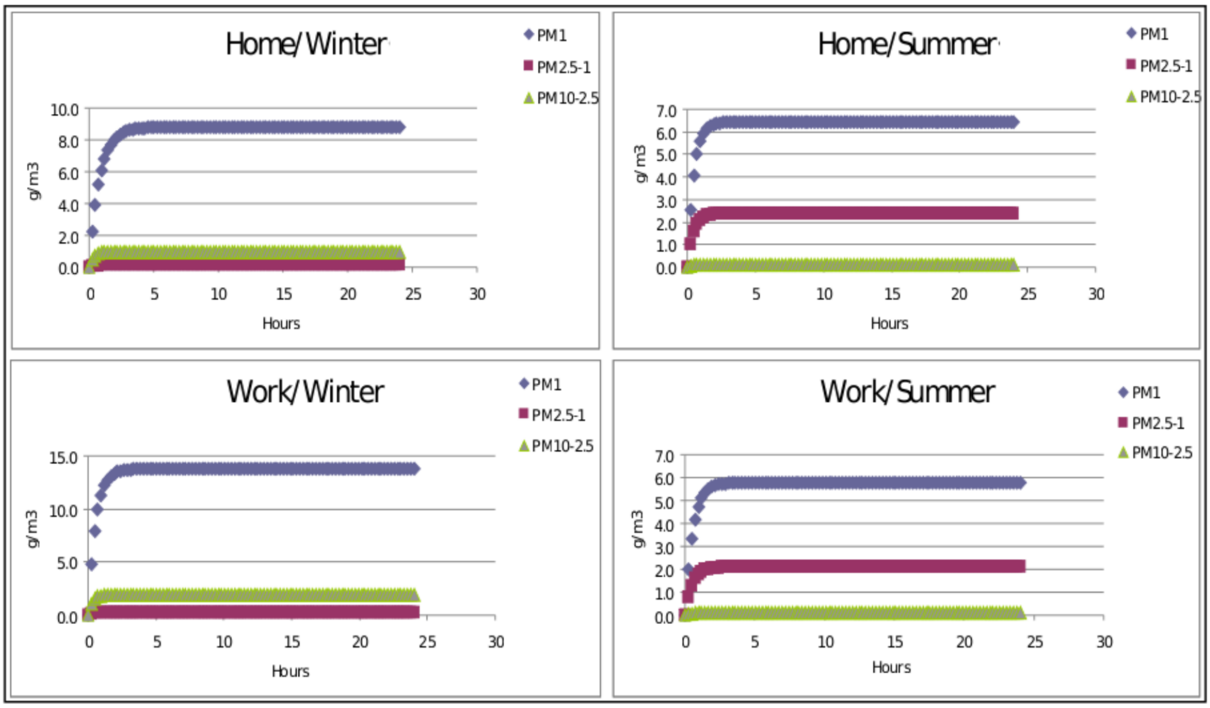

Fig. 1. Results of indoor $PM_{10\text{-}2.5}$, $PM_{10\text{-}2.5}$,and PM_1 simulations.

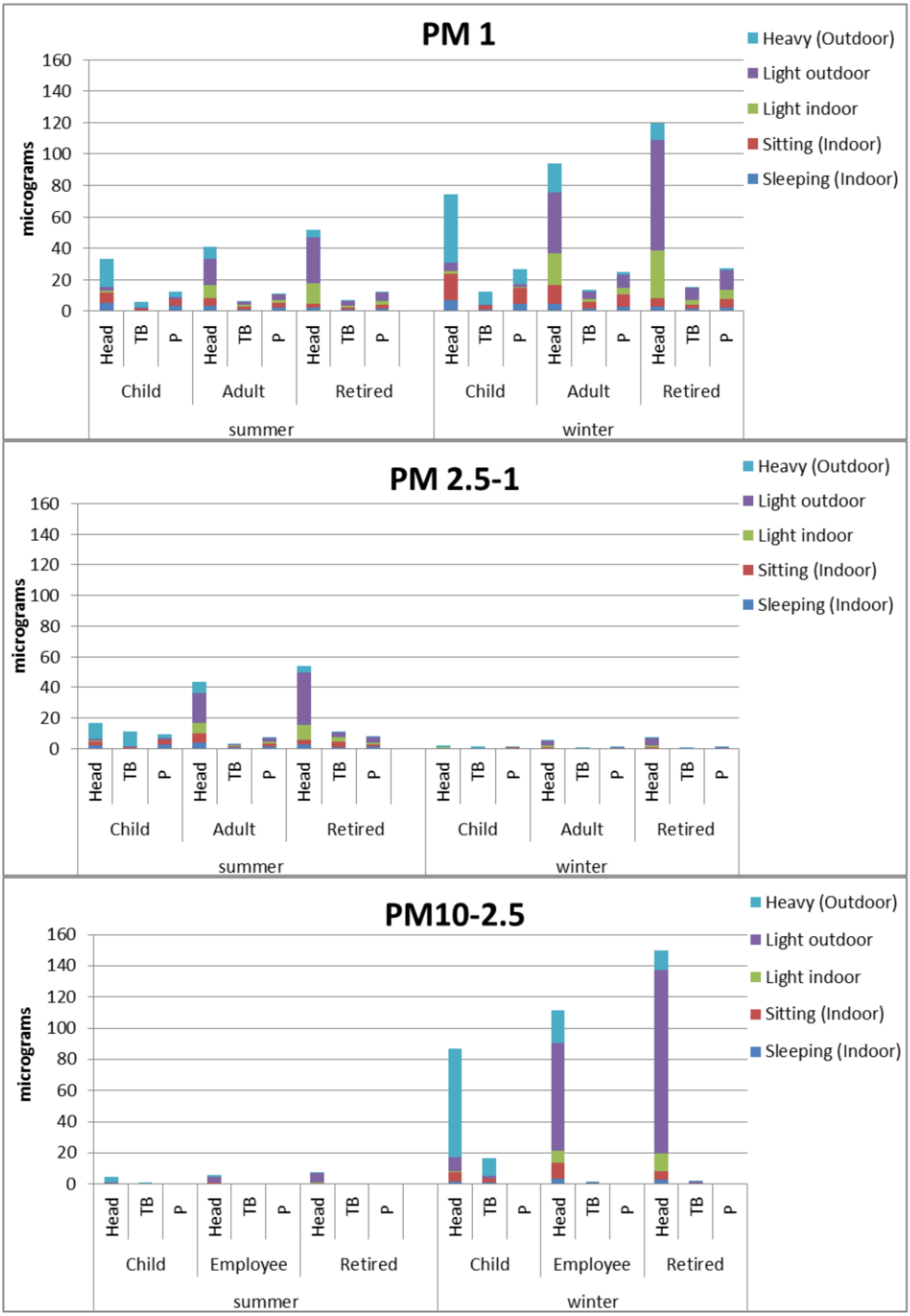

Fig. 2. PM deposited doses per day accumulated in the in the head, tracheobronchial (TB), and pulmonary/alveolar (P) regions of the human respiratory system.

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