An approach to assess the Particulate Matter exposure for the population living around a cement plant: Modelling indoor air and...

Article *in* Environmental Research · September 2015

DOI: 10.1016/j.envres.2015.09.008

Montse Mari
Universitat Rovira i Virgili

Vikas Kumar
Universitat Rovira i Virgili

Joaquim Rovira
Universitat Rovira i Virgili

Marta Schuhmacher
Universitat Rovira i Virgili

Environmental Research 143 (2015) 10–18

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

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], 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

ARTICLE INFO

Article history:
Received 6 June 2015
Received in revised form
7 September 2015
Accepted 8 September 2015

Keywords:
Cement
Fine particulate matter
Indoor/outdoor exposure
Human respiratory tract model

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

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

http://dx.doi.org/10.1016/j.envres.2015.09.008

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 $PM_{10-2.5}$, $PM_{2.5-1}$, 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

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)[f]	TV (ml)[g]	FRC(ml)[h]	UTR (ml)[i]
Child	10	Sleeping	9.6[a]	139.5[d]	36[d]	17	304	1484	25
		Sitting	11.5[a]			19	333		
		Light indoor	0.4[a]			32	583		
		Light outdoor	0.5[a]			32	583		
		Heavy	2.0[a]			45	752		
Adult	45	Sleeping	8.1[b]	175[e]	69.7[e]	12	625	3455	50
		Sitting	10.4[b]			12	750		
		Light indoor	2.8[b]			20	1250		
		Light outdoor	2.3[b]			20	1250		
		Heavy	0.4[b]			26	1920		
Retired	75	Sleeping	8.6[c]	175[e]	69.2[e]	9	625	3755	50
		Sitting	7.8[c]			9	750		
		Light indoor	3.7[c]			22	1250		
		Light outdoor	3.7[c]			22	1250		
		Heavy	0.2[c]			25	1920		

[a] (Cohen Hubal et al., 2000)
[b] (IEC, 2012); c:(INSEE, 2010)
[d] (Carrascosa et al., 2008)
[e] (INE, 2012); f :(US EPA, 2011)
[g] (ICRP, 1994)
[h] (Stocks and Quanjer, 1995)
[i] (Brown et al., 2013)

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, $PM_{2.5\text{-}1}$ and $PM_{10\text{-}2.5}$, 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.

2.4. Multiple Path Particle Dosimetry model (MPPD2.11)

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). MPPD model is very trusted

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				(Wallace et al., 2002)
	Working: 1.00				(Orosa and Baaliña, 2008)
PM properties					
Number of size group	PM_1, $PM_{2.5\text{-}1}$, $PM_{10\text{-}2.5}$				
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 (μg/m^3)		Mean	Min	Max	(Sánchez-Soberón et al., 2015)
	Winter				
	PM_1	31	26	42	
	$PM_{2.5\text{-}1}$	1.0	0.4	2.0	
	$PM_{10\text{-}2.5}$	19	11	31	
	Summer				
	PM_1	13	9.0	20	
	$PM_{2.5\text{-}1}$	7.0	0.0	14	
	$PM_{10\text{-}2.5}$	1.0	0.0	6.0	

model in the area of airway particle dosimetry and used equally in research, education, industries and regulatory agencies. Model has gone through many years of development and test and validation cycle and currently one of the most mature model available in the market. There is detail and updated user help and documentation available on the model website (ARA, 2014). The use of this model is justified since the MPPD version 2.11 includes age-specific lung models and the possibility of assessing several sizes of particles (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 US EPA (2011). Default model values for Upper Respiratory Tract (URT) volumes were used. FRCs were calculated using following equations presented by Stocks and Quanjer (1995):

$$\textit{Children}: \textit{FRC}\ (\textit{in milliliter}) = 0.125 \times 10^{-3} \times \textit{Height}\ (\textit{centimeters})^{3.298} \textit{Adult and Retired}: \textit{FRC}\ (\textit{in liter}) = 2.34 \times \textit{Height}\ (\textit{meters}) + 0.01 \times \textit{Age}\,(\textit{years}) - 1.09$$

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 BF and TV for the different aforementioned activities. The following equation was used to evaluate the deposited dose (Yeh and Schum, 1980):

$$\textit{Deposited dose}\ (\mu g) = DF \times \textit{ambient conc.}\ (\mu g/m^3) \times TV\ \left(m^3/\textit{breath}\right) \times BF\ (\textit{breath}/\textit{min}) \times T\ (\textit{min})$$

3. Results and discussion

3.1. 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, higher in winter due to a higher contribution from traffic and heating systems, and the presence of anticyclonic conditions in the area (Pey et al., 2010; Rovira et al., 2011)($PM_{10\text{-}2.5}$: 19 μg/m^3 , $PM_{2.5\text{-}1}$: 1 μg/m^3, and PM_1:

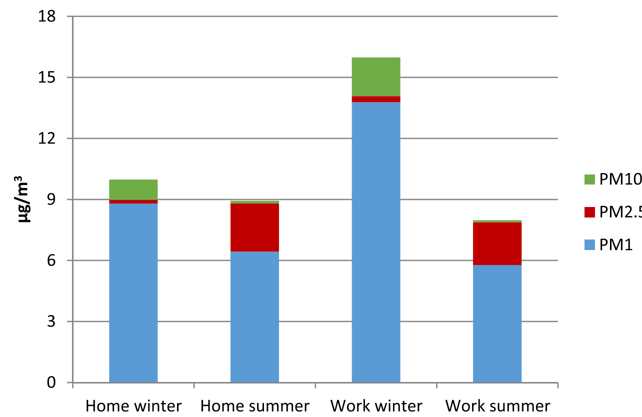

Fig. 1. Results of indoor $PM_{10\text{-}2.5}$, $PM_{10\text{-}2.5}$, and PM_1 simulations.

31 μg/m^3), with the exception of $PM_{2.5\text{-}1}$, which was larger in summer ($PM_{10\text{-}2.5}$: 1 μg/m^3, $PM_{2.5\text{-}1}$: 7 μg/m^3, and PM_1: 13 μg/m^3) (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 $PM_1 > PM_{10\text{-}2.5} > PM_{2.5\text{-}1}$ 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 exposure to ambient PM 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 μg/m^3 in an indoor environment with no emission sources that were increased to 296 μg/m^3 when smoking 6 cigarettes, 289 μg/m^3 due to a frying event and 326 μg/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

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	0.262	0.036	0.172	0.137	0.053	0.085	0.108	0.062	0.099
Sitting	0.269	0.037	0.164	0.158	0.051	0.101	0.126	0.058	0.118
Light indoor	0.317	0.047	0.108	0.347	0.038	0.076	0.367	0.038	0.068
Light outdoor	0.317	0.047	0.108	0.347	0.038	0.075	0.367	0.038	0.067
Heavy	0.345	0.065	0.075	0.535	0.036	0.046	0.526	0.036	0.046
Average	**0.274**	**0.039**	**0.157**	**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**

unknown since emission rates for the same process may be very different (Hussein et al., 2015).

3.2. 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 DFs were obtained for each of the considered activities. Deposition fractions were estimated according to 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). As reported in previous studies using the same model (Li et al., 2015), there were no differences between summer and winter DFs. This is a direct consequence of the model here used, since it assumed that DFs does not depend on the PM concentrations. The head region was the part of the respiratory tract where higher percentages of deposition were calculated for all particle sizes and all age groups. Coarse particles addressed the highest deposition rates in this region. 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. These results are in agreement with those reported by Winter-Sorkina and Cassee (2002). Regarding $PM_{2.5-1,}$ head region addressed the highest deposition rates, 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 $PM_{1,}$ children experienced higher DFs than adults and retired for sleeping and sitting in head and P regions. The pattern of deposition for PM_1 was the same as for $PM_{2.5-1}$ for every population group, being the DFs higher in *P* than in TB regions. Differences in DFs among different age groups and respiratory regions described 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 the model used in the present study, 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.

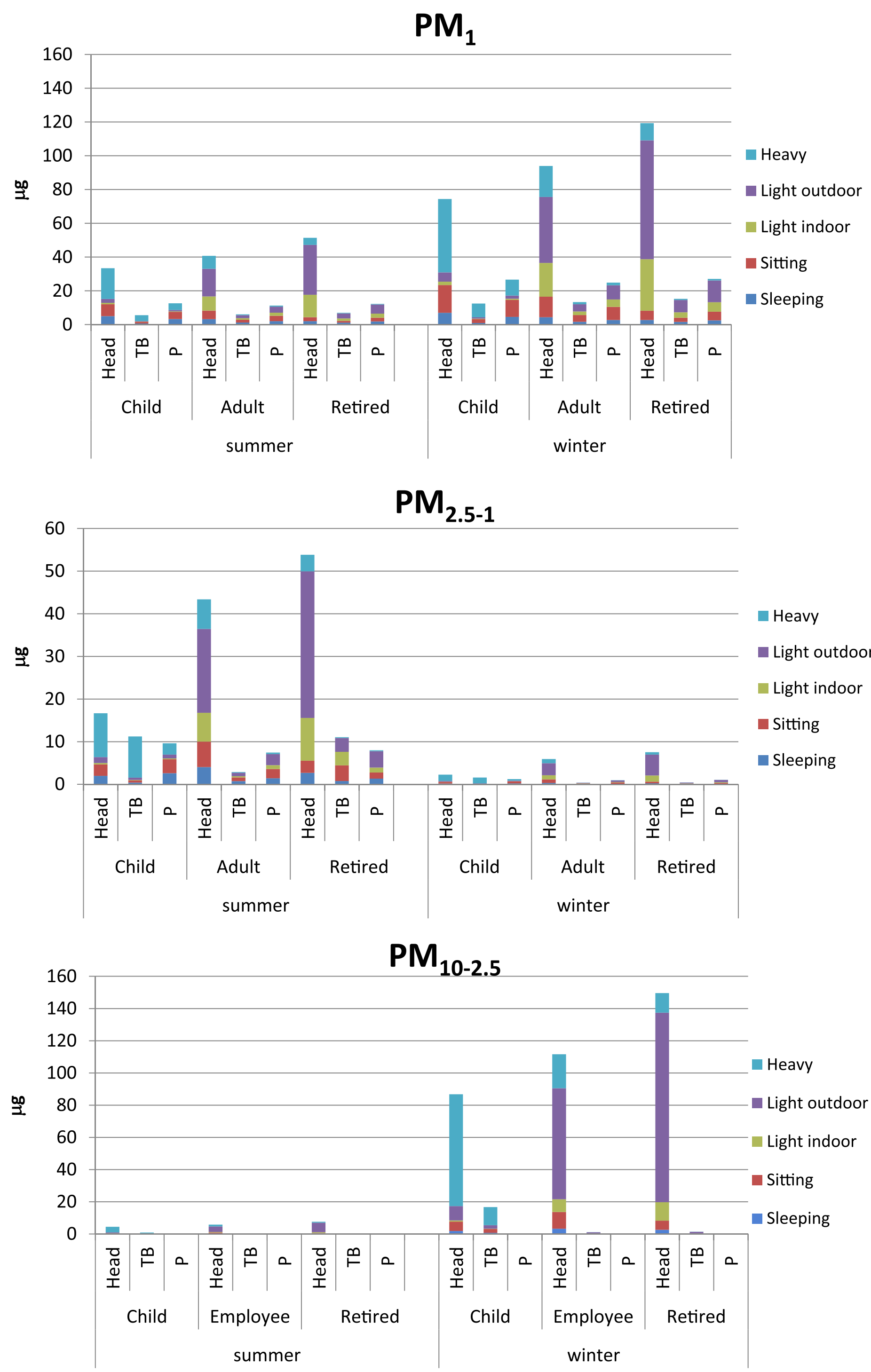

Fig. 2. Estimated PM deposited mass per day accumulated in the in the head, tracheobronchial (TB), and pulmonary/alveolar (P) regions of the human respiratory system.

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. FRC and URT could also be a source of variability for the DFs. Increases close to 65% of FRC could lead to decreases as far as 25% in pulmonary DFs, while increases of 40% URT could trigger decreases from 3-12% in the different

Table 4
Minimum, mean, and maximum calculated PM deposited doses for the totality of the respiratory tract

		winter			summer		
		min	mean	max	min	mean	max
PM_1	Child	94.1	114	151	34.2	51.6	77.9
	Adult Employee	102	132	176	38.8	58.2	88.2
	Retired	114	162	208	45.5	70.7	103.6
$PM_{2.5-1}$	Child	2.01	5.07	10.1	0.00	37.5	75.0
	Adult Employee	2.88	7.27	14.4	0.00	53.7	107
	Retired	3.44	9.00	17.2	0.00	72.9	126
$PM_{10-2.5}$	Child	57.0	104	161	0.00	5.39	31.8
	Adult Employee	59.2	113	173	0.00	5.88	34.3
	Retired	72.3	151	218	0.00	7.75	39.5

parts of the respiratory system (Winter-Sorkina and Cassee, 2002).

3.3. Deposited doses of PM in the HRT

Fig. 2 shows the estimated 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 located in the head/throat part of the respiratory tract, being the values 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 reported 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). This 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 calculated in the TB and P regions for adults, retired, and children, respectively. Maximum and minimum deposition doses followed the same trend than average values regarding population groups (retired > adults > children) and respiratory tract regions (head > TB > P) (Table 4). Higher variations were calculated in summer, when deposited mass could be close to six times higher than average values ($PM_{10-2.5}$), being in agreement with outdoor PM ranges. Apart from variations coming from the range of outdoor PM, some variability in results could be obtained depending on the assumptions made for the rest of inputs. In the present study we assumed the same activity pattern for summer and winter, since it was taken from studies based on annual data. However, activity patterns could be very different between these two seasons. Furthermore, ranges of FRC and UTR for the three population groups were not taken into consideration. Therefore, different results are expected when assessing the variability of all these parameters, being necessary future analyses in this field.

Although we did not find any reference relating deposited doses and health problems, it is possible to have a preliminary idea of the effects by comparing our levels of outdoor concentrations with those limits established by the World Health Organization (WHO, 2005). According to this organization, mean annual guidelines for outdoor PM_{10} and $PM_{2.5}$ are respectively 20 and 10 $\mu g/m^3$. These values are surpassed in both periods, meaning that some kind of long term adverse effects are expected. Since in our simulations most of the PM mass is deposited in the head region, diseases such as rhinitis, pharyngitis or sinusitis are the most likely (Vincent, 2005). Furthermore, due to the higher deposition mass of coarse PM in TB region in children, it is also expected a higher impact of asthma in this population group.

4. Conclusions

Human health risk assessment may be improved 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 its 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 plays an important role in the deposited dose. For all three particle sizes, retired people have recorded the highest 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 a higher accumulation of fine particles ($PM_{2.5-1}$ and PM_1) in the pulmonary regions (P and TB) of retired people and children, which are the most 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 integrated model showed to be suitable to evaluate the PM exposure and deposited doses in the different parts of the human respiratory tract considering specific data for different exposure groups. However, for the two evaluated periods, high variability was reported in the deposited PM doses in the different parts of the respiratory tract, as result of the different outdoor PM concentrations considered. Ambient PM concentrations are very variable according to daily circumstances such as sources and meteorological conditions. The influence of the cement plant in ambient PM was noted in previous studies (Sánchez-Soberón et al., 2015), but contribution from this facility have not been quantified yet. However, the assessment here described could be used as a worst case scenario for the cement facility. 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 in the model validation, reduce uncertainty about the actual risk to the population, and clarify the contribution from cement plant to different health effects.

Funding sources

Two organizations were the main funding sources of the present study:

- The Spanish Ministry of Economy and Competitiveness (MINECO), through the project CTM2012-32778.
- The European Union, through the HEALS project FP7-ENV-2013-603946, included in the Seventh Framework Programme.

Acknowledgments

Financial support was received by the Spanish Ministry of Economy and Competitiveness (MINECO), through the project CTM2012-32778. F. Sánchez-Soberón received a doctoral scholarship as part of the project above mentioned. We also want to thank the European Union Seventh Framework Programme for the funding received through the HEALS project FP7-ENV-2013-603946. The authors also want to thank Quentin Aiello for his collaboration through the investigation.

References

Abt, E., Suh, H., Catalano, P., Koutrakis, P., 2000. Relative contribution of outdoor and indoor particle sources to indoor concentrations. Env. Sci Technol 34, 3579–3587.

ARA, 2014. ARA :: Products :: MPPD [WWW Document]. URL 〈http://www.ara.com/products/mppd.htm〉 (accessed 8.24.15).

Behera, S., Betha, R., Huang, X., Balasubramanian, R., 2015. Characterization and estimation of human airway deposition of size-resolved particulate-bound trace elements during a recent haze episode in Southeast Asia. Environ. Sci. Pollut. Res. 22, 4265–4280. http://dx.doi.org/10.1007/s11356-014-3645-6.

Brown, J.S., Gordon, T., Price, O., Ashagarian, B., 2013. Thoracic and respirable particle definitions for human health risk assessment. Part. Fibre Toxicol. 10, 1–12. http://dx.doi.org/10.1186/1743-8977-10-12.

Carrascosa, A., Fernández, J.M., Fernández, C., Ferrández, A., Longás, López-Siguero, J.P., Sánchez, E., Sobradillo, B., Yeste, F., 2008. Estudio transversal español de crecimiento. Parte II: valores de talla, peso e índice de masa corporal desde el nacimiento a la talla adulta . An. Pediatría 68, 552–569.

Chen, C., Zhao, B., 2011. Review of relationship between indoor and outdoor particles: I/O ratio, infiltration factor and penetration factor. Atmos. Environ. 45, 275–288. http://dx.doi.org/10.1016/j.atmosenv.2010.09.048.

Cheng, K.-C., Goebes, M.D., Hildemann, L.M., 2010. Association of size-resolved airborne particles with foot traffic inside a carpeted hallway. Atmos. Environ. 44, 2062–2066. http://dx.doi.org/10.1016/j.atmosenv.2010.02.027.

Cohen Hubal, E.A., Sheldon, L.S., Burke, J.M., McCurdy, T.R., Berry, M.R., Rigas, M.L., Zartarian, V.G., Freeman, N.C., 2000. Children's exposure assessment: a review of factors influencing Children's exposure, and the data available to characterize and assess that exposure. Environ. Health Perspect. 108, 475–486.

Dimitroulopoulou, C., Bartzis, J., 2014. Ventilation rates in European office buildings: A review. Indoor Built Environ. 23, 5–25.

Fantke, P., Jolliet, O., Evans, J.S., Apte, J.S., Cohen, A.J., Hänninen, O.O., Hurley, F., Jantunen, M.J., Jerrett, M., Levy, J.I., Loh, M.M., Marshall, J.D., Miller, B.G., Preiss, P., Spadaro, J.V., Tainio, M., Tuomisto, J.T., Weschler, C.J., McKone, T.E., 2015. Health effects of fine particulate matter in life cycle impact assessment: findings from the Basel Guidance Workshop. Int. J. Life Cycle Assess. 20, 276–288. http://dx.doi.org/10.1007/s11367-014-0822-2.

Ferro, A.R., Kopperud, R.J., Hildemann, L.M., 2004. Source Strengths for Indoor Human Activities that Resuspend Particulate Matter. Environ. Sci. Technol. 38, 1759–1764. http://dx.doi.org/10.1021/es0263893.

Ham, W.A., Ruehl, C.R., Kleeman, M.J., 2011. Seasonal Variation of Airborne Particle Deposition Efficiency in the Human Respiratory System. Aerosol Sci. Technol. 45, 795–804.

Hänninen, O., Sorjamaa, R., Lipponen, P., Cyrys, J., Lanki, T., Pekkanen, J., 2013. Aerosol-based modelling of infiltration of ambient PM2.5 and evaluation against population-based measurements in homes in Helsinki. Finland. J. Aerosol Sci. 66, 111–122. http://dx.doi.org/10.1016/j.jaerosci.2013.08.004.

Hassanvand, M.S., Naddafi, K., Faridi, S., Arhami, M., Nabizadeh, R., Sowlat, M.H., Pourpak, Z., Rastkari, N., Momeniha, F., Kashani, H., Gholampour, A., Nazmara, S., Alimohammadi, M., Goudarzi, G., Yunesian, M., 2014. Indoor/outdoor relationships of PM_{10}, $PM_{2.5}$, and PM_1 mass concentrations and their water-soluble ions in a retirement home and a school dormitory. Atmos. Environ. 82, 375–382. http://dx.doi.org/10.1016/j.atmosenv.2013.10.048.

Hoek, G., Kos, G., Harrison, R., de Hartog, J., Meliefste, K., ten Brink, H., Katsouyanni, K., Karakatsani, A., Lianou, M., Kotronarou, A., Kavouras, I., Pekkanen, J., Vallius, M., Kulmala, M., Puustinen, A., Thomas, S., Meddings, C., Ayres, J., van Wijnen, J., Hameri, K., 2008. Indoor-outdoor relationships of particle number and mass in four European cities. Atmos. Environ. 42, 156–169.

Hussein, T., Wierzbicka, A., Löndahl, J., Lazaridis, M., Hänninen, O., 2015. Indoor aerosol modeling for assessment of exposure and respiratory tract deposited dose. Atmos. Environ. 106, 402–411. http://dx.doi.org/10.1016/j.atmosenv.2014.07.034.

ICRP, 1994. Human respiratory tract model for radiological protection: a report of a task group of the International Commission on Radiological Protection. Ann ICRP 24, 1–482.

IEC, 2012. Enquesta de l'ús del temps 2010-2011: principals resultats. – (Estadística Social). Institut d'Estadística de Catalunya. Available at: http://www.idescat.cat/cat/idescat/publicacions/cataleg/pdfdocs/eut-pr2010-11.pdf.

INE, 2012. Índice de masa corporal por grupos de edad. 2011-2012. Inst. Nac. estadística. Available at: http//www.ine.es/jaxi/tabla.do?type=pcaxis&path=/t00/mujeres_hombres/tablas_1/l0/&file=d06001.px.

INSEE, 2010. Conditions de vie-Société - Depuis 11 ans, moins de tâches ménagères, plus d'Internet. Insee. Available at: 〈http://www.insee.fr/fr/themes/document.asp?ref_id=ip1377〉.

Kelly, F.J., Fussell, J.C., 2012. Size, source and chemical composition as determinants of toxicity attributable to ambient particulate matter. Atmos. Environ. 60, 504–526. http://dx.doi.org/10.1016/j.atmosenv.2012.06.039.

Kim, K.H., Kabir, E., Kabir, S., 2015. A review on the human health impact of airborne particulate matter. Environ. Int. 74, 136–143.

Korhonen, P., Kokotti, H., Kalliokoski, P., 2000. Survey and mitigation of occupational exposure of radon in workplaces. Build. Environ. 35, 555–562. http://dx.doi.org/10.1016/S0360-1323(99)00048-7.

Li, X., Yan, C., Patterson, R.F., Zhu, Y., Yao, X., Zhu, Y., Ma, S., Qiu, X., Zhu, T., Zheng, M., 2015. Modeled Deposition of Fine Particles in Human Airway in Beijing. China. Atmos. Environ. . http://dx.doi.org/10.1016/j.atmosenv.2015.06.045

Marcon, A., Pesce, G., Girardi, P., Marchetti, P., Blengio, G., de Zolt Sappadina, S., Falcone, S., Frapporti, G., Predicatori, F., de Marco, R., 2014. Association between PM10 concentrations and school absences in proximity of a cement plant in northern Italy. Int. J. Hyg. Environ. Health 217, 386–391. http://dx.doi.org/10.1016/j.ijheh.2013.07.016.

McGrath, J.A., Byrne, M.A., Ashmore, M.R., Terry, A.C., Dimitroulopoulou, C., 2014. Development of a probabilistic multi-zone multi-source computational model and demonstration of its applications in predicting PM concentrations indoors. Sci. Total Environ. 490, 798–806. http://dx.doi.org/10.1016/j.scitotenv.2014.05.081.

Monn, C., 2001. Exposure assessment of air pollutants: a review on spatial heterogeneity and indoor/outdoor/personal exposure to suspended particulate matter, nitrogen dioxide and ozone. Atmos. Environ. 35, 1–32. http://dx.doi.org/10.1016/S1352-2310(00)00330-7.

Nazaroff, W.W., Cass, G.R., 1989. Mathematical modeling of indoor aerosol dynamics. Environ. Sci. Technol. 23, 157–166. http://dx.doi.org/10.1021/es00179a003.

Orosa, J.A., Baaliña, A., 2008. Passive climate control in Spanish office buildings for long periods of time. Build. Environ. 43, 2005–2012. http://dx.doi.org/10.1016/j.buildenv.2007.12.001.

Patterson, R.F., Zhang, Q., Zheng, M., Yifang, Z., 2014. Particle Deposition in Respiratory Tracts of School-Aged Children. Aerosol Air Qual. Res. 14, 64–73.

Patton, A.P., Perkins, J., Zamore, W., Levy, J.I., Brugge, D., Durant, J.L., 2014. Spatial and temporal differences in traffic-related air pollution in three urban neighborhoods near an interstate highway. Atmos. Environ. 99, 309–321. http://dx.doi.org/10.1016/j.atmosenv.2014.09.072.

Pey, J., Pérez, N., Querol, X., Alastuey, A., Cusack, M., Reche, C., 2010. Intense winter atmospheric pollution episodes affecting the Western Mediterranean. Sci. Total Environ. 408, 1951–1959. http://dx.doi.org/10.1016/j.scitotenv.2010.01.052.

Querol, X., Alastuey, A., Pandolfi, M., Reche, C., Pérez, N., Minguillón, M.C., Moreno, T., Viana, M., Escudero, M., Orio, A., Pallarés, M., Reina, F., 2014. 2001-2012 trends on air quality in Spain. Sci. Total Environ. 490, 957–969.

Rovira, J., Mari, M., Schuhmacher, M., Nadal, M., Domingo, J.L., 2011. Monitoring environmental pollutants in the vicinity of a cement plant: a temporal study. Arch. Environ. Contam. Toxicol. 60, 372–384. http://dx.doi.org/10.1007/s00244-010-9628-9.

Rovira, J., Nadal, M., Schuhmacher, M., Domingo, J.L., 2014. Environmental levels of PCDD/Fs and metals around a cement plant in Catalonia, Spain, before and after alternative fuel implementation. Assessment of human health risks. Sci. Total Environ., 121–129. http://dx.doi.org/10.1016/j.scitotenv.2014.03.061 485-486.

Saber, E.M., Heydari, G., 2012. Flow patterns and deposition fraction of particles in the range of 0.1–10 μm at trachea and the first third generations under different breathing conditions. Comput. Biol. Med. 42, 631–638. http://dx.doi.org/10.1016/j.compbiomed.2012.03.002.

Salma, I., Füri, P., Németh, Z., Balásházy, I., Hofmann, W., Farkas, Á., 2015. Lung burden and deposition distribution of inhaled atmospheric urban ultrafine particles as the first step in their health risk assessment. Atmos. Environ. 104, 39–49. http://dx.doi.org/10.1016/j.atmosenv.2014.12.060.

Sánchez-Soberón, F., Rovira, J., Mari, M., Sierra, J., Nadal, M., Domingo, J.L., Schuhmacher, M., 2015. Main components and human health risks assessment of PM_{10}, $PM_{2.5}$, and PM_1 in two areas influenced by cement plants. Atmos. Environ. 210, 109–116. http://dx.doi.org/10.1016/j.atmosenv.2015.08.020.

Sarigiannis, D.Α, Karakitsios, S.P., Kermenidou, M., Nikolaki, S., Zikopoulos, D., Semelidis, S., Papagiannakis, A., Tzimou, R., 2014. Total exposure to airborne particulate matter in cities: the effect of biomass combustion. Sci. Total Environ. 493, 795–805. http://dx.doi.org/10.1016/j.scitotenv.2014.06.055.

Sarigiannis, D.Α, Karakitsios, S.P., Zikopoulos, D., Nikolaki, S., Kermenidou, M., 2015. Lung cancer risk from PAHs emitted from biomass combustion. Environ. Res. 137, 147–156. http://dx.doi.org/10.1016/j.envres.2014.12.009.

Schweizer, C., Edwards, R.D., Bayer-Oglesby, L., Gauderman, W.J., Ilacqua, V., Jantunen, M.J., Lai, H.K., Nieuwenhuijsen, M., Künzli, N., 2007. Indoor time–microenvironment–activity patterns in seven regions of Europe. J. Expo. Sci. Environ. Epidemiol. 17, 170–181.

Stocks, J., Quanjer, P.H., 1995. Reference values for residual volume, functional residual capacity and total lung capacity. ATS Workshop on Lung Volume Measurements. Official Statement of The European Respiratory Society. Eur Respir J 8, 492–506.

US EPA, 2011. Exposure Factors Handbook: 2011 Edition, National Centre of Environmenatl Assessment, U.S. Environmental Protection Agency, Washington, D.C., U.S.A. Sept. 2011.

US EPA, 2000a. Indoor Air Quality Modeling. IAQX v1.1 can be downloaded at: 〈http://www.epa.gov/nrmrl/appcd/mmd/iaq.html〉.

US EPA, 2000b. Indoor Air Quality Modeling [WWW Document]. URL 〈http://www.epa.gov/nrmrl/appcd/mmd/iaq.html〉 (accessed 10.13.14).

Vincent, J.H., 2005. Health-related aerosol measurement: a review of existing sampling criteria and proposals for new ones. J. Environ. Monit. 7, 1037–1053.

Wallace, L., Emmerich, S., Howard-Reed, C., 2002. Continuous measurements of air change rates in an occupied house for 1 year: the effect of temperature, wind, fans, and windows. J Expo Anal Env. Epidemiol 12, 296–306.

Wang, J., Smedje, G., Nordquist, T., Norbäck, D., 2015. Personal and demographic factors and change of subjective indoor air quality reported by school children in relation to exposure at Swedish schools: A 2-year longitudinal study. Sci. Total Environ. 508, 288–296.

Watson, A.Y., Bates, R.R., Kennedy, D., 1988. Biological Disposition of Airborne Particles: Basic Principles and Application to Vehicular Emissions, Air Pollution, the Automobile, and Public Health. National Academies Press, (US), Washington (DC).

WHO, 2013. Health effects of Particulate Matter. Policy implications for countries in eastern Europe, Caucasus and central Asia, WHO Regional Office for Europe, Copenhagen, Denmark. ISBN 978 92 890 0001 7.

WHO, 2006. Air quality guidelines - global update 2005. World Health Organization, Geneva, Switzerland. WHO/SDE/PHE/OEH/06.02 .

Wilkinson, K.E., Lundkvist, J., Netrval, J., Eriksson, M., Seisenbaeva, G.A., Kessler, V. G., 2013. Space and time resolved monitoring of airborne particulate matter in proximity of a traffic roundabout in Sweden. Environ. Pollut. 182, 364–370. http://dx.doi.org/10.1016/j.envpol.2013.07.043.

Winter-Sorkina, R., Cassee, F.R., 2002. From concentration to dose: factors influencing airborne particulate matter deposition in humans and rats. RIVM Rep. 650010031/2002.

Yeh, H.-C., Schum, G.M., 1980. Models of human lung airways and their application to inhaled particle deposition. Bull. Math. Biol. 42, 461–480. http://dx.doi.org/10.1007/bf02460796.