Science of the Total Environment 524–525 (2015) 178–186

Contents lists available at ScienceDirect

Science of the Total Environment

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

Indoor aerosol size distributions in a gymnasium

Amaya Castro [a], Ana I. Calvo [a], Célia Alves [b], Elisabeth Alonso-Blanco [c], Esther Coz [c], Liliana Marques [b], Teresa Nunes [b], Jose Manuel Fernández-Guisuraga [a], Roberto Fraile [a,*]

[a] Department of Physics (IMARENAB), University of León, 24071 León, Spain
[b] Centre for Environment and Marine Studies, Department of Environment, University of Aveiro, 3810-193 Aveiro, Portugal
[c] Centre for Energy, Environment and Technology Research (CIEMAT), Department of Environment, 28040 Madrid, Spain

HIGHLIGHTS

- In the indoor environment of a gym PM_{10} concentrations are highly variable.
- Sports activities, occupancy rates and cleaning are important factors to PM.
- Sports activities lead to the resuspension of particles from the surfaces.
- The use of magnesia alba contributes to an indoor air with many particles >1 μm.
- The maximum respirable fractions could reach values like those found in industry.

ARTICLE INFO

Article history:
Received 10 December 2014
Received in revised form 2 March 2015
Accepted 27 March 2015
Available online xxxx

Editor: P. Kassomenos

Keywords:
Aerosol size distribution
Alveolar fraction
Fine mode
Gymnasium
Magnesia alba
Tracheobronchial fraction

ABSTRACT

In this study, an indoor/outdoor monitoring program was carried out in a gymnasium at the University of Leon, Spain. The main goal was a characterization of aerosol size distributions in a university gymnasium under different conditions and sports activities (with and without magnesia alba) and the study of the mass fraction deposited in each of the parts of the respiratory tract. The aerosol particles were measured in 31 discrete channels (size ranges) using a laser spectrometer probe. Aerosol size distributions were studied under different conditions: i) before sports activities, ii) activities without using magnesia alba, iii) activities using magnesia alba, iv) cleaning procedures, and v) outdoors. The aerosol refractive index and density indoors were estimated from the aerosol composition: 1.577–0.003i and 2.055 g cm^{-3}, respectively. Using the estimated density, the mass concentration was calculated, and the evolution of PM_1, $PM_{2.5}$ and PM_{10} for different activities was assessed. The quality of the air in the gymnasium was strongly influenced by the use of magnesia alba ($MgCO_3$) and the number of gymnasts who were training. Due to the climbing chalk and the constant process of resuspension, average PM_{10} concentrations of over 440 μg m^{-3} were reached. The maximum daily concentrations ranged from 500 to 900 μg m^{-3}. Particle size determines the place in the respiratory tract where the deposition occurs. For this reason, the inhalable, thoracic, tracheobronchial and respirable fractions were assessed for healthy adults and high risk people, according to international standards. The estimations show that, for healthy adults, up to 300 μg m^{-3} can be retained by the trachea and bronchi, and 130 μg m^{-3} may reach the alveolar region. The different physical activities and the attendance rates in the sports facility have a significant influence on the concentration and size distributions observed.

1. Introduction

Different studies have pointed out the importance of evaluating and controlling indoor particulate matter levels (Halios and Helmis, 2007; Hussein et al., 2015; Oh et al., 2014; Owen et al., 1992; Wolkoff, 2013; Žitnik et al., 2010). This is due to the fact that, nowadays, people spend more than 90% of their time indoors. Homes, schools/universities, work and entertainment places are among the most common indoor spaces (Massey et al., 2012; Salma et al., 2013; Wolkoff, 2013). Sports facilities arouse particular interest in the study of indoor air quality (IAQ), due to the contrast between the aim of physical fitness and the risk of respiratory problems associated with the practice of sports. One important aspect linked to sports activities is the increase of ventilation rates in athletes and other sportspeople, and the subsequent increase in the amount of pollutants drawn into the lungs (Daigle et al., 2003). Children

Abbreviations: BC, black carbon; CMD, Count Median Diameter; IAQ, indoor air quality; PCASP, Passive Cavity Aerosol Spectrometer Probe; PM, particulate matter; POM, particulate organic matter; SMD, surface mean diameter; TSP, total suspended particle; VMD, volume mean diameter; VOCs, volatile organic compounds.

* Corresponding author at: Dpto. de Física, Fac de CC. Biológicas y Ambientales, 24071 León, Spain.
E-mail address: roberto.fraile@unileon.es (R. Fraile).

http://dx.doi.org/10.1016/j.scitotenv.2015.03.118
0048-9697/

are especially susceptible to these health problems because of their higher physical activity, higher metabolic rate and the resultant increase in minute ventilation (Braniš et al., 2009; Chalupa et al., 2004; Gauderman et al., 2004).

The concentration, composition and sources of indoor air pollutants vary considerably from one micro-environment to another (Colbeck and Nasir, 2010; Alves et al., 2013a; Sangiorgi et al., 2013; Batterman et al., 2012). As a consequence, different indoor aerosol size distributions are registered. The study of aerosol size distribution constitutes an essential tool when air quality studies are carried out. It provides information related to the concentration of particles that can be retained on the different zones of the respiratory tract (Donaldson et al., 2000; Kreyling et al., 2006) and, on the other hand, it contributes to knowledge on aerosol sources, formation, and growth mechanisms (Lan et al., 2011). This information is essential when investigating mitigation measures. Generally, the particles that can reach the different zones of the human respiratory tract are classified as: i) particles larger than 10 μm in diameter, which are retained in the extrathoracic region, ii) particles smaller than 10 μm, which may pass into the tracheobronchial region, iii) particles smaller than 2.5 μm which can reach the alveoli and consequently the bloodstream, which may endanger human health (Pope et al., 2002), and iv) particles smaller than 1 μm, which, according to medical studies, are considered the highest health risk (Dockery et al, 1993; Dockery, 2001; Pope, 2000). Important relationships have been pointed out between indoor levels of coarse particles and the number of occupants and activities carried out (Braniš and Šafránek, 2011; Buonanno et al., 2013).

Previous studies have shown the relevance of particulate matter in sports facilities (Alves et al., 2013b, 2014), highlighting the importance of the chemical composition and morphology of aerosols. However, the number of studies on aerosol size distributions is still small. Weinbruch et al. (2012) studied the influence of the different kinds of magnesia alba on the dust concentrations in indoor climbing gyms, including also particle size distributions.

Given the relevant information obtained from this aerosol characteristic, a deeper study of this topic is essential to provide i) a complete characterization of particles, and ii) feasible measures for reducing particles in this kind of facility. As a result, it will be possible to follow healthy habits, such as sports, reducing the risk of respiratory disease.

The objectives of the present study are:

- to characterize the aerosol size distributions in a university gymnasium under different conditions and sports activities (with and without magnesia alba);
- to compare the data with those observed without sports activities and with outdoor measurements; and
- to determine firstly the inhalable and thoracic fractions according to the Spanish standard UNE 77213, equivalent to ISO 7708:199, and then the tracheobronchial and respirable fractions for healthy adults and high risk people (children, frail or sick people).

This study is a useful tool for identifying the main sources of particulate matter in sports facilities such as gymnasiums, as well as for developing appropriate control strategies to minimize the adverse health effect on sportspeople.

This study complements two previous papers already published on the chemical composition and morphology of aerosols in this sports facility (Alves et al., 2013b, 2014).

2. Methodology

2.1. Description of sports facilities

A gymnasium at the University of Leon, Spain, was the sports facility chosen to carry out the monitoring program. The gymnasium is 15 m wide, is 27 m long and has a height of 10.6 m. It has no windows but a horizontal axis half-cylinder skylight (5 m diameter and 20.3 m length) centered on the roof. The vinyl flooring is nearly totally covered by gym mats and safety mattresses. The sports equipments include asymmetric bars/high bar, rings, parallel bars, beams, a pummel horse, a tumble track, trampolines, wall bars, and a dug pit with foam cubes. A side gate was frequently open when the gymnasium was busy, due to the high temperatures reached in summer after the late morning hours. The gym does not have any mechanical ventilation system. Further details have been described in Alves et al. (2013b). During the sampling campaign, it was occupied by college gymnasts between 7:00 and 12:00 (UTC) and between 15:00 and 17:00 (UTC).

2.2. Sampling and measurement equipments

The monitoring campaign was carried out between 15 and 21 July, 2012. The campaign was planned for the duration of a summer activity that lasted a week. Sampling with activities was conducted for five days, while another two days (weekend) were taken as background. Although the sample size was limited by the duration of sports activities, the homogeneity of the inter-daily pattern ensured the repeatability of the activities studied. Sampling could not have been made during the school year because gym activities are different from one day to another, without a temporal pattern, which would make difficult the possibility of reaching robust conclusions.

Several instruments were operating in order to characterize aerosols, gases and comfort parameters in the gymnasium. The results related to gases and environmental conditions (temperature, relative humidity, CO_2, CO and total volatile organic compounds) were presented in Alves et al. (2013b) and the morphology and chemical composition of particles can be found in Alves et al. (2014). This study completes these two previous papers, and presents a complete characterization of aerosol size distributions and its impact on the respiratory tract, under different activities, in this sports facility.

Particle size spectra were measured in 31 discrete channels (size ranges between 0.1 and 10 μm latex particle size) using a laser spectrometer probe (Passive Cavity Aerosol Spectrometer Probe, PMS Model PCASP-X). The principle of this instrument is based on the measurement of the intensity of the light scattered by the particles when passing through a laser light beam (He–Ne, 632.8 nm). The instrument detects single particles and groups them into different channels.

Several corrections need to be made on the number of counts indicated by the spectrometer to determine the exact number of particles per unit of volume sampled in each channel. The value of the sample volume has been adjusted according to the altitude (832 m asl) of the sampling point (Calvo et al., 2010). Similarly, the measurement in each time interval has been corrected by the spectrometer activity. This instrument generally underestimates the true diameter of ambient aerosols and a correction by the refractive index is necessary to bring the particle size distributions measured close to the real ones. The diameters corresponding to the different channels (particle bin sizes) were corrected using the refractive index in a model based on the Mie Theory (developed by Bohren and Huffman, 1983). Thus, the device was calibrated by the manufacturer using polystyrene latex (PSL) particles of a known size. The refractive index of latex beads (1.59–0i) is different from that of atmospheric particles, resulting in an aerosol size distribution that is "PSL size equivalent". In this study the refractive index and density were derived from aerosol composition (Alves et al., 2014), following the methodology by Levin et al. (2010), assuming that PM_{10} constituents are present as particular chemical compounds with a specific density and a typical refractive index. The values obtained were: 1.549–0.025i and 1.577–0.003i, and 1.940 and 2.055 g cm^{-3} outside and inside the gymnasium.

In order to evaluate the influence of the variability in the estimated refractive index on the estimated particle diameters, a sensitivity test was carried out. Fig. 1 shows the variation in the mean particle diameter

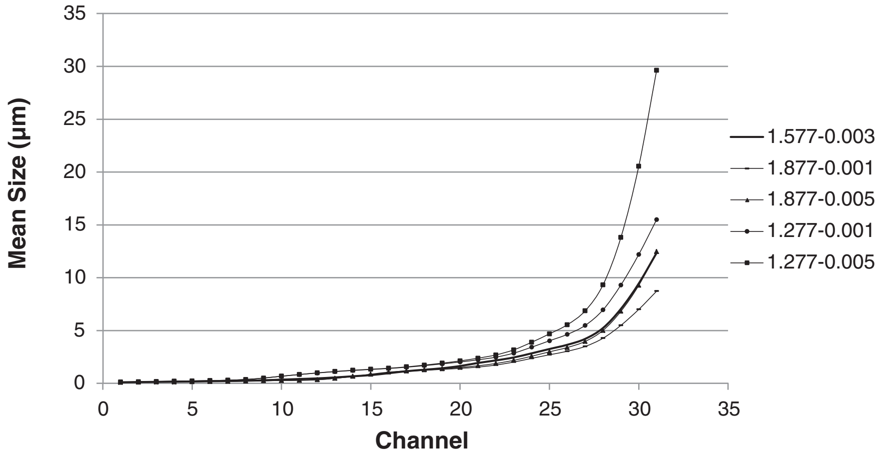

Fig. 1. Mean diameters (μm) corresponding to the different channels of the PCASP when using different refractive indices (1.577 ± 0.300-i (0.003 ± 0.002)).

(μm) corresponding to the different channels (particle class sizes) of the PCASP as a function of variations in the real and imaginary parts of the refractive index: 1.577 ± 0.300-i (0.003 ± 0.002). The uncertainty assigned to the real and imaginary parts is related to the uncertainty in the determination of the components that contribute to both parts. Thus, some of the analyzed filters presented a non-negligible percentage of unknown constituents that have been allocated to minerals and metals (between 20 and 55%), with an important real part. An uncertainty of ±0.3 has been assigned. However, the imaginary part is a measure of the absorptive capacity of the particles, and black carbon (BC) is the major contributor. Given that half of the filters presented BC mass fractions lower than 3%, an uncertainty of ±0.002 in the imaginary part has been estimated.

From channel 1 to channel 23, the diameters estimated for the different refractive indices were always less than 3 μm, and no important differences were observed. The most relevant differences were observed for larger diameters.

Regarding to the aerosol density estimated in this study, similar densities have been used in some other studies for all the aerosol spectra (e.g. Weinbruch et al. (2012) in a gym used a value of 2.3 g cm^{-3} for aerosol between 0.25 and 32 μm). Anyway, the values are close to the density of commercial magnesia alba powder (2.16 g cm^{-3}) provided by the supplier.

Table 1
Codes and activities in the gymnasium (occupancy periods and weekend) and outdoors for different sampling periods.

Code	Activities	Time interval (UTC)
I	Before sports activities	4:00–7:00
II	Sports activities without using magnesia alba in the morning (tatamis)	Total time (II, III and IV) 7:00–12:00
III	Sports activities without using magnesia alba in the morning (pit and tatamis)	
IV	Sports activities using magnesia alba in the morning (pit and tatamis)	
V	Vacant period	12:00–15:00
VI	Sports activities without using magnesia alba in the afternoon (tatamis)	Total time (VI, VII and VIII) 15:00–17:00
VII	Sports activities without using magnesia alba in the afternoon (pit and tatamis)	
VIII	Sports activities without using magnesia alba in the afternoon (pirouettes)	
IX	Cleaning activities	17:00–18:00
X	After sports activities (0 h–2 h)	18:30–20:30
XI	After sports activities (2 h–4 h)	20:30–22:30
XII	Maximum of magnesia alba concentration	
XIII	Weekend	24 h
XIV	Outdoors	30 min

Furthermore, a complementary electron scanning microscopy study was conducted during the campaign (Alves et al., 2014). This study allowed the assessment of the size segregated chemical composition, and thus, to obtain more information about the characteristics of the particles and to substantiate the assumptions made for either the treatment of the size distribution data or the density adopted for the PCASP-X.

The results of the microscopy study were consistent with the PM_{10} speciation given by Alves et al. (2014). The highest difference in chemical composition of the indoor samples for the gymnasium was found between the submicrometric and supermicrometric ranges. More than 90% of the PM_{10} volume was attributed to particles larger than 1 μm, and the chemical composition did not vary much in these sizes. Thus, the uncertainty associated with the estimation of the density through the gravimetric measurements was rather low and validated by the microscopy.

The highest errors could be linked to the submicrometric range, in which soot (aggregates of elemental carbon with graphitic structure from combustion) and organic compounds, as well as ammonium sulfate, were the prevalent constituents. Some salts (e.g. NaCl and KCl) were also abundant in this size range. The origin of these nano-salts has yet to be solved, but probably is a consequence of the perspiration during the exercises in the sports facilities. An estimation of the density for this size range based on these results, using typical values found in the literature (Alves et al., 2014), gives an effective density of 1.78 (approximately varying from 1.7 to 1.9 g cm^{-3}, depending on the sample). This represents between 10 and 15% of error for this size range. However, since this size range accounted for less than 10% of the total volume in PM_{10}, the errors associated with the mass estimation by using the reference density of 2.055 g cm^{-3} are negligible.

Using the density calculated, and assuming the sphericity of particles, the mass concentration was estimated, and the evolution of PM_1, $PM_{2.5}$ and PM_{10} was assessed. The spectrometer was placed next to a wall in the gym and at a 1.5 m height to ensure safety. Measurements were taken every minute.

During the sampling campaign, the sports facility was occupied daily in the morning (between 7:00 and 12:00 UTC) by gymnasts (16 to 29 gymnasts, with ages between 7 and 14), and of these, between 8 and 16 used magnesia alba. In the afternoon (between 15:00 and 17:00 UTC) there were only 4 to 8 gymnasts, aged between 18 and 30, and they never used magnesia alba. There was a much higher attendance in the morning because children from a summer school sponsored by the university were playing in the gymnasium.

2.3. Methodology

In order to carry out a complete characterization of aerosol size distributions, measurements were grouped into fourteen categories (Table 1): activities in the gym (codes I to XII), weekend (code XIII) and outdoor (code XIV). Among the activities in the gym, those related to the use of climbing chalk (hydrated magnesium carbonate hydroxide or magnesia alba) are of high relevance. This drying agent is an essential component used by athletes for their hands, and it has been proved a significant contributor to the levels of particles in sports facilities (Weinbruch et al., 2008).

A limited number of measurements were performed outdoors. Only one aerosol spectrometer was available and the device is fragile. As a result, the spectrometer was moved outside only a limited number of times.

Athletes are exposed to aerosol particles that enter the human respiratory tract and may pose an important risk to respiratory diseases. The aerosol size fractions associated with health problems were evaluated following the Spanish standard UNE 77213, which is equivalent to the ISO 7708:1995.

These standards define conventions for atmospheric particle size fractions to assess possible health effects in the workplace and ambient environment. The conventions specify the relationships between aerodynamic diameters and aerosol fractions collected or measured by the sampling instrument. These fractions represent approximately the part that reaches, under average conditions established by ISO 7708:1995, different areas of the respiratory tract. Particle sampling conventions have been established, expressed as curves describing "penetration" to the region of interest in terms of the particle aerodynamic diameter. From the experimental size distributions, first, the inhalable and thoracic fractions, and then the tracheobronchial and respirable fractions were assessed for healthy adults and high-risk groups (children, elderly or infirm people).

This study presents the analysis of aerosol size distributions in the gymnasium and its deposition in the human respiratory tract, through the inhalable, thoracic, tracheo-bronchial and respirable fractions estimated.

3. Results and discussion

3.1. Aerosol number, surface and volume distributions

In the morning, there were between 16 and 29 gymnasts, and of these, between 8 and 16 used magnesia alba. The total number of particles seems to be poorly influenced by the different activities carried out in the gym. Thus, during the periods of sports activities without using magnesia alba (II and III) the mean number of particles registered was 590 ± 170 and 490 ± 150 particles cm^{-3}, respectively, and during sports activities using this drying agent (IV) the number of particles was 520 ± 160 particles cm^{-3} (Table 2). Regarding the Count Median Diameter (CMD), a slight increase was observed, registering a value of 0.16 μm in activity periods previous to the use of magnesia and 0.17 μm when using magnesia. The highest concentration of particles when using magnesia (XII) was 600 ± 160 particles cm^{-3} with a CMD of 0.19 μm.

A decrease in the number of particles was registered during vacant periods. In the afternoon, the number of particles during the periods of sports activities without using magnesia decreased with respect to the morning because there were fewer gymnasts in the sports arena (between 4 and 8).

During nocturnal periods, the number of particles increased significantly, reaching values as high as 620 particles cm^{-3} before sports activities. This increase is experienced in the fine mode (Fig. 2). Formation of new aerosol particles by nucleation and growth has been recently observed at night in chamber experiments (Ortega et al., 2012). The nocturnal events have been explained by the oxidation of volatile organic compounds (VOCs). Thus, VOCs emitted during the cleaning procedures in the late afternoon may have contributed to nocturnal nucleation events (Alves et al., 2013b).

In contrast, the surface and volume size distributions are greatly influenced by the different activities carried out in the gym. In the morning, when athletes start sports activities, a progressive increase of the total surface area is observed, changing from 140 ± 90 $\mu m^2\ cm^{-3}$ in period II (without using magnesia) to 360 ± 80 $\mu m^2\ cm^{-3}$, in period IV (with magnesia), and reaching a maximum value of 570 ± 130 $\mu m^2\ cm^{-3}$ (period XII). A similar behavior was observed in the surface mean diameter, shifting from 1.1 ± 1.0 μm to 2.6 ± 0.5 μm and reaching a maximum value of 2.7 ± 0.5 μm. Similarly, the total volume and the volume mean diameter shifted from 70 ± 80 $\mu m^3\ cm^{-3}$ and 4.7 ± 0.6 μm in period II to 250 ± 70 $\mu m^3\ cm^{-3}$ and 5.6 ± 0.2 μm in period IV. A maximum value of 380 ± 100 $\mu m^3\ cm^{-3}$ (period XII) was observed.

Table 2 shows that the total number of particles during different activities is similar, and the standard deviation represents 30 to 40% of the mean. These results could lead to the conclusion that there are no significant differences between the distinct activities. In order to see if there are differences between aerosol size distributions associated with the various activities, the Kruskal–Wallis non-parametric test (Kruskal and Wallis, 1952) followed by Dunn's test (Dunn, 1964) was applied. Statistically significant differences were observed in every pair-wise test

Table 2
Total number of particles, total surface, total volume, Count Median Diameter (CMD), surface mean diameter (SMD), volume mean diameter (VMD) and Geometric Standard Deviation (σ_g) of the number, surface and volume distributions obtained for different activities in the gymnasium, weekend and outdoors.

Code	Number size distribution			Surface size distribution			Volume size distribution		
	N_T (cm^{-3})	CMD (μm)	σ_g	S_T ($\mu m^2\ cm^{-3}$)	SMD (μm)	σ_g	V_T ($\mu m^3\ cm^{-3}$)	VMD (μm)	σ_g
I	620 ± 180	0.16 ± 0.02	1.41 ± 0.03	70 ± 20	0.3 ± 0.1	2.5 ± 1.0	70 ± 30	0.13 ± 0.03	2.5 ± 1.1
II	590 ± 170	0.16 ± 0.01	1.50 ± 0.16	140 ± 90	1.1 ± 1.0	4.3 ± 0.8	70 ± 80	4.7 ± 0.6	2.6 ± 0.5
III	490 ± 150	0.16 ± 0.02	1.67 ± 0.13	310 ± 140	2.5 ± 0.3	3.4 ± 0.4	210 ± 100	5.6 ± 0.1	1.9 ± 0.1
IV	520 ± 160	0.17 ± 0.01	1.77 ± 0.16	360 ± 80	2.6 ± 0.5	3.4 ± 0.5	250 ± 70	5.6 ± 0.2	1.9 ± 0.1
V	440 ± 150	0.17 ± 0.01	1.64 ± 0.17	170 ± 70	1.8 ± 0.7	4.0 ± 0.6	100 ± 60	5.1 ± 0.5	2.0 ± 0.2
VI	420 ± 150	0.16 ± 0.01	1.55 ± 0.08	120 ± 60	1.4 ± 0.7	4.5 ± 0.6	60 ± 50	5.0 ± 0.4	2.1 ± 0.2
VII	300 ± 100	0.17 ± 0.00	1.61 ± 0.06	150 ± 30	2.2 ± 0.0	3.9 ± 0.4	100 ± 30	5.9 ± 0.5	1.9 ± 0.0
VIII[a]	379	0.17	1.60	182	2.1	4.0	119	5.7	1.9
IX	450 ± 190	0.16 ± 0.00	1.48 ± 0.05	70 ± 10	0.7 ± 0.3	4.4 ± 0.3	22 ± 4	4.1 ± 0.5	2.7 ± 0.5
X	460 ± 170	0.16 ± 0.00	1.45 ± 0.03	56 ± 12	0.4 ± 0.2	3.6 ± 0.7	10 ± 3	2.9 ± 1.0	3.5 ± 0.8
XI	530 ± 170	0.15 ± 0.01	1.40 ± 0.02	56 ± 16	0.3 ± 0.1	3.0 ± 0.7	6 ± 1	1.8 ± 0.7	4.2 ± 0.7
XII	600 ± 160	0.19 ± 0.00	1.96 ± 0.11	570 ± 130	2.7 ± 0.5	3.0 ± 0.7	380 ± 100	5.3 ± 0.8	1.9 ± 0.1
XIII[a]	318	0.17	1.37	34	0.2	2.2	2	1.0	7.1
XIV[a]	228	0.17	1.37	36	0.6	5.0	13	5.8	2.9

[a] One day sampling.

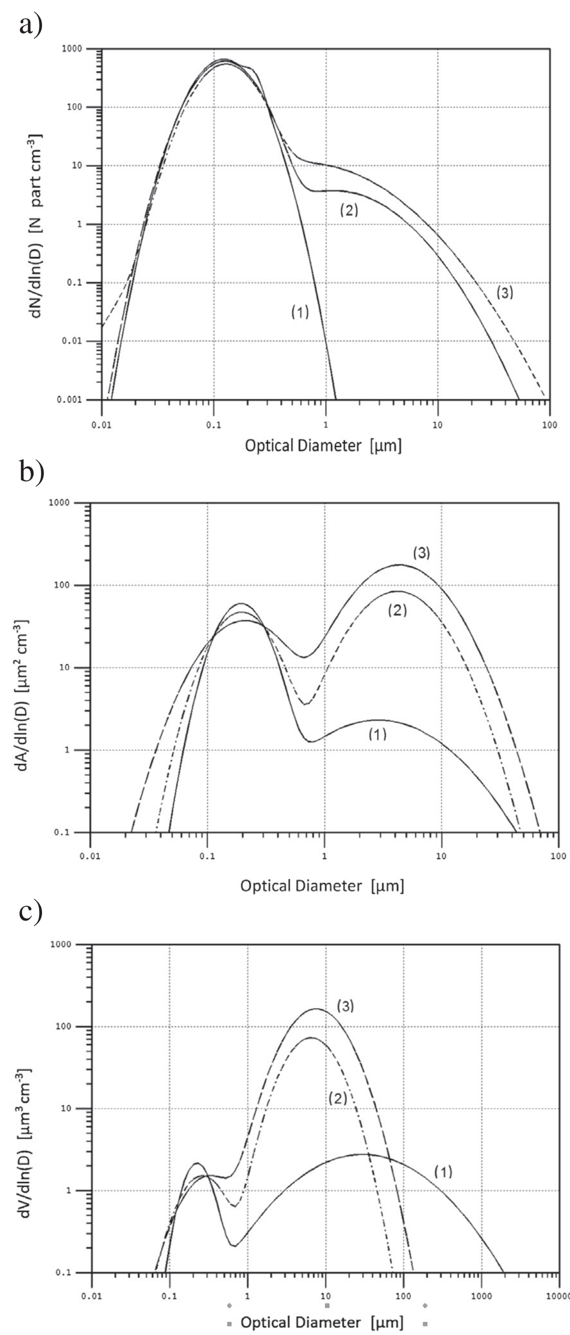

Fig. 2. Theoretical aerosol size bimodal (a) number, (b) surface area and (c) volume distributions for (1) before sports activities (code I), (2) for sports activities without using magnesia in the morning (codes II and III) and (3) using magnesia (code IV).

($p < 0.001$) at the 0.05 level of significance. Firstly, the test shows significant differences between the XIII code (weekend) and the periods when sports activities are being developed (II to VIII codes). Nevertheless, before the activities and during (and after) the cleaning periods, the distributions are similar.

The test also showed that there are significant differences between the size distributions of activities III and IV and the size distributions of activities I, IX, X and XI. This means that during sports activities with magnesia and before, size distributions are different from those found before the start of activities in the gym, from distributions in the cleaning period and a few hours after cleaning. This means that the process of resuspension is as important in air pollution in the gym as the use of magnesia in sports, since there are no significant differences between III and IV.

From these results, we might wonder whether we can join the groups which do not show significant differences. For example, groups I, II, V and IX represent very different activities, so it does not make sense to do a joint data processing. Groups VI, VII and VIII have shown no differences in the distributions, but represent different sports activities that may involve different processes of resuspension, by the different intensities of the exercises performed by athletes in each activity.

The differences among the periods established are also evident when the mass concentrations are estimated. This is due to the different aerosol size distributions found for the activities carried out in the gym (see Section 3.3).

In order to check the accuracy of the measured data, the standard deviations of the data from each of the bins have been calculated for the size distributions at intervals of 5 min. It has been observed that they represent a relative error not exceeding 5%. This means that the accuracy is acceptable and the possible error is noticeably smaller than the differences observed between the different distributions studied.

3.2. Fine and coarse modes

The size distributions are highly variable when the activities in the gymnasium are changing throughout the day (Table 3). They show a bimodal profile, presenting a first fine mode (CMD < 1 μm) with a significant number of particles, and few particles belonging to a second fine mode, or a coarse mode (CMD ≥ 1 μm).

The fine and coarse modes are also very different depending on the type of activity inside the facility. It was observed that:

- The distributions are lognormal, with a single fine mode, before sports activities (code I), when cleaning is taking place (IX), 4 h after cleaning (X and XI), at the weekend (XIII) and outdoors (XIV).
- In the morning, with the simultaneous presence in the sports facility of about 20 gymnasts, the activities started without using magnesia (II). A large number of particles were recorded in the coarse mode (around 30 particles cm^{-3} and CMD of 1.27 μm). These particles were previously deposited on the surfaces of floor, mats, foam cubes, gym equipment, etc., and were resuspended to the surrounding environment due to complex effects. The dry deposition takes place since the end of the previous day's activities (for about 14 h) on these surfaces. Subsequently (activity III), gymnasts use the pit and the tatamis, at the same time. The pit contains large foam cubes, which accumulate a lot of dust and magnesia, both difficult to remove by cleaning. In these cases, the distributions are bimodal with fine and coarse modes (around 19 particles cm^{-3} and CMD of 1.00 μm) (Fig. 2). Later, gymnasts begin to perform exercises using magnesia

Table 3
Number of particles, Count Median Diameter (CMD) and Geometric Standard Deviation (σ_g) of the number distributions obtained for different activities in the gymnasium (occupancy periods and weekend) and outdoors for the first and second fine modes and coarse mode.

Code	First fine mode			Second fine mode			Coarse mode		
	N (cm^{-3})	CMD (μm)	σ_g	N (cm^{-3})	CMD (μm)	σ_g	N (cm^{-3})	CMD (μm)	σ_g
I	768	0.13	1.57	–	–	–			
II	608	0.13	1.60	–	–	–	30	1.27	4.04
III	616	0.13	1.61	–	–	–	19	1.00	2.67
IV	622	0.13	1.58	32	0.64	3.17			
V	551	0.13	1.55	15	0.55	3.80			
VI	517	0.13	1.52	10	0.50	3.85			
VII	336	0.14	1.53	8	0.93	2.63			
VIII	402	0.15	1.50	11	0.88	2.71			
IX	553	0.13	1.53	–	–	–			
X	565	0.13	1.53	–	–	–			
XI	608	0.13	1.50	–	–	–			
XII	648	0.13	1.60	150	0.16	6.00			
XIII	418	0.14	1.55	–	–	–			
XIV	235	1.16	1.40	–	–	–			

Table 4
Mass concentration: TSP, PM_1, $PM_{2.5}$, PM_{10}, $PM >_{10}$ and $PM_{2.5-10}/PM_{10}$.

Code	TSP ($\mu g\ m^{-3}$)	PM_1 ($\mu g\ m^{-3}$)	$PM_{2.5}$ ($\mu g\ m^{-3}$)	PM_{10} ($\mu g\ m^{-3}$)	$>PM_{10}$ ($\mu g\ m^{-3}$)	$PM_{2.5-10}/PM_{10}$ %
I	12 ± 6	5 ± 2	6 ± 2	10 ± 3	2 ± 4	41 ± 18
II	140 ± 160	5 ± 1	16 ± 14	120 ± 150	15 ± 15	83 ± 5
III	400 ± 200	7 ± 3	44 ± 20	380 ± 190	60 ± 20	88 ± 2
IV	520 ± 140	8 ± 1	51 ± 11	440 ± 130	80 ± 20	88 ± 2
V	210 ± 130	5 ± 1	23 ± 9	190 ± 110	21 ± 16	87 ± 3
VI	130 ± 100	4 ± 1	14 ± 8	120 ± 90	13 ± 14	86 ± 2
VII	210 ± 60	4 ± 1	19 ± 1	180 ± 50	32 ± 9	89 ± 3
VIII	250 ± 90	5 ± 1	24 ± 8	220 ± 70	30 ± 40	89 ± 3
IX	45 ± 8	3 ± 1	9 ± 1	40 ± 9	5 ± 2	78 ± 6
X	21 ± 6	3 ± 1	6 ± 1	20 ± 5	2 ± 1	65 ± 11
XI	13 ± 3	4 ± 1	6 ± 1	13 ± 3	0 ± 0	54 ± 14
XII	800 ± 200	14 ± 4	90 ± 20	700 ± 200	100 ± 90	86 ± 4
XIII	3.2	2.1	2.7	3.2	0	17
XIV	23 ± 20	2 ± 0	8 ± 1	23 ± 20	0 ± 0	45 ± 33

alba (IV), registering bimodal distributions with two fine modes. For each day, measurements of maximum concentrations of magnesia (XII) indicate a very large number of particles (150 particles cm^{-3}) in the second fine mode. This suggests that the use of magnesia alba causes, in the sports facility, a significant change in air quality due to the gradual emergence of many sub-micron particles. Weinbruch et al. (2012), however, show that the use of magnesia alba predominantly leads to the emission of particles with diameters above 1 μm in indoor climbing gyms, in which magnesia alba is used for drying hands.

- During 3 h, in the vacant period (V), processes for the dry deposition of the particles initiate. Later, a small group of gymnasts (between 4 and 8) used the gym for 2 h in the afternoon. They started exercising on the tatami mats (VI), then used the pit and tatamis simultaneously (VII), and finally they performed pirouettes on the floor (VIII). During these three activities, a decrease in the number of particles has been recorded in relation to the morning, in fine modes. Comparing the activity of the morning with the afternoon it can be concluded that the number of gymnasts in the room is a very important factor affecting indoor air quality.
- Subsequently, the cleaning activities of the enclosure (code IX) started. This alters the characteristics of the size distributions. That change is still observed 4 h after the gym has been cleaned (codes X and XI). The fine mode fits a lognormal distribution, but the coarse mode is inexistent.
- At the weekends (XIII) the number of particles in the fine mode decreased, the coarse mode is not observed and the size distribution is similar to the one detected every day before the sports activities start in the gym.

3.3. Mass concentration

From the estimated particle density (2055 $kg\ m^{-3}$) it was possible to estimate the mass concentration of total suspended particles (TSP), PM_1, $PM_{2.5}$, PM_{10} and particles larger than PM_{10} (Table 4). As soon as sports activities began in the morning (code II), significant increases in the concentration of PM_{10} were observed. The main cause is the resuspension of dust deposited on the equipment, on the pit and on the tatamis. Subsequently, with the use of magnesia alba by gymnasts (phase IV), average concentrations of 440 and 51 $\mu g\ m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively, were recorded. Maximum daily concentrations, ranging between 500 and 900 $\mu g\ m^{-3}$ and between 70 and 110 $\mu g\ m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively, were registered. This indicates that there was a strong environmental contamination inside the gym while gymnasts were training with magnesia. Weinbruch et al. (2008) found similar values, and even higher amounts, in indoor climbing halls. During the vacant period (3 h; code V), the concentration decreased to an average value of 190 $\mu g\ m^{-3}$. In the afternoon, as the number of gymnasts was much lower, the mass concentration was not greater than 220 $\mu g\ m^{-3}$. This level is lower than the value of 380 $\mu g\ m^{-3}$ observed in the morning, when more people were in the gym. The cleaning activities caused a drastic decrease in the mass concentrations (40 $\mu g\ m^{-3}$), which is progressive in the next 4 h (up to 13 $\mu g\ m^{-3}$). These values are maintained until the next morning, before the sports activities started again. The evolution of TSP during the temporal sequence of daily activities can be observed in Fig. 3.

While sports activities take place, particles with diameters larger than 2.5 μm, contribute nearly 90% of PM_{10} mass. This value is much higher than before the start of the sports activities ($PM_{2.5}/PM_{10}$ = 41%). Two main processes contribute to remove large particles: i) cleaning activities ($PM_{2.5}/PM_{10}$ = 78%, code IX), and ii) dry deposition ($PM_{2.5}/PM_{10}$ = 65% and 54%, codes X and XI, respectively). The use of liquid chalk, instead of the common magnesia alba, has been recently proven to be an effective and inexpensive measure to reduce particle levels in gymnasiums (Weinbruch et al., 2012).

3.4. Dry deposition and terminal settling velocity

In the morning, when the sports activities begin, before the athletes use magnesia, resuspension of particles deposited on surfaces and different gym equipment occurs. It causes, as has been seen previously, a significant increase in the mass concentration of suspended particles larger than 1 μm (Table 4). Later, when athletes use magnesia alba, larger particles appear, which are added to those from resuspension. This means that dry deposition plays an important role during the period

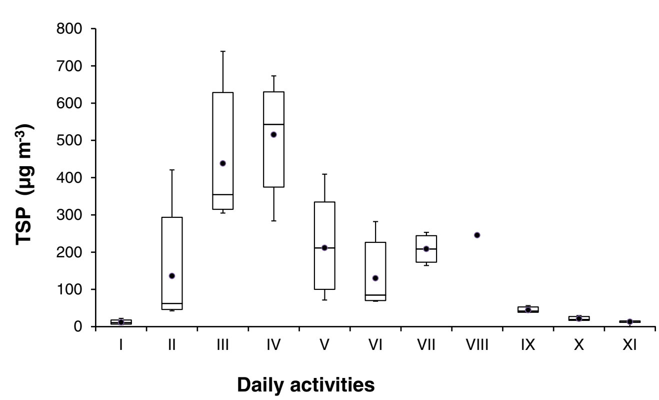

Fig. 3. Evolution of TSP during the sequence of daily activities in the gymnasium (see Table 1 for activity codes) in terms of mean, median, 10th and 90th percentiles, and minimum and maximum values.

of inactivity. The cleaning activities are conducted mainly on surfaces and soil elements but not in the pit area, filled with foam cubes. Therefore, cleansing is not able to eliminate all the deposited particles, so the next day the phenomenon of resuspension takes place again, especially when the athletes use the pit.

In the gym, between the end of the ordinary morning activities and the beginning of the evening activities, a gradual decrease in the number and mass of suspended particles was observed. Together with the cessation of aerosol release and resuspension, a drop in the aerosol concentration by dry deposition was registered.

By plotting the amount of particulate matter as a function of time, the rate of particle decline shows an exponential shape between the maximum and minimum values. That is, the number of particles above the minimum follows an exponential decay. Indeed, the exponential fit of all daily measurements presents significant values of R^2 (for a level of statistical significance $\alpha = 0.01$), between 0.70 and 0.98.

When representing the aerosol mass at the midday break as a function of time, an exponential fitting is also obtained, with significant R^2 between 0.47 and 0.78. Exponent coefficients vary in a range from 0.0058 to 0.0102 min^{-1}. This means that the mass of aerosol takes between 68 and 120 min to be halved.

On the basis of aerosol size, three different groups (PM_1, $PM_{1–2.5}$ and $PM_{2.5–10}$) were established. The aerosol mass in each group also decreases exponentially with time. The time that the mass of the aerosol takes to halve is always higher for smaller aerosols (PM_1) and decreases for medium ($PM_{1–2.5}$) and coarse aerosols ($PM_{2.5–10}$). This is in agreement with their different sedimentation rates, which increase with size. The ratio between these times for the groups $PM_{1–2.5}/PM_{2.5–10}$ presents slight daily variations ranging between 1.22 and 1.36, with an average value of 1.3.

3.5. Inhalable, thoracic, tracheobronchial and respirable fractions

The percentages corresponding to the different mass fractions (in % and μg m^{-3}) of aerosols in the gymnasium were evaluated taking into account the estimated density of the particles, the aerodynamic diameters of the channels of the spectrometer, and the number of particles in each channel. The results for different activities (I to XII), weekend (code XIII) and outdoors (code XIV) are shown in Table 5. Before the different sports activities (code I), in the interval from 2 h to 4 h after the sports activities (code XI), and at the weekend (code XIII), the percentage of the mass of particles inhaled in each fraction and the mass retained in the different parts of the respiratory tract had a similar behavior. For high risk population, around 42% of the mass inhaled reached the alveolar region (bronchioles and alveoli), while a percentage of around 50% was estimated for a healthy adult. These mass fractions applied to the mass concentration of particles, showed that, in the case of a healthy adult, no more than 4 μg m^{-3} is retained by the trachea and bronchia (tracheobronchial region) because they are not able to cross the nonciliated airways. As a consequence, no more than 6 μg m^{-3} reaches the alveolar region (bronchioles and alveoli). For high risk population, these concentrations were 6 and 4 μg m^{-3}, respectively.

A significant increase in the number of large particles was associated with physical activities. Therefore, the deposition rates in the alveolar region were smaller (10% during activities using magnesia alba) than those registered without sports activities. The reason is that large particles cannot reach the alveolar region.

A very different behavior is observed when sports activities are initiated with or without using magnesia alba in the morning or afternoon. In the morning, for a healthy adult or for high risk population, such as

Table 5
Inhalable, thoracic, tracheobronchial and respirable mass fractions (% and μg m^{-3}) in healthy adults and high risk population (children, frail or sick people) deposited in the respiratory tract for different activities in the gymnasium, weekend and outdoors.

Activity code	Inhalable fraction	Thoracic fraction	Tracheobronchial fraction Healthy adult	Tracheobronchial fraction High risk	Respirable fraction Healthy adult	Respirable fraction High risk
	%	%	%	%	%	%
I	84 ± 11	71 ± 17	26 ± 8	34 ± 9	45 ± 24	40 ± 30
II	70 ± 20	51 ± 14	35 ± 11	43 ± 13	16 ± 4	8 ± 3
III	76 ± 7	53 ± 5	40 ± 4	49 ± 5	13 ± 2	5 ± 1
IV	80 ± 1	54 ± 2	40 ± 0	49 ± 1	10 ± 2	5 ± 1
V	80 ± 1	56 ± 4	41 ± 1	50 ± 2	15 ± 3	6 ± 2
VI	80 ± 1	56 ± 3	40 ± 1	49 ± 2	15 ± 2	7 ± 2
VII	79 ± 2	51 ± 6	39 ± 3	47 ± 5	13 ± 3	5 ± 1
VIII	79 ± 0	51 ± 0	39 ± 0	47 ± 0	12 ± 0	5 ± 0
IX	82 ± 1	62 ± 3	39 ± 2	50 ± 3	23 ± 5	12 ± 4
X	83 ± 4	66 ± 12	36 ± 5	46 ± 7	30 ± 15	20 ± 12
XI	87 ± 2	77 ± 6	32 ± 8	44 ± 9	45 ± 12	33 ± 13
XII	80 ± 1	58 ± 5	41 ± 1	52 ± 3	16 ± 4	6 ± 2
XIII[a]	88	81	21	30	60	52
XIV[a]	76	43	29	35	14	8
	Inhalable fraction	Thoracic fraction	Tracheobronchial fraction Healthy adult	Tracheobronchial fraction High risk	Respirable fraction Healthy adult	Respirable fraction High risk
	μg m^{-3}	μg m^{-3}	μg m^{-3}	μg m^{-3}	μg m^{-3}	μg m^{-3}
I	10 ± 1	8 ± 2	3 ± 1	4 ± 1	5 ± 3	4 ± 3
II	100 ± 30	70 ± 19	50 ± 15	60 ± 18	20 ± 6	11 ± 4
III	300 ± 30	200 ± 20	180 ± 18	200 ± 20	60 ± 8	20 ± 3
IV	400 ± 3	300 ± 9	200 ± 2	300 ± 5	70 ± 9	30 ± 5
V	170 ± 2	120 ± 8	90 ± 2	110 ± 4	30 ± 6	12 ± 4
VI	100 ± 1	70 ± 3	50 ± 1	60 ± 2	20 ± 3	8 ± 2
VII	160 ± 3	110 ± 13	80 ± 7	100 ± 11	30 ± 7	10 ± 2
VIII	190 ± 0	130 ± 0	100 ± 0	110 ± 0	30 ± 0	12 ± 0
IX	40 ± 0	30 ± 2	18 ± 1	22 ± 1	10 ± 2	6 ± 2
X	18 ± 1	14 ± 3	8 ± 1	10 ± 1	6 ± 3	4 ± 3
XI	11 ± 0	10 ± 1	4 ± 1	6 ± 1	6 ± 2	4 ± 2
XII	600 ± 10	400 ± 40	300 ± 10	400 ± 30	130 ± 30	50 ± 14
XIII[a]	3	3	1	1	2	2
XIV[a]	17	10	7	8	3	2

[a] One day sampling.

children, frail or sick people, the percentages of deposition in the tracheobronchial area (about 35%–49%, for codes II, III, IV) increased, and, as a consequence, the percentages in the respirable or alveolar fraction decreased (about 5%–16%). These results are due to the different particle size distributions when different sports activities are taking place in the gym. The large particles present in the air do not reach the alveoli, but are retained in the tracheobronchial region by the trachea and bronchi. From the particle size distribution, in the tracheobronchial region it can be seen that during the activities using magnesia an average of 200 ± 2 μg m^{-3} cannot cross the nonciliated airways and is retained by the trachea and bronchi in a healthy adult, and 300 ± 5 μg m^{-3} if the population is high risk. On average, a maximum value of 300 ± 10 μg m^{-3} was observed in healthy adults and 400 ± 30 μg m^{-3} in high risk population. The remaining mass per volume unit, 70 ± 9 μg m^{-3}, reaches the alveolar region (bronchioles and alveoli) in a healthy adult, and 30 ± 5 μg m^{-3} in high risk population. In this region a maximum value of 130 ± 30 μg m^{-3} was observed in healthy adults, and 50 ± 14 μg m^{-3} in high risk population.

In the afternoon, sports activities are performed without magnesia alba and the number of athletes in the gym is lower. Although the mass fractions are similar to those found in the morning, the size distributions of particles are different. It was found that maximum concentrations of up to 100 μg m^{-3} are retained by the trachea and bronchi, and 30 μg m^{-3} reach the alveolar region.

Weinbruch et al. (2008) compiled the medians of the inhalable and respirable fractions of personal exposure for various industries in Germany. Except in the building industry, the median of the inhalable fraction was in the range of 0.3–4 mg m^{-3}. The study presented here has been developed in a university gym with a low occupational level and with only between 8 and 16 athletes using magnesia alba. A direct relationship was observed between the number of athletes and the mass concentration registered in the morning (more athletes) and the afternoon (Table 4). Despite the small number of athletes, the maximum values of the inhalable fraction observed (0.6 mg m^{-3}) are higher than those registered in many industrial work places such as in the mining (0.3 mg m^{-3}) or textile industry (0.4 mg m^{-3}). In the gym, the maximum respirable fractions (alveolic) were 0.130 mg m^{-3} and when the occupational level was higher, it could reach values similar to those in mining, in the textile industry, the leather industry or even in the timber and plastics industry and in the food industry (between 0.2 and 0.3 mg m^{-3}).

In the vacant period, which lasted for approximately 3 h, between the morning and afternoon activities, the dry deposition was slow and caused considerable changes in the size distributions. Their behavior was similar to those registered during the periods with sports activities in the afternoon.

However, in the afternoon, after the cleaning activities, the percentages for the different fractions were nearer the values of deposition observed before the sports activities. This reveals that particles originated by the use of magnesia alba are more efficiently eliminated by cleaning activities than by dry deposition phenomena.

It is important to take into account that in the morning, magnesia alba is used mainly by children. They are included in the high risk category because they are especially susceptible to health problems due to their higher physical activity, higher metabolic rate and the resultant increase in minute ventilation (Braniš et al., 2009; Chalupa et al., 2004; Gauderman et al., 2004).

4. Conclusions

In the indoor environment of a gymnasium, PM_{10} concentrations are highly variable, depending on the activities carried out, the occupancy rates and the cleaning. Some activities, such as gymnastics, lead to a constant resuspension process of particles from the surfaces of tatamis and foam cubes. The use of magnesia alba as a drying agent for hands contributes to a dusty indoor air because of a gradual emergence of many particles larger than 1 μm and many sub-micron particles. The particle size distributions are different when different gymnastic activities are practiced in the gym. The presence of substantial amounts of large particles has been observed in the air. Many of them do not reach the alveolar region, because they are retained in the tracheobronchial region by the trachea and bronchi. Particles from magnesia alba, and especially those from resuspension of dust settled when sports activities take place, are eliminated more efficiently by cleaning activities than by dry deposition phenomena. In the gym, when the occupational level was higher, the maximum respirable fractions were similar to those found in several industries like the mining, textile or leather industry.

The very dusty conditions observed in a sporting arena, such as the one in this study, may serve as an impediment to participation in physical activity for allergic practitioners. In addition to being an indoor asthma trigger, magnesia alba is suspected of causing nervous system depression, cardiac disturbances and respiratory tract irritation, although these aspects are not yet fully documented. Given the results of the present investigation, it becomes imperative to take up further studies on the nature and health effects of airborne particulate chalk dusts in gymnasiums.

To prevent likely health outcomes, mitigation measures should be adopted. The daily utilization of powerful vacuum cleaners using multi-stage HEPA filtration systems with graduated filters is highly recommended. A regular renewal of tatami and foam cubes is also advised, and the use of liquid chalk, instead of the common magnesia alba, is proposed. The installation of indoor air multi-stage filtration systems is also advised. Given that the health effects of these particles are not well established, the precautionary principle should be applied in conjunction with other preventive and remedial measures to reduce indoor levels.

Acknowledgments

This study was partially funded by the Centre of Environmental and Marine Studies (CESAM) of the University of Aveiro (PEst-C/MAR/LA0017/2011 and UID/AMB/50017/2013), by the Spanish Ministry of Science and Innovation (Grant TEC2010-19241-C02-01) and by AEROCLIMA project (Fundación Ramón Areces, CIVP16A1811). The authors are grateful to Darrel Baumgardner for his help with the code developed by Bohern and Huffman. Thanks to the Faculty of Physical Education and Sports, University of León, for allowing us the access to the sports facilities and also to Guillermo Arias and Elisa Estapé for their kindness and availability.

References

Alves, C., Nunes, T., Silva, J., Duarte, M., 2013a. Comfort parameters and particulate matter (PM_{10} and $PM_{2.5}$) in school classrooms and outdoor air. Aerosol Air Qual. Res. 13, 1521–1535. http://dx.doi.org/10.4209/aaqr.2012.11.0321.

Alves, C., Calvo, A.I., Castro, A., Fraile, R., Evtyugina, M., Bate-Epey, E.F., 2013b. Indoor air quality in two university sports facilities. Aerosol Air Qual. Res. 13, 1723–1730. http://dx.doi.org/10.4209/aaqr.2013.02.0045.

Alves, C., Calvo, A.I., Marques, L., Castro, A., Nunes, T., Coz, E., Fraile, R., 2014. Particulate matter in the indoor and outdoor air of a gymnasium and a fronton. Environ. Sci. Pollut. Res. 21, 12390–12402. http://dx.doi.org/10.1007/s11356-014-3168-1.

Batterman, S., Du, L., Mentz, G., Mukherjee, B., Parker, E., Godwin, C., Chin, J.Y., O'Toole, A., Robins, T., Rowe, Z., Lewis, T., 2012. Particulate matter concentrations in residences: an intervention study evaluating stand-alone filters and air conditioners. Indoor Air 22, 235–252.

Bohren, C.F., Huffman, D.R., 1983. Absorption and Scattering of Light by Small Particles. Wiley, New York.

Braniš, M., Šafránek, J., 2011. Characterization of coarse particulate matter in school gyms. Environ. Res. 111, 485–491.

Braniš, M., Šafránek, J., Hytychová, A., 2009. Exposure of children to airborne particulate matter of different size fractions during indoor physical education at school. Build. Environ. 44, 1246–1252.

Buonanno, G., Fuoco, F.C., Morawska, L., Stabile, L., 2013. Airborne particle concentrations at schools measured at different spatial scales. Atmos. Environ. 67, 38–45.

Calvo, A.I., Pont, V., Castro, A., Mallet, M., Palencia, C., Roger, J.C., Dubuisson, P., Fraile, R., 2010. Radiative forcing of haze during a forest fire in Spain. J. Geophys. Res. 115, D08206.

Chalupa, D.C., Morrow, P.E., Oberdörster, G., Utell, M.J., Frampton, M.W., 2004. Ultrafine particle deposition in subjects with asthma. Environ. Health Perspect. 112, 879–882.
Colbeck, I., Nasir, Z.A., 2010. Indoor air pollution. In: Colbeck,, M.L.A.I. (Ed.), Human Exposure to Pollutants via Dermal Absorption and Inhalation, Environmental Pollution. Springer Science+Business Media B.V.
Daigle, C.C., Chalupa, D.C., Gibb, F.R., Morrow, P.E., Oberdörster, G., Utell, M.J., Frampton, M.W., 2003. Ultrafine particle deposition in humans during rest and exercise. Inhal. Toxicol. 15, 539–552.
Dockery, D.W., 2001. Epidemiologic evidence of cardiovascular effects of particulate air pollution. Environ. Health Perspect. 109, 483–486.
Dockery, D.W., Pope III, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris, B.G., Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. N. Engl. J. Med. 329, 1573–1759.
Donaldson, K., Stone, V., Gilmour, P.S., Brown, D.M., MacNee, W., 2000. Ultrafine particles: mechanisms of lung injury. Philos. Trans. R. Soc. London, Ser. A 358, 2741–2749.
Dunn, O.J., 1964. Multiple comparisons using rank sums. Technometrics 6, 241–252.
Gauderman, W.J., Avol, E., Gilliland, F., Vora, H., Thomas, D., Berhane, K., McConnell, R., Kuenzli, N., Lurmann, F., Rappaport, E., Margolis, H., Bates, D., Peters, J., 2004. The effect of air pollution on lung development from 10 to 18 years of age. N. Engl. J. Med. 351, 1057–1067.
Halios, C.H., Helmis, C.G., 2007. On the estimation of characteristic indoor air quality parameters using analytical and numerical methods. Sci. Total Environ. 381, 222–232.
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.
Kreyling, W.G., Semmler-Behnke, M., Möller, W., 2006. Ultrafine particle–lung interactions: does size matter? J. Aerosol Med. 19, 74–83.
Kruskal, W.H., Wallis, W.A., 1952. Use of ranks in one-criterion variance analysis. J. Am. Stat. Assoc. 47, 583–621.
Lan, Z.-J., Chen, D.-L., Li, X., Huang, X.-F., He, L.-Y., Deng, Y.-G., Feng, N., Hu, M., 2011. Modal characteristics of carbonaceous aerosol size distribution in an urban atmosphere of South China. Atmos. Res. 100, 51–60.
Levin, E.J.T., McMeeking, G.R., Carrico, C., Mack, L., Kreidenweis, S.M., Wold, C.E., Moosmüller, H., Arnott, W.P., Hao, W.M., Collett, J.L., Malm, W.C., 2010. Biomass burning smoke aerosol properties measured during FLAME. J. Geophys. Res. 115, D18210.
Massey, D., Kulshrestha, A., Masih, J., Taneja, A., 2012. Seasonal trends of PM_{10}, $PM_{5.0}$, $PM_{2.5}$ & $PM_{1.0}$ in indoor and outdoor environments of residential homes located in North-Central India. Build. Environ. 47, 223–231.
Oh, H.-J., Nam, I.-S., Yun, H., Kim, J., Yang, J., Sohn, J.-R., 2014. Characterization of indoor air quality and efficiency of air purifier in childcare centers, Korea. Build. Environ. 82, 2013–2214.
Ortega, I.K., Suni, T., Boy, M., Grönholm, T., Manninen, H.E., Nieminen, T., Ehn, M., Junninen, H., Hakola, H., Hellén, H., Valmari, T., Arvela, H., Zegelin, S., Hughes, D., Kitchen, M., Cleugh, H., Worsnop, D.R., Kulmala, M., Kerminen, V.-M., 2012. New insights into nocturnal nucleation. Atmos. Chem. Phys. 12, 4297–4312.
Owen, M.K., Ensor, D.S., Sparks, L.E., 1992. Airborne particle sizes and sources found in indoor air. Atmos. Environ. 26, 2149–2162 (Part A. General Topics).
Pope III, C.A., 2000. Review: epidemiological basis for particulate air pollution health standards. Aerosol Sci. Technol. 32, 4–14.
Pope, I.C., Burnett, R.T., Thun, M.J., Calle, E.E., Krewsky, D., Ito, K., Thurston, G.D., 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. JAMA 287 (9), 1132–1141.
Salma, I., Dosztály, K., Borsós, T., Söveges, B., Weidinger, T., Kristóf, G., Péter, N., Kertész, Z., 2013. Physical properties, chemical composition, sources, spatial distribution and sinks of indoor aerosol particles in a university lecture hall. Atmos. Environ. 64, 219–228.
Sangiorgi, G., Ferrero, L., Ferrini, B.S., Lo Porto, C., Perrone, M.G., Zangrando, R., Gambaro, A., Lazzati, Z., Bolzacchini, E., 2013. Indoor airborne particle sources and semi-volatile partitioning effect of outdoor fine PM in offices. Atmos. Environ. 65, 205–214.
Weinbruch, S., Dirsch, T., Ebert, M., Hofmann, H., Kandler, K., 2008. Dust exposure in indoor climbing halls. J. Environ. Monit. 10, 648–654.
Weinbruch, S., Dirsch, T., Kandler, K., Ebert, M., Heimburger, G., Hohenwarter, F., 2012. Reducing dust exposure in indoor climbing gyms. J. Environ. Monit. 14, 2114–2120.
Wolkoff, P., 2013. Indoor air pollutants in office environments: assessment of comfort, health, and performance. Int. J. Hyg. Environ. Health 216, 371–394.
Žitnik, M., Kastelic, A., Rupnik, Z., Pelicon, P., Vaupetič, P., Bučar, K., Novak, S., Samardžija, Z., Matsuyama, S., Catella, G., Ishii, K., 2010. Time-resolved measurements of aerosol elemental concentrations in indoor working environments. Atmos. Environ. 44, 4954–4963.