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Effect of physical exertion on the deposition of urban aerosols in the human respiratory system

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Abstract

Deposition of element-specific particulate matter in the respiratory system of a Caucasian-type healthy adult male and female was computed by a stochastic lung deposition model for different reference levels of physical exertion using mass size distributions in the aerodynamic diameter interval of 0.125–16 μm experimentally determined in urban environments. Particles with an aerodynamic diameter smaller than about 0.3 μm are deposited in the whole respiratory system decreasingly with rising physical exertion, while the opposite is observed for particles with an aerodynamic diameter larger than about 0.7 μm (except for the highest physical activity). It is the light exercise that causes the largest extrathoracic (ET) deposition efficiency of the particles in this last diameter range, and, consequently, the smallest tracheobronchial and acinar depositions. The results obtained indicate that ET deposition depends primarily on the size distribution of the inhaled particles, while physical exertion plays a minor role. In contrast, deposition fractions of different aerosol species in the lungs are very similar to each other for a given physical exertion, despite the rather diverse size distributions of some species, but depend significantly on the subject's physical exertion. The differential deposition curves generally exhibit two peaks, one in the tracheobronchial and one in the acinar region. Both differential and regional deposition fractions do not change in a monotonical fashion with physical exertion but display maximum values approximately at the exertion level corresponding to the switching point between the nose-breathing mode and the combined nose- and mouth-breathing mode. Deposition rates (mass doses), however, increase monotonically with physical exertion due to increased ventilation rates, and more particles reach the deeper parts of the lung. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Human respiratory tract; Modelling; Atmospheric aerosols; Aerosol deposition; Aerosol doses; Physical exertion

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1. Introduction

A research project was designed to address the needs for a comprehensive characterisation of airborne particulate matter (PM) and their effects in Budapest, Hungary, and to asses the human exposure to potentially toxic air pollutants (Salma, Maenhaut, Zemplén-Papp, & Záray, 2001). As part of that programme, detailed size distributions were determined, since particle diameter is one of the most important aerosol properties that is closely related to chemical composition, atmospheric residence time, optical behaviour and deposition in the human respiratory system. It was found that the mass size distributions for typical anthropogenic elements were different at the various urban sampling locations mainly due to resuspension processes (Salma, Maenhaut, & Záray, 2002b). These experimentally determined size distributions were further utilised for the computation of deposition fractions of different elements for a healthy adult male, female and 5-year-old child under sitting activity breathing conditions to specifically examine the effect of varying size distributions on aerosol deposition (Salma, Balásházy, Winkler-Heil, Hofmann, & Záray, 2002a).

In the present paper, extending the scope of the previous research, deposition fractions of various aerosol species, including PM, were computed for a healthy adult male and female for different reference levels of physical exertion. Thus, the main objectives of this study are to assess the effect of physical exertion on aerosol deposition, deposition rates and surface doses.

2. Computation of deposition fractions and surface depositions

Deposition fractions in the human respiratory system were computed by the stochastic lung deposition model IDEAL, version 4. Salient features of the model are described in Koblinger and Hofmann (1990); and Hofmann and Koblinger (1990, 1992). For modelling purposes, the human respiratory system is divided into an extrathoracic (ET) region, a tracheobronchial (TB) tree, and an acinar (Aci) region. The last two regions are composed of a system of bifurcation units. In case of an adult human lung, bifurcation units from 1 through 15 represent the TB tree, while the Aci region consists of bifurcation units 16 through 25 (ICRP66, 1994). In the stochastic model, the median number of bifurcation units is 23, consistent with other morphometric lung models (ICRP66, 1994). In the figures of this paper, the ET region is marked by bifurcation unit number 0. For a wide range of particle sizes and breathing patterns, the stochastic lung deposition model exhibited satisfactory and favourable agreement with extensive sets of experimental data on total and regional depositions, properly reflecting the various tendencies reported in the measurements with monodisperse aerosols (Hofmann & Koblinger, 1992).

In addition to deposition fractions, the present model also computes mean surface areas of each airway generation to obtain deposited mass per unit surface area (surface deposition). Computation of the surface area was performed for an adult male performing sitting activity with the deposition mechanisms being switched off in order to ensure that the particles are transported along the full airway path up to its physical end. In the TB tree, the mean bronchial surface area A_i for the generation i is calculated as the product of the average surface area S_i of a single bronchial airway in the generation i, and of the modified number of bronchial airways $N_i(1 - p_i)$ in the generation i (see later). The number of bronchial airways N_i in the ith generation is calculated as 2^{i-1} till the 12th airway generation. From the 13th generation on, it is modified by a termination probability function (i.e., the probability p_i that a selected airway is a terminal bronchiole, thus terminating the tracheobronchial region), which was derived by statistical analysis of morphometric data (Koblinger & Hofmann, 1985). Hence the surface area is

$$A_i = S_i N_i (1 - p_i) = \frac{\sum_{j=1}^{k} S_{ij}}{k} N_i (1 - p_i). \qquad (1)$$

In the Aci region, the surface area of an individual airway was calculated on the assumption that each airway has the same dimensions but it can be alveolated to a different degree. The extent of the alveolisation depends on how far the airway is located from the first alveolated unit (i.e., from the bronchiolus respiratorius). It is supposed that the bronchiolus respiratorius is alveolated in 20%, the following generation in 40%, etc., so that the fourth generation after the bronchiolus respiratorius is already fully alveolated. It is further assumed that each alveolus has the same diameter of 200 μm, and is represented by a hemisphere. The total acinar surface area A_{tot} is considered to be 148 m^2 under the conditions specified above (ICRP66, 1994). The mean surfaces area A_i of the airway generation i was calculated as the total acinar surface area multiplied by the ratio of the number of acinar airway selections l_i for the generation i to the sum of all acinar airway selections, hence

$$A_i = \frac{l_i}{\sum_{i=13}^{35} l_i} A_{\mathrm{tot}}. \qquad (2)$$

For the airways between generations 13 and 22, which can be either bronchial or acinar, the total surface area was computed as the sum of the bronchial and acinar surface areas. The mean surface areas of the airways for the other reference levels of physical exertion were derived from that for the sitting activity by multiplying the surface data with the ratio of the functional residual capacity plus tidal volume for the two physical exertion levels, raised to the power of two-thirds.

The average mass size distributions, characterised by histograms, in the aerodynamic diameter (AD) interval of 0.125–16 μm, utilised in the computations as input parameters, were experimentally determined from the aerosol samples collected by cascade impactors at four urban locations, and analysed by particle-induced X-ray emission spectrometry at Ghent University (Salma et al., 2002b). The sampling sites represent an urban background (campus of the Central Research Institute for Physics, KFKI), two downtown sites (Eötvös University's campus at Lágymányos, and Széna Square), and a road tunnel (Castle District Tunnel, CD Tunnel). The locations are characterised by gradually increasing aerosol mass concentration (Salma et al., 2001). On the basis of the average size distributions, the elements were classified into two groups (Salma et al., 2002b). Elements Na, Mg, Al, Si, P, Ca, Ti, Fe, Ga, Sr, Zr, Mo and Ba having a unimodal coarse-mode size distribution for all data sets are attributable to dispersion, and soil and road dust resuspension processes. Elements S, Cl, K, V, Cr, Mn, Ni, Cu, Zn, Ge, As, Se, Br, Rb and Pb either have a unimodal accumulation-mode size distribution or clearly exhibit a bimodal size distribution at the urban background. Significant mass in the fine particles points to anthropogenic sources. When comparing the sampling sites, however, these size distributions show substantial differences. In addition to the size distributions of the elements, mass size distributions of PM were also derived utilising the mean coarse- and fine-fraction particulate masses gravimetrically measured, and the coarse- and accumulation-mode mass median ADs and geometric standard deviations, obtained by averaging the corresponding parameters of the most abundant coarse and fine elements (Salma, Dal Maso, Kulmala, & Záray, Gy., 2002c), and were also used in the present computations.

Table 1
Respiratory physiological parameters utilised in the model for an adult male and female performing reference levels of physical exertion

Parameter	Resting (sleeping)	Sitting activity	Light exercise	Heavy exercise
Exertion (% of max workload)	8	12	32	64
Male				
Tidal volume (cm^3)	625	750	1250	1923
Breathing cycle (s)	5.0	5.0	3.0	2.3
Female				
Tidal volume (cm^3)	444	464	992	1364
Breathing cycle (s)	5.0	4.3	2.9	1.8

In the present paper, Caucasian-type healthy adult males and females performing different reference levels of physical exertion are considered. (Note: there are no recommended breathing parameters for children for heavy exercise.) Respiratory physiological parameters utilised in the model for the males and females as recommended by ICRP66 (1994) are summarised in Table 1. Orientation of the respiratory system in resting (sleeping) is different from that in the other levels of physical exertion; nevertheless, it does not influence significantly the deposition. In the ET and TB regions, the effect of gravitational settling is negligible in comparison with the effect of the other mechanisms. In the Aci region, the gravity angle of the airways is uniformly distributed between 0° and 180°, so the different orientation does not really have effect on the Aci deposition. For heavy exercise, it is assumed furthermore that the fraction of the total ventilatory airflow passing through the nose is 40% for the healthy adult normal nasal augmenters (nose breathers), and that the rest of 60% is inhaled through the mouth. The other input parameters were identical to those described and used in the previous work (Salma et al., 2002a, Table 1), or to those specified in the reference data set (Hofmann & Koblinger, 1990, 1992).

3. Results and interpretation

3.1. Particle deposition

Deposition in the ET, TB and Aci regions, and in the total respiratory system (Tot), calculated for an adult male performing different reference levels of physical exertion and for monodisperse aerosols as a function of particle aerodynamic diameter in the interval from 0.022 to 11.3 μm are shown in Fig. 1. It can be seen that the curves for different physical exertion levels cross each other in the interval of 0.3–0.7 μm AD within ET, TB and Aci regions, except for ET deposition curves for light and heavy exercise, which do not cross each other. For particles with an AD smaller than 0.3 μm, ET and TB depositions decrease monotonically with rising physical activity. Deposition of these particles occurs primarily by Brownian motion (diffusion), and, hence, deposition is decreased by the shorter residences time in these regions as a result of an increased respiratory frequency. As a consequence of the lower ET and TB depositions, Aci deposition of these particles increases with physical exertion since more particles reach the more peripheral region. For particles with an AD

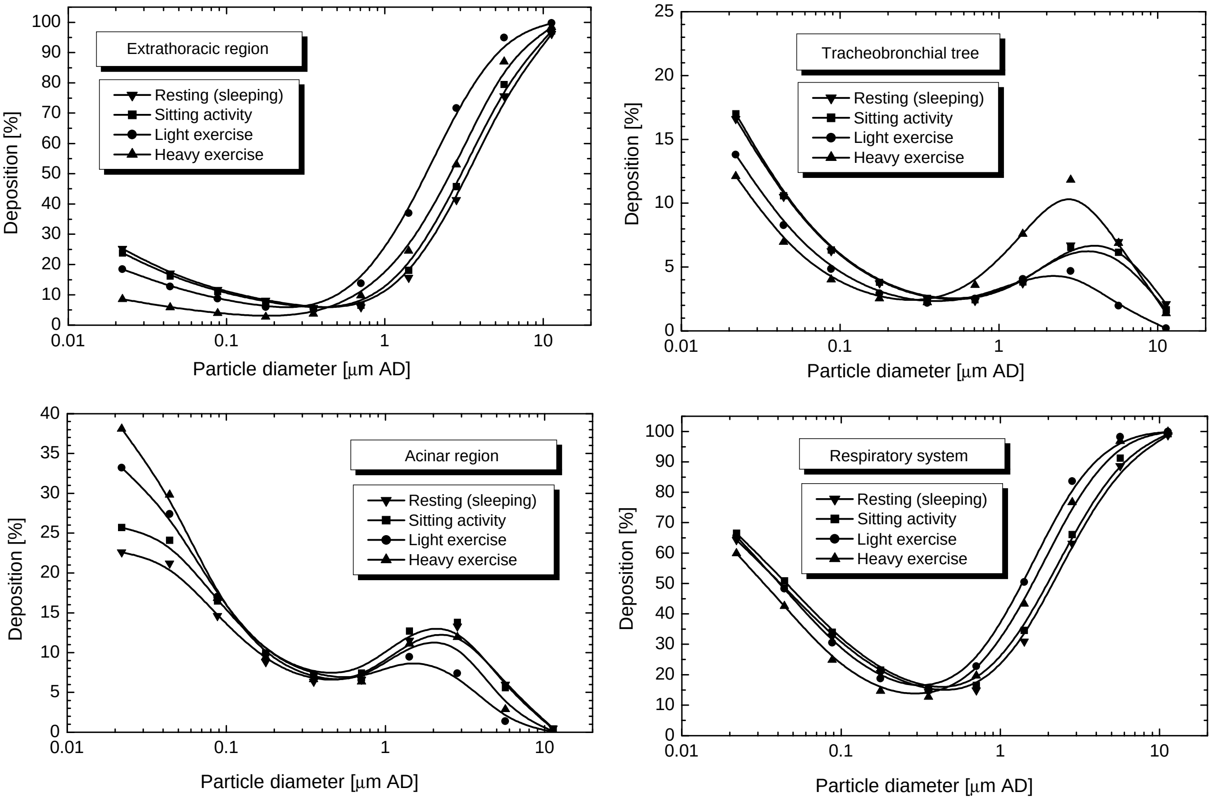

Fig. 1. Deposition in the extrathoracic, tracheobronchial and acinar regions, and in the total respiratory system as function of the aerodynamic diameter computed for an adult male under resting (sleeping), sitting activity, light exercise and heavy exercise breathing conditions.

larger than 0.7 μm, regional depositions do not change monotonically with physical exertion. It is the light exercise that causes the largest ET deposition and, consequently, the smallest TB and Aci depositions. The maximum of the TB deposition in this size range is shifted from 4 μm AD for resting and sitting activity to 2 μm AD for light exercise, and to 3 μm AD for heavy exercise. The modest shift of the maximum in the latter case is caused by a partial shift to the mouth-breathing mode at heavy exercise. At the same time, the maximum of the Aci deposition does not seem to change significantly with physical exertion, remaining at approximately 2 μm AD.

As a result of the individual regional depositions, the curves representing total deposition also cross each other at 0.3–0.5 μm AD. In contrast to regional deposition, no monotonic tendency can be observed with regard to physical exertion. The shapes of the deposition curves for different levels of exertion, however, are very similar to each other.

3.2. *Differential depositions*

Differential depositions (i.e., deposition fractions as function of the bifurcation unit number) in the thoracic region for a given gender and for a specified physical exertion level are similar to

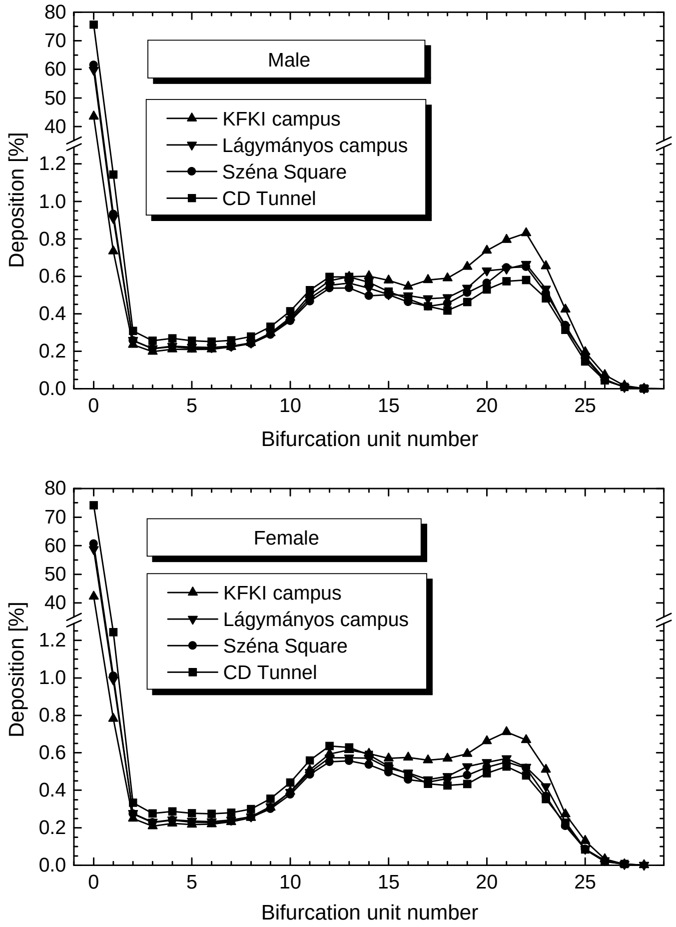

Fig. 2. Differential deposition of Ni for an adult male and female at the KFKI campus (urban background), Lágymányos campus (downtown), Széna Square (downtown) and Castle District Tunnel for heavy exercise breathing condition. The extrathoracic region is represented by the bifurcation unit number 0.

each other as far as the shape and absolute values are concerned regardless of the measured size distributions and aerosol species. This phenomenon was previously discussed in more detail for the sitting activity (Salma et al., 2002a). To demonstrate the extent of potential deviations, differential distributions of Ni for the adult male and female performing heavy exercise at the four sampling sites are displayed in Fig. 2. Nickel is mainly of anthropogenic origin, and has rather diverse size distributions at the sampling sites (Salma et al., 2002b). Deposition fractions are generally larger for the male than for the female but the shape of the deposition curves again remains quite similar. The differential depositions are similar to each other even for aerosol species of completely different origin. For example, deposition of Ni (a typical anthropogenic element) and Fe (a typical soil-derived element) for the adult male under sitting activity and heavy exercise breathing conditions at one of the downtown sites are displayed in Fig. 3. From the similarities and differences between the curves one can infer that physical exertion plays a more decisive role for particle deposition than the size

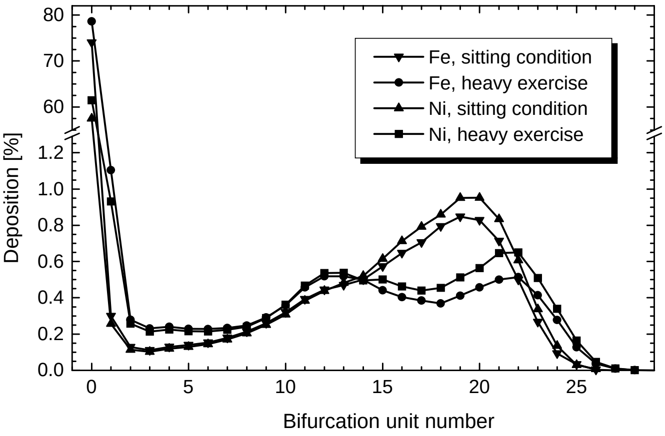

Fig. 3. Differential deposition of Ni (as a typically anthropogenic element) and Fe (as a typically soil-derived element) for an adult male under sitting activity and heavy exercise breathing conditions at a downtown site (Széna Square). The extrathoracic region is represented by the bifurcation unit number 0.

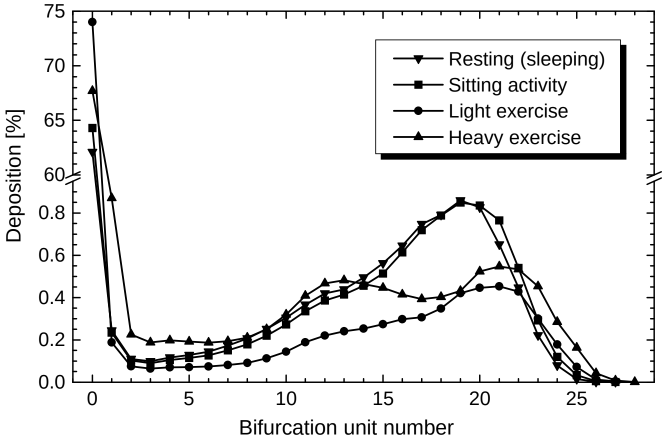

Fig. 4. Differential deposition of particulate matter for an adult male performing reference levels of physical exertion at a downtown site (Széna Square). The extrathoracic region is represented by the bifurcation unit number 0.

distribution. (Note: just the opposite is true for the ET region. See Fig. 3 or Tables 3 and 4.) The small differences between the deposition curves for the same physical exertion that can be observed occur primarily in the Aci region regardless of the physical exertion level.

Because of the relative insensitivity to size distributions discussed above, one aerosol species, namely PM, was selected to asses specifically the effect of physical exertion on the deposition of aerosols. Differential deposition fractions of PM for the adult male performing the four reference levels of exertion are shown on Fig. 4. Deposition in the lung exhibits generally two maxima that occur at bifurcation unit numbers 12–13 and within an interval of 19–22 as demonstrated in Fig. 5. The former peak belongs to the TB region, while the latter one appears in the Aci region.

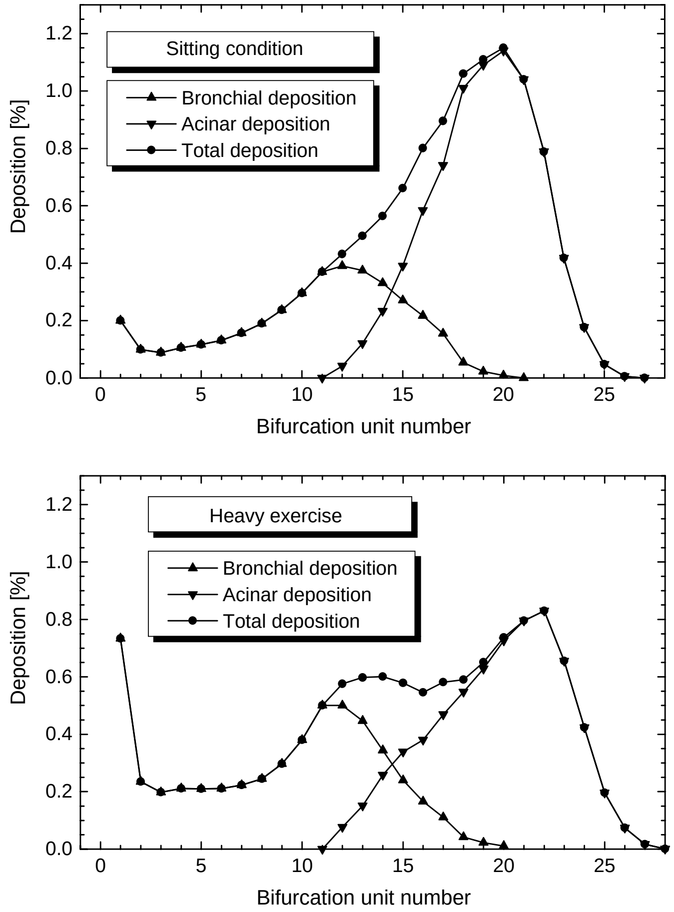

Fig. 5. Differential deposition of Ni consisting of tracheobronchial and acinar depositions for an adult male under sitting activity and heavy exercise breathing conditions at the urban background (KFKI campus).

The two peaks are generated by different relative contributions of the TB and Aci depositions to total deposition. It can be seen that by changing from sitting activity to heavy exercise, TB deposition (peak) is increased, and, consequently, Aci deposition (peak) is decreased, resulting in two marked peaks. The tracheobronchial peak always appears at the bifurcation unit number of about 12 regardless of the subject's gender and physical exertion, and the deposition values of the peak for a given gender do not change monotonically with physical exertion (see Fig. 4). Contrary to that, the maximum of the acinar peak depends on the subject's gender and age, and it is shifted towards larger bifurcation unit numbers with increasing physical exertion (see later). Deposition values of the acinar peak for a given gender do not change monotonically with physical exertion; and its maximum value possibly decreases with the relative mass of the coarse mode in the size distribution (see Fig. 2). When the two peaks are close enough to each other, a broad maximum (doublet) is observed instead (cf. Salma et al., 2002a, Fig. 3c for child). It is interesting to observe in Fig. 4 that the largest difference occurs for the trachea: the deposition for heavy exercise standing

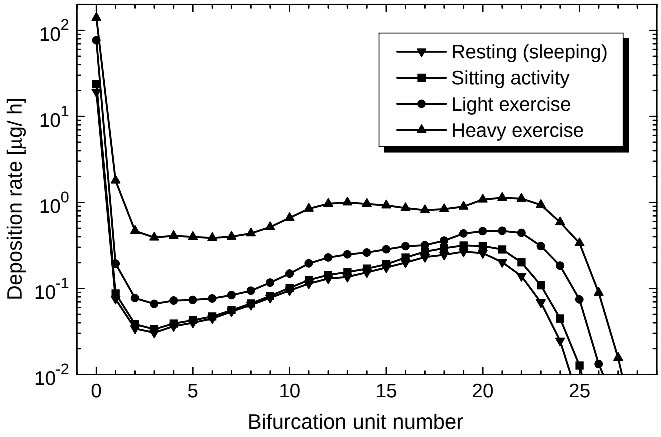

Fig. 6. Differential deposition rate of particulate matter as function of the bifurcation unit number for an adult male performing reference levels of physical exertion at a downtown site (Széna Square). The extrathoracic region is represented by the bifurcation unit number 0.

out from those for the other exertion levels. This is an effect of the mouth-breathing mode adopted for heavy exercise. Deposition of the anthropogenic elements in the trachea increases monotonically with the relative mass of the coarse mode in the size distribution until it reaches the deposition of the soil-derived elements.

Deposited amounts for different levels of physical exertion are naturally also modified by changes of the total breathing volume. Differential deposition rates (mass doses) of PM (in μg/h) for the adult male performing reference levels of physical exertion at one of the downtown sites (Széna Square) are shown in Fig. 6. Resting, sitting activity, light exercise and heavy exercise are characterised by ventilation rates of 0.45, 0.54, 1.5 and 3.0 m^3/h, respectively (ICRP66, 1994). The median atmospheric concentration of PM_{10} at the sampling location considered, i.e., at Széna Square, is 69 $\mu g/m^3$ (Salma et al., 2001). The deposition rate in all parts of the human respiratory system increases monotonically with the order of physical exertion from resting to sitting activity, light exercise and heavy exercise due to increased ventilation rates. It can be seen that the depositions for heavy exercise are clearly separated from the other data, and that the largest differences can be observed in the first half of TB region and in the last few bifurcation units. In addition to these differences, the aerosol particles penetrate deeper into the lung (i.e., reach larger numbers of bifurcation units) with increasing physical exertion.

3.3. Regional depositions

Deposition fractions of PM in the ET region, TB tree and Aci region for the adult male performing reference levels of physical exertion at the four sampling sites in Budapest are displayed in Table 2. It can be seen that the regional depositions adopt extreme values at about light exercise, i.e., at a ventilation rate slightly larger than 1.5 m^3/h. While ET and total depositions show a maximum, TB and Aci depositions have a minimum there. This ventilation rate seems to coincide with the switching point from nose-breathing to breathing partly through the mouth that typically occurs at

Table 2
Deposition fractions (in %) of particulate matter in the extrathoracic region (ET), tracheobronchial tree (TB) and acinar region (Aci) for an adult male performing reference levels of exertion at the KFKI campus (urban background), Lágymányos campus (downtown), Széna Square (downtown) and Castle District Tunnel

Sampling site	KFKI campus			Lágymányos campus			Széna Square			Castle District Tunnel		
Exertion	ET deposition	TB	Aci	ET deposition	TB	Aci	ET deposition	TB	Aci	ET deposition	TB	Aci
Resting (sleeping)	48	4.0	6.9	43	3.7	6.5	62	3.8	5.6	65	4.0	5.7
Sitting activity	50	3.8	7.2	45	3.5	7.1	64	3.5	5.8	67	3.7	5.8
Light exercise	61	2.5	4.8	55	2.3	4.9	74	2.0	3.5	78	2.0	3.3
Heavy exercise	54	5.4	6.0	48	4.8	5.8	68	4.8	4.5	71	5.0	4.6

Table 3
Deposition fractions, means and standard deviations (SD, all in %) of some typically anthropogenic elements in the extrathoracic region (ET), tracheobronchial tree (TB) and acinar region (Aci) for an adult male under heavy exercise breathing conditions at the KFKI campus, Lágymányos campus, Széna Square and within the Castle District Tunnel. For comparison, mean deposition fractions and standard deviations of the soil-derived elements are also displayed

Sampling site	KFKI campus			Lágymányos campus			Széna Square			Castle District Tunnel		
	ET	TB	Aci	ET	TB	Aci	ET	TB	Aci	ET	TB	Aci
Element	Deposition			Deposition			Deposition			Deposition		
S	21	4.0	6.8	17	3.5	7.0	26	3.8	6.2	52	5.0	5.6
Cl	49	5.4	5.9	66	5.2	4.7	72	5.1	4.1	76	6.1	4.6
V	42	5.7	6.9	52	4.8	5.5	51	4.4	5.4	79	5.3	4.0
Ni	43	5.3	6.6	60	5.4	5.4	61	5.3	5.2	76	6.2	4.9
Cu	46	6.1	7.0	55	6.7	6.7	65	7.1	6.4	69	7.4	6.3
Zn	35	5.7	7.3	50	5.4	6.2	55	5.4	5.7	70	6.1	5.2
As	40	6.1	7.0	58	4.7	5.0	57	4.9	5.1	75	5.5	4.5
Se	16	4.2	7.4	39	4.5	6.0	44	4.2	5.6	71	4.5	4.0
Br	23	4.5	7.0	30	4.2	6.3	35	4.6	6.3	59	5.1	5.6
Pb	14	3.9	6.9	33	5.1	7.2	41	5.1	6.5	63	5.5	5.6
Mean		5.1	6.9		5.0	6.0		5.0	5.6		5.7	5.0
SD		0.9	0.4		0.9	0.8		0.9	0.7		0.8	0.8
Soil-derived elements												
Mean	74	6.1	4.9	80	5.3	3.9	83	4.9	3.4	83	5.2	3.6
SD	3	0.3	0.4	3	0.3	0.5	3	0.5	0.6	3	0.5	0.5

about 2.1 $\mathrm{m^3/h}$ (Niinimaa, Cole, Mintz, & Shephard, 1981). Thoracic deposition (i.e., the sum of TB and Aci), expressed as a percentage of the total deposition fraction, also shows a minimum, with a value of 7%, at about light exercise. For the other exertion levels, thoracic deposition represents 12–13% of the total deposition.

Deposition fractions of some typical anthropogenic elements in the ET, TB and Aci regions for the adult male and female at the four sampling locations are displayed in Tables 3 and 4, respectively.

Table 4
Deposition fractions, means and standard deviations (SD, all in %) of some typically anthropogenic elements in the extrathoracic region (ET), tracheobronchial tree (TB) and acinar region (Aci) for an adult female under heavy exercise breathing conditions at the KFKI campus, Lágymányos campus, Széna Square and within the Castle District Tunnel. For comparison, mean deposition fractions and standard deviations of the soil-derived elements are also displayed

Sampling site	KFKI campus			Lágymányos campus			Széna Square			Castle District Tunnel		
	ET	TB	Aci	ET	TB	Aci	ET	TB	Aci	ET	TB	Aci
Element	deposition			deposition			deposition			deposition		
S	20	3.9	5.8	16	3.5	6.3	25	3.9	5.4	51	5.2	4.9
Cl	48	5.6	5.1	65	5.5	4.2	71	5.4	3.7	75	6.4	4.2
V	41	5.8	6.1	51	4.9	4.8	50	4.6	4.7	78	5.6	3.6
Ni	42	5.5	5.8	59	5.7	4.8	61	5.6	4.5	74	6.6	4.4
Cu	44	6.3	6.1	53	7.0	5.9	63	7.4	5.6	67	7.8	5.5
Zn	34	5.7	6.1	49	5.6	5.4	54	5.6	4.9	69	6.4	4.6
As	39	6.2	6.1	57	4.9	4.4	56	5.1	4.5	74	5.9	3.9
Se	15	4.1	6.3	38	4.6	5.3	43	4.3	5.0	69	4.8	3.5
Br	22	4.5	6.0	29	4.2	5.6	34	4.7	5.5	58	5.4	4.8
Pb	14	3.9	6.0	32	5.2	6.1	40	5.2	5.6	62	5.8	4.9
Mean		5.2	5.9		5.1	5.3		5.2	4.9		6.0	4.4
SD		1.0	0.3		0.9	0.7		1.0	0.6		0.8	0.6
Soil-derived elements												
Mean	73	6.5	4.4	79	5.7	3.5	82	5.3	3.1	82	5.5	3.3
SD	3	0.2	0.4	3	0.3	0.4	3	0.5	0.5	3	0.5	0.5

Mean deposition fractions for the ET region have such a large standard deviation due to the different size distributions that they are not meaningful, and, thus, are not included in the tables. In contrast, TB and Aci depositions of soil-derived elements were rather similar to each other, and, therefore, mean deposition fractions and their standard deviations are only shown. Conclusions that can be drawn from the present data sets are similar, as far as the tendencies are concerned, to those previously obtained for sitting activity (Salma et al., 2002a). In order to explore the effect of size distribution on deposition, regional depositions for the male and female performing heavy exercise were compared to the corresponding values for sitting activity (Salma et al., 2002a, Tables 2 and 3, respectively). For the male performing heavy exercise, deposition in the ET region is increased by 18% (for Pb and Se in the urban background) through 7% (for the soil-derived elements) depending on the actual size distribution. The difference decreases with the relative mass of the coarse mode in the size distribution. In the TB region, a more serious increase of 35–40% is observed for both anthropogenic and soil-derived elements. Deposition in the Aci region is decreased by 16–23% for the anthropogenic elements, and by about 25% for the soil derived elements. It is important, however, to mention that the depositions for heavy exercise strongly depend on the actual combination of the nose- and mouth-breathing modes. As a result of these changes, total deposition is increased by about 5%, and thoracic deposition, expressed as a percentage of total deposition, is decreased by 5–6% for heavy exercise. These tendencies are similar for the female, though the differences between genders, based on the two data sets, are smaller. The mean male-to-female deposition ratio

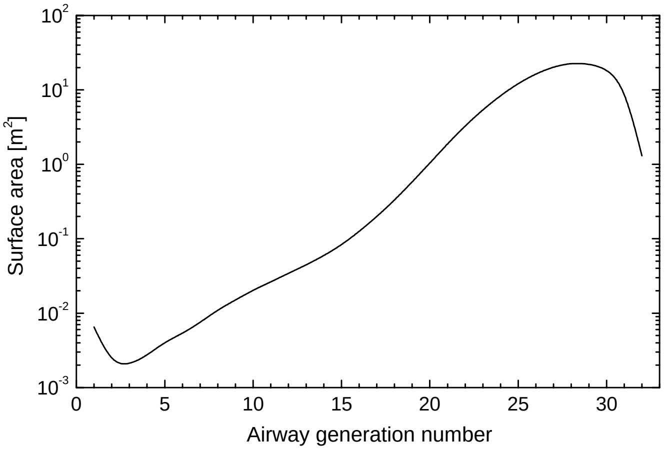

Fig. 7. Mean surface area of bifurcation units for an adult male under sitting activity breathing conditions.

for the ET, TB and Aci regions, and the total respiratory system for heavy exercise are 1.02, 0.96, 1.14 and 1.02, respectively, while the same comparison for sitting activity yields ratios of 1.07, 0.94, 1.30 and 1.08, respectively.

3.4. Surface depositions

The mean surface area of the airway generations for the adult male performing sitting activity is displayed in Fig. 7. It comprises five orders of magnitude, and shows a minimum at generation numbers 2–3 and a broad maximum between generation numbers 26–30. The total surface area of the lung for the adult male resting (sleeping), performing sitting activity, light exercise and heavy exercise are 145, 148, 160 and 175 m^2, respectively, obtained by scaling the surface areas for the sitting activity as described in Section 2.

The surface area data were utilised to derive surface deposition rates (surface mass doses). Surface deposition rates of PM (in $\mu g/m^2/h$) for the male performing reference levels of physical exertion at one of the downtown sites (Széna Square) are shown in Fig. 8. The deposition values are of the same order as those calculated for an assumed size distribution by a different lung deposition model (Venkataraman & Kao, 1999). While the surface deposition rates increase again with physical exertion similar to the trends observed above, the shape of the curves is completely different from that for the deposition rates. The first few bifurcation units receive higher than average surface doses of aerosols. For resting, sitting activity and light exercise, surface deposition rates are highest in tracheobronchial generations 2–3, because the internal surface available for deposition is smallest in this region. For heavy exercise, the maximum is even shifted to the trachea as a result of the mouth-breathing mode. The slight elevation at about bifurcation unit number 12 with increasing physical exertion is a result of the increased tracheobronchial deposition peak discussed above. Surface deposition rates in the Aci region (above bifurcation unit number 16) are typically by one or two orders of magnitude smaller than those in the upper TB region, though aerosol particles reach deeper parts of the lung with rising physical exertion. The large surface dose in the first few generation numbers, as one

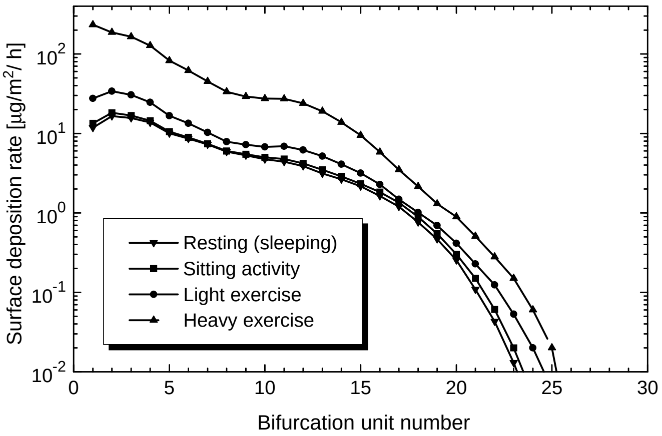

Fig. 8. Differential surface deposition rate of particulate matter as function of the bifurcation unit number for an adult male performing reference levels of physical exertion at a downtown site (Széna Square).

of the causes, can possibly be related to the aggravation of upper respiratory illnesses and to lung tumours, which arise primarily in the TB region, in particular in segmental and subsegmental bronchi (ICRP66, 1994).

4. Discussion and conclusions

Studies investigating the adverse effects of PM either alone or in combination with other air pollutants on human health and welfare rely upon different measures of the airborne particles. Atmospheric mass concentration is one, though possibly the most simple, and therefore, the most accessible of these indicators. The mass concentrations for PM (used to) deal with total suspended particulates or are restricted more often to certain size fractions, i.e., to aerosol particles with an aerodynamic diameter $\leqslant 2.5\,\mu m$ ($PM_{2.5}$ fraction) and/or $\leqslant 10\,\mu m$ (PM_{10} fraction) (US EPA, 1997). Positive and statistically significant correlations exist between elevated levels of particulate air pollution and different health indicators, such as exacerbation of chronic obstructive pulmonary disease, as well as increased overall morbidity and mortality rates (Folinsbee, 1992; Dockery et al., 1993; Pope, Dockery, & Schwartz, 1995). In several investigations, the dependency on chemical composition and/or on speciation of inhaled air particulates was also proved. In addition to that, the particle-related effects could potentially be amplified by highly reactive (possibly short-lived) free radicals or peroxides, or some other species of the particles (Vedal, 1997). Epidemiological studies also indicate associations between the size of inhaled particles and the development of pulmonary diseases (Schwartz, 1994, Brunekreef, Dockery, & Krzyzanowski, 1995). Size distributions are, therefore, also considered to be an important property for the dosimetry of aerosols. Some other epidemiological studies as well as animal inhalation experiments support the hypothesis that physical (e.g., particle size, shape, and electric charge) and chemical properties (e.g., solubility or transportability) of single particles are also involved in their potentially toxic, genotoxic, and carcinogenic health effects.

In the present and a previous (Salma et al., 2002a) studies, however, depositions of urban-type aerosols in the lung (thoracic region) do not seem to change very significantly with their measured size distribution in the AD range investigated, i.e., 0.125–16 μm. Two reasons can be advanced to explain the relatively weak dependence of thoracic, i.e., bronchial and acinar, deposition on particle diameter. First, the particle size distributions, though differing among the various locations, are relatively wide. As a result of this, deposition in the ET and thoracic regions represents a combination of deposition efficiencies for a wide range of particle sizes, thus producing similar average deposition fractions. Second, deposition efficiencies for large and small particle sizes in thoracic airways are higher than those for intermediate particle ADs, with a minimum between 0.1 and 1 μm. By the same token, however, the deposition efficiencies of nasal and oral passages are also higher. This pre-filtering effect reduces the percentage of large and small particles penetrating into the bronchial and acinar region, thus causing again similar thoracic deposition fractions.

The computations presented here suggest that the level of physical exertion plays a much greater role in particle deposition than particle size in the diameter range studied. All particle deposition mechanisms considered here are functions of flow rate, thereby affecting the residence time (Brownian motion and gravitational settling) or the particle velocity (inertial impaction) in human airways. Consequently, computed particle deposition patterns, expressing the fraction of particles deposited during a single breath, depend sensitively on the assumed physical activity. More importantly, however, higher physical exertion also increases the inhaled volume per breath and the number of breaths, thus inhaling many more particles. This effect is demonstrated in Fig. 6, where the deposition rate for heavy exercise is roughly an order of magnitude higher than for sitting activity.

The higher deposition at the maximum exertion level is also partly caused by switching from nose-only breathing to mixed nose-and-mouth breathing. Since oral deposition efficiencies are consistently smaller than those for nasal deposition, more particles can reach the bronchial and acinar airways. The slight dependence of particle deposition on gender, as observed in our study, may be caused primarily by differences in related breathing patterns.

In the present study, mass size distributions were used for computing the deposition fractions because the deposited particles are expected or assumed to be dessolved in the mucus layer, and hence their mass is considered to be of relevance. Nevertheless, health effects can sometimes depend on the particle number size distributions especially for ultrafine particles (with AD $\leqslant 0.1$ μm), or for the aerosols containing radon progeny. As illustrated in Fig. 1, deposition of ultrafine particles in both TB and Aci regions strongly depend on particle diameter. In addition, defending capacity of the Aci region is limited primarily by the number of macrophages (relative to the number of deposited particles). Conclusions of the present study suggest that the ultrafine particles of urban-type aerosols are possibly mainly responsible for the particle size dependence of pulmonary diseases. The results and conclusions are to be further utilised for a risk assessment study.

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