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Effect of particle mass size distribution on the deposition of aerosols in the human respiratory system

Imre Salma[a,*], Imre Balásházy[b], Renate Winkler-Heil[c], Werner Hofmann[c], Gyula Záray[a,d]

[a]*Department of Chemical Technology and Environmental Chemistry, L. Eötvös University, H-1518 Budapest, P.O. Box 32, Hungary*
[b]*KFKI Atomic Energy Research Institute, H-1525 Budapest, P.O. Box 49, Hungary*
[c]*Institute of Physics and Biophysics, University of Salzburg, A-5020 Salzburg, Hellbrunner Str. 34, Austria*
[d]*Research Group of Environmental and Macromolecular Chemistry of the Hungarian Academy of Sciences, H-1518 Budapest, P.O. Box 32, Hungary*

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Abstract

Elemental mass size distributions were experimentally determined in atmospheric aerosols collected at four different locations in Budapest, Hungary, comprising a urban background site, two downtown sites and a road tunnel. Based on these distributions, deposition fractions for the various elements in the respiratory system were calculated for a healthy Caucasian adult male, female and 5-year-old child under sitting breathing conditions by a stochastic lung deposition model. The highest deposition values were observed in the extrathoracic region regardless of subject's age and gender, and chemical species and size distributions. Deposition in the tracheobronchial tree and acinar region was much smaller than that in the extrathoracic region. Variations in the deposition fractions due to differences in the size distributions were really significant only in the extrathoracic region. Surprisingly, the different size distributions yielded similar depositions in the thoracic region for a given gender as far as the shape of the deposition curve and the total amount are concerned. Regional deposition fractions were compared for the male, female and child, and for various size distributions (sampling location) and elements. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Human respiratory tract model; Deposition of aerosols; Size distribution

* Corresponding author. Fax: +36-1-209-0602.
E-mail address: salma@para.chem.elte.hu (I. Salma).

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1. Introduction

In general, human beings come into direct contact with atmospheric aerosols by breathing or via their skin. Dust deposited on environmental surfaces can also be a significant source of some aerosol species, in particular for children. The major route for aerosols to enter the human body is the respiratory system (Vincent, 1990). Health effects, adverse or therapeutic, of the inhaled particulate matter are determined by complex sets of physiological and/or physical, chemical and biological properties of both the respiratory system and the aerosol (ICRP66, 1994). The atmospheric concentration of the aerosol species and the volume respired are the basic input quantities for risk assessment. Intake (inhalation and subsequent deposition in the respiratory system), uptake (absorption into the blood), redistribution, storage and removal (clearance and excretion) of the aerosol species from the body are the most important processes involved. A characteristic feature of the effects of inhaled aerosols in the respiratory system is their apparent site selectivity (Schlesinger & Lippmann, 1978). Differences in biological response are caused primarily by the superposition of highly inhomogeneous deposition patterns (sometimes the so-called hot spots are formed), and of the heterogeneous distribution of sensitive cells. Several mathematical models of the human respiratory system have been developed to calculate the deposition of ambient aerosols (Weibel, 1963; Soong, Nicolaides, Yu, & Soong, 1979; Yeh & Schum, 1980; Koblinger & Hofmann, 1990; Fabriès, 1993). In order to model the fate of inhaled particles, several input parameters (including aerosol features as well) are required, and the results of these calculations together with some other aerosol properties allow us to estimate the transfer of different chemical species in the inhaled particulate matter from the air into the human body.

Physicochemical properties of many aerosol species (mostly elements) were characterized within the framework of a research project at four urban sampling sites in Budapest (Salma, Maenhaut, Zemplén-Papp, & Záray, 2001a). It was found that both the atmospheric concentrations and mass size distributions for typical anthropogenic elements were quite different at the various urban locations. The main objectives of this paper are to calculate deposition fractions based on the experimental size distributions for a healthy adult male, female and 5-year-old-child under sitting breathing conditions, to compare and interpret the results, to explain the relationships between the deposition patterns, to examine the effect of varying size distributions on the deposition.

2. Modeling aerosol deposition in human respiratory system

Deposition fractions in the human respiratory system were computed by the stochastic lung deposition model IDEAL (version 4), which was originally jointly developed at the University of Salzburg and KFKI Atomic Energy Research Institute (salient features of that model are described in Koblinger & Hofmann, 1990, and Hofmann & Koblinger, 1992). For modeling purposes, the human respiratory system is divided into an extrathoracic (oro- or nasopharyngeal) region, tracheobronchial tree and acinar region. The extrathoracic region comprises nasal and oral passages, and the throat. Particle deposition in this region is modeled by semi-empirical equations derived by Stahlhofen, Rudolf, and James (1989), for larger particles, and Cheng et al.

Table 1
Values of the respiratory physiological parameters utilized in the model together with some anatomical parameters (marked by *) for a Caucasian adult male, female and a 5-year-old child under sitting breathing conditions (12% of the maximal workload) as recommended by ICRP66 (1994)

Parameter	Unit	Male	Female	Child
Tidal volume	cm^3	750	464	213
Functional residual capacity	cm^3	3301	2681	767
Extrathoracic volume	cm^3	50	40	13.3
Breathing cycle	s	5	4.3	2.4
Weight*	kg	73	60	20
Height*	cm	176	163	110

(1996), for submicron particles (Hofmann & Koblinger, 1992). The tracheobronchial tree and the acinar region are modeled by a sequence of cylindrical tubes asymmetrically branching into two daughter airways. These regions are considered to be made up by a system of bifurcation units, which are composed of half of the parent tube and half of the daughter tubes. In the acinar region, in addition to the bifurcations, nearly hemispherical alveoli appear on the wall of the tubes. Proceeding further into the acinar region, more and more alveoli cover the walls of the tubes. The respiratory system is eventually terminated by an alveolar sac, which is completely covered by alveoli. In general, bifurcation units from 1 through 15 represent the tracheobronchial tree of an adult human, while the acinar region consists of the bifurcation units from 16 through 25 (ICRP66, 1994). These average numbers are subject to significant intrasubject variations and may also be modified by gender, age and individual variability. The morphological parameters of the model are selected from the statistical distributions obtained from the morphometric data of Raabe, Yeh, Schum, and Phalen (1976), constrained by statistical relationships between some of the morphometric parameters (Koblinger & Hofmann, 1985). In the stochastic model, the path of an inhaled particle through the series of bifurcation units is selected randomly by the Monte Carlo method. Airflow and particle transport through the selected path are described by analytical equations, i.e., deposition is calculated deterministically. Deposition can be caused by the simultaneous effects of Brownian motion, inertial impaction and gravitational settling. If the particle is not deposited during the inspiratory phase, it will be exhaled. During the expiratory phase, it follows the same path that was selected for inspiration. Special cases, e.g., fibrous or hygroscopic aerosols, or electrically charged particles were not considered in the present work.

There are two types of data that have to be specified in the input of the program IDEAL-4. The first group comprises morphological and physiological parameters, which are presently defined in the stochastic model (default values). A reference set of these input data was chosen according to Hofmann and Koblinger (1990) forming the basis of all calculations. The other group of the input data includes the mode of breathing through a full breathing cycle, and size and density of the inhaled particles. As to the breathing mode, a healthy Caucasian-type adult male, female and a 5-year-old child under sitting breathing conditions (at 12% of the maximal workload) were considered. The respiratory physiological parameters required for the model together with some other general parameters are summarized in Table 1 (their values utilized throughout the calculations are those recommended by ICRP66 (1994)). Nose breathing and a symmetric breathing cycle with zero breath-hold time were assumed, which are typical for sitting activity. As far as particle size is concerned, it was supplied from the size distributions determined at the various sampling sites. The density of the aerosol particles was set to unity as the size distributions were measured for equivalent aerodynamic diameters (EAD, see below).

3. Particle size distributions

The mass size distributions were derived from the aerosol samples collected at four urban locations. The urban background represented by the campus of the Central Research Institute for Physics (KFKI) is situated upwind of the town. One downtown site was chosen at the Eötvös University's campus at Lágymányos, which has, in addition to its downtown location, a good overall airshed circulation and ventilation. The second downtown site was located in a small park at the Széna Square, which has a more closed downtown character. The fourth sampling site was within the Castle District Tunnel (CD Tunnel). The locations are characterized by gradually increasing overall aerosol mass concentration. The mean atmospheric concentrations for the coarse inorganic aerosol species at the Lágymányos campus, Széna Square and the tunnel are higher than at the urban background by average factors of 2.6 ± 1.1, 3.8 ± 2.1 and 65 ± 33, respectively. Similar comparisons of the sampling locations for the fine size fraction yield factors of 2.0 ± 1.1 and 2.0 ± 1.0 and 7 ± 4, respectively (Salma et al., 2001a). Battelle-type single-orifice PIXE International cascade impactors with seven impaction stages and a backup filter stage were used as sampling device. The cut-off diameters for 50% collection efficiency of the impaction stages are 16, 8, 4, 2, 1, 0.5 and 0.25 μm EAD, and the 50% collection efficiency for the filter stage is considered to be at 0.125 μm EAD. The samples were collected on semi-consecutive days in the non-heating season in April–June 1999. A total number of six daily samples were collected at the KFKI campus, five daily samples were taken at the Lágymányos campus and five samples were collected in two mornings within the tunnel. At the Széna Square, separate samples were collected over daylight (10 samples) and night (11 samples) (Salma, Maenhaut, Zemplén-Papp, & Bobvos, 1998). The aerosol samples were analyzed by particle-induced X-ray emission spectrometry for up to 29 elements without any sample treatment at the Ghent University, Belgium (Maenhaut & Raemdonck, 1984; Salma, Maenhaut, Cafmeyer, Annegarn, & Andreae, 1994).

Size distributions were derived for 28 elements. (Data of Nb were above detection limit for a few CI stages only.) The individual size distributions were averaged for the five data subsets, i.e., for the KFKI campus, Lágymányos campus, Széna Square over night, Széna Square over daylight and CD Tunnel. For the purposes of the present modeling, the size distributions for the Széna Square over night and daylight were further averaged in order to represent the whole day. On the basis of the average size distributions, the elements could be classified into two groups (Salma, Maenhaut, & Záray, 2001b). Elements in group 1, i.e., Na, Mg, Al, Si, P, Ca, Ti, Fe, Ga, Sr, Zr, Mo and Ba have essentially a unimodal size distribution for all data sets with most of their mass in the coarse mode, and with little mass below 1 μm EAD. They are attributable to dispersion, and soil and road dust resuspension processes. The group is referred to below as soil-derived elements. There is little variation in the shape of the size distributions from one location to another. Average size distributions of Si are plotted

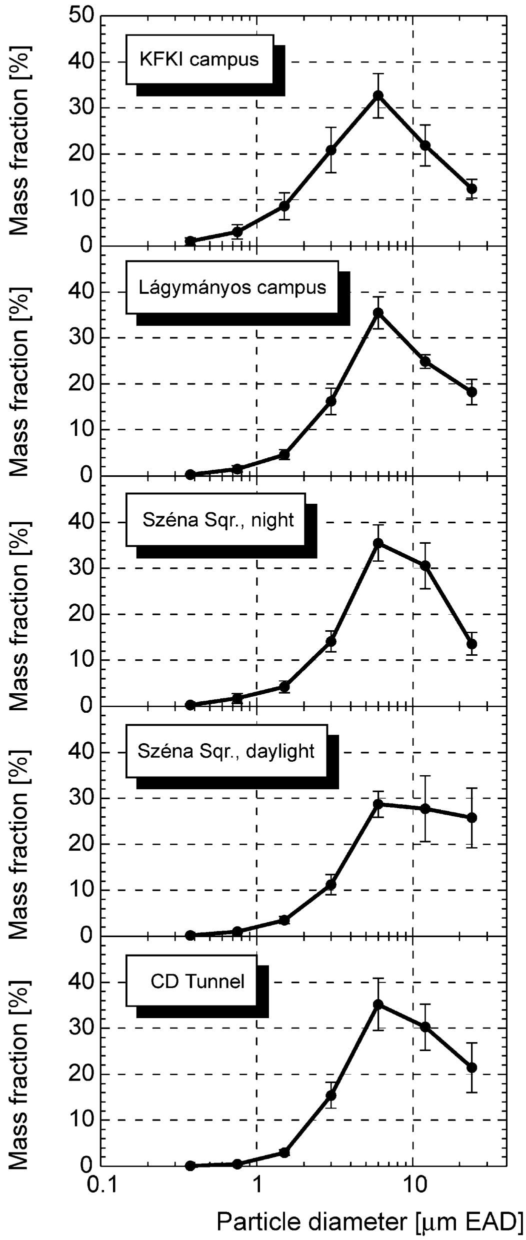

Fig. 1. Average mass size distributions of Si for the KFKI campus (urban background), Lágymányos campus (downtown), Széna Square (downtown) over night and daylight, and Castle District Tunnel. The error bars indicate standard deviations.

in Fig. 1 for illustration purposes. Group 2 contains S, Cl, K, V, Cr, Mn, Ni, Cu, Zn, Ge, As, Se, Br, Rb and Pb. Average size distributions of Pb as a representative example are displayed in Fig. 2. The elements either have a unimodal size distribution with their mass occurring primarily

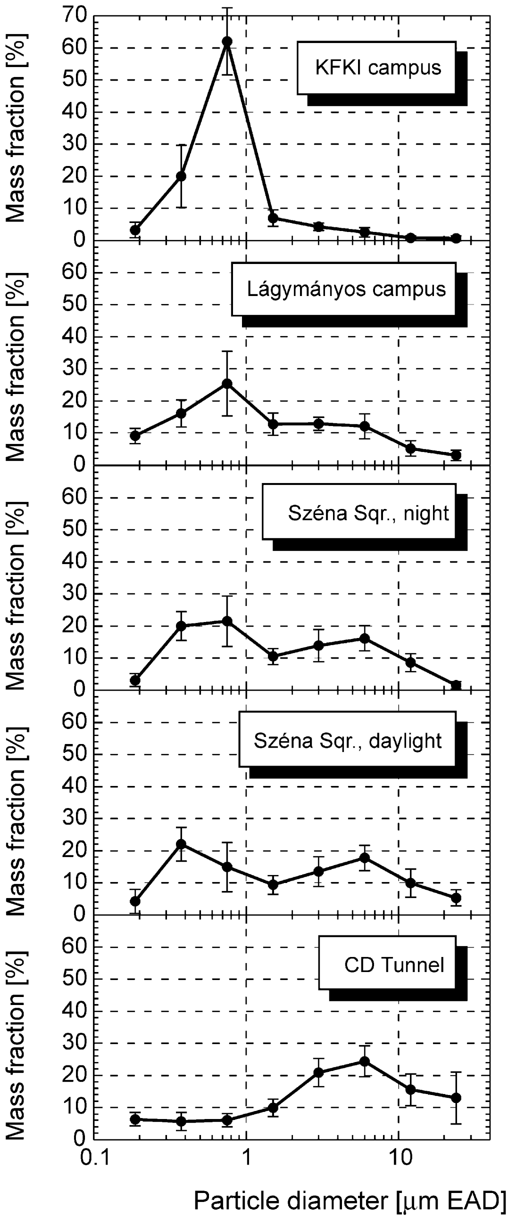

Fig. 2. Average mass size distributions of Pb for the KFKI campus (urban background), Lágymányos campus (downtown), Széna Square (downtown) over night and daylight, and Castle District Tunnel. The error bars indicate standard deviations.

in the accumulation mode or exhibit a clearly bimodal size distribution at the urban background site. Significant mass in the fine particles points to anthropogenic sources. When comparing the sampling sites, however, these size distributions show substantial differences. There is an evident tendency for the accumulation mode to decrease, and for the coarse mode to increase with increasing overall aerosol mass concentration. The group is referred to below as typically anthropogenic elements. The size distributions measured were published in a separate paper (Salma, Maenhaut, & Záray, 2001b), and are utilized as input parameters for computing the deposition fractions of the elements in the human respiratory system.

4. Deposition fractions

Deposition fractions in the human respiratory tract as a function of the bifurcation unit number for an adult male, female and child at the four urban locations are illustrated by the deposition of Pb, as displayed in Fig. 3. Deposition is generally lower for the female than for the male, and it is lower for the child than for the female. (Deposition in the extrathoracic region will be discussed in the next paragraph). Maximal depositions in the lung or thoracic region (below the larynx) occur at bifurcation unit numbers of about 20 for the male, of 18–19 for the female, and of 16 for the child, which all belong to the acinar region. The overall shape of the deposition curve for the male and female is quite similar. Nevertheless, there is an interval around the bifurcation unit number of 12 where an elevation (shoulder) shows up. The phenomenon has an increasing tendency with increasing relative mass of the coarse mode in the size distributions. In addition, the shoulder becomes more evident for the child for whom its maximum value can be comparable to or even higher than the maximal value of the acinar deposition (see Fig. 3). The appearance of the shoulder is caused by differences in the relative importance of individual tracheobronchial and acinar depositions. The deposition patterns obtained suggest that, in the lungs, it is the tracheobronchial deposition in particular for children that is the most sensitive to the changes in the size distributions (see also below). Except for this elevation, the depositions for a given gender are not really different as far as the shape of the deposition pattern and its total amount are concerned despite the rather significant differences between the size distributions for the different sampling sites (see Fig. 2). An explanation can be given by examining the dependence of regional depositions on the particle diameter. Extrathoracic, tracheobronchial, acinar and total deposition fractions calculated for the adult male under sitting breathing conditions for monodisperse aerosols as a function of the particle diameter are shown in Fig. 4. It can be seen that all regional depositions exhibit a minimum at around 0.4–0.5 μm EAD. The minimum coincides with the range of the mass median aerodynamic diameter of the accumulation mode of the anthropogenic elements (see Fig. 2 or Salma, Maenhaut, & Záray, 2001b). On the one hand, differences in the accumulation mode of the size distributions have rather limited effects on the thoracic deposition because these particles are generally not deposited; they remain mainly airborne, and so are exhaled. On the other hand, differences in the thoracic deposition caused by the diversity in the coarse mode of the size distributions are also not significant because the filtration mechanisms of the extrathoracic region are rather effective in this size range. Most coarse particles in the air inspired are, therefore, already trapped in nasal passages and, thus, do not reach the lung (note: this is the reason why the tracheobronchial and acinar depositions drop at approximately 4 and 2 μm EAD, respectively.) As far as the soil-derived elements (group 1) are concerned, deposition patterns are rather similar to each other for all locations and for a given gender due to only small differences in related size distributions (see Fig. 1).

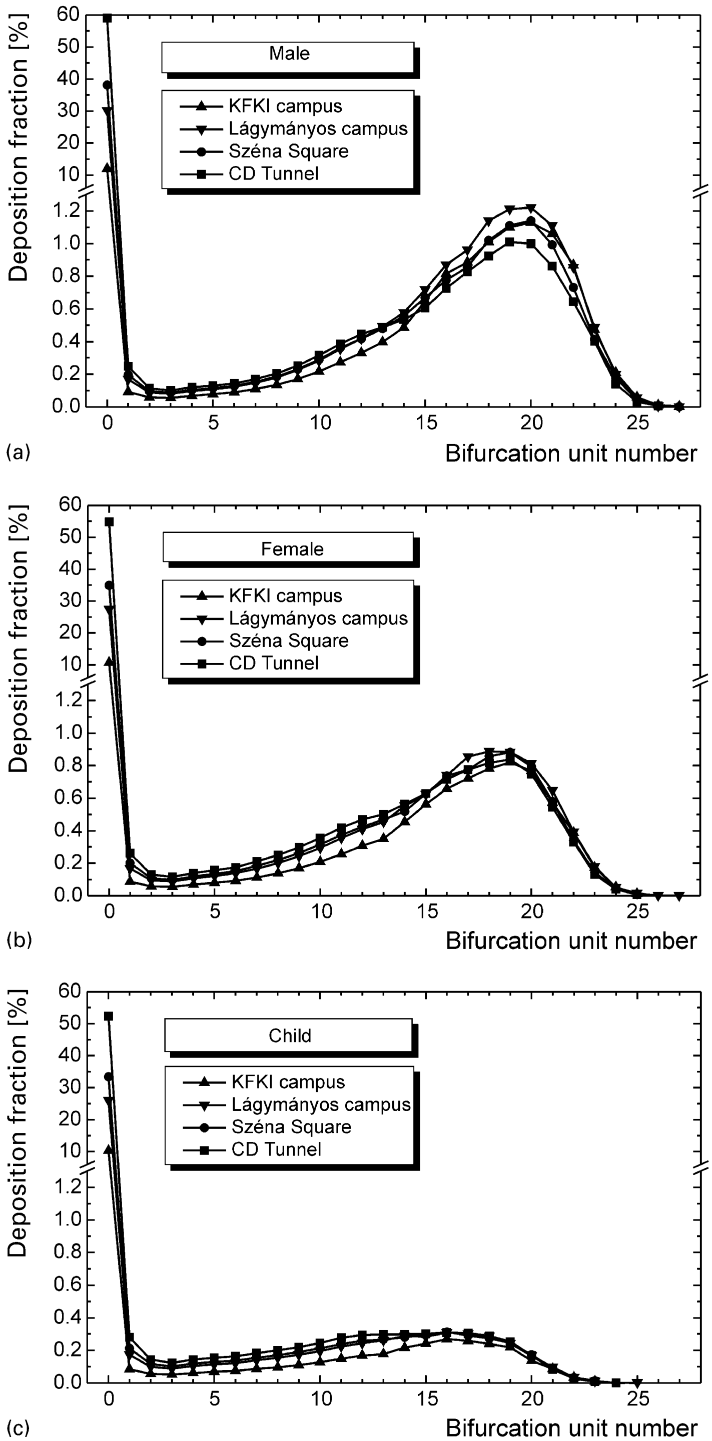

Fig. 3. Deposition fractions of Pb as a function of the bifurcation unit number for an adult male, female and a 5-year-old child at the KFKI campus (urban background), Lágymányos campus (downtown), Széna Square (downtown) and Castle District Tunnel. The extrathoracic region is represented by the bifurcation unit number 0.

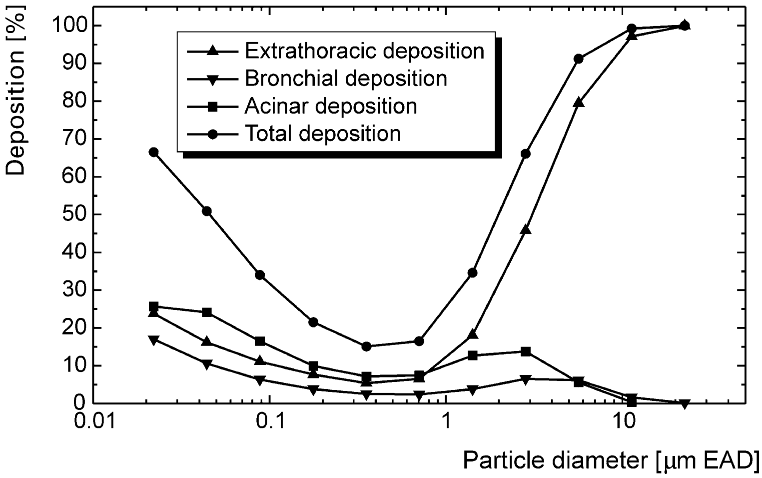

Fig. 4. Extrathoracic, tracheobronchial, acinar and total depositions as function of the equivalent aerodynamic particle diameter calculated for an adult male under sitting breathing conditions.

Deposition of typically anthropogenic elements in the extrathoracic region (D_{ET}), tracheobronchial tree (D_{TB}) and acinar region (D_{Aci}) for an adult male, female and child at the four urban locations are displayed in Tables 2–4, respectively. Mean deposition fractions for the extrathoracic region have such a large standard deviation that they are not meaningful, and, thus, are not displayed in the tables. Regional depositions of soil-derived elements (group 1) were rather similar to each other, and, therefore, mean deposition fractions and standard deviations for them are only shown. It can be seen that the maximal regional deposition for all elements and for all sampling locations occurs in the extrathoracic region. The extrathoracic deposition exhibits a monotonically decreasing tendency for the male, female and child. However, the ratio of the deposition fraction for the male to that of the child does not depend on the size distribution (sampling location), and a mean ratio of $(1.14 \pm 0.02)\%$ was derived. Similarly, extrathoracic deposition ratios for the female and child were found to be nearly constant for all size distributions (at all locations) yielding a mean value of $(1.05 \pm 0.01)\%$. Extrathoracic deposition also has an increasing tendency in the order of the sampling locations: KFKI campus, Lágymányos campus, Széna Square and CD Tunnel, hence with increasing relative mass of the coarse mode in the size distribution. At the same time, its value varies in a considerable range. The largest spread in the deposited fractions for the different sampling locations was observed for Se; they are 54%, 52% and 49% for the male, female and child, respectively. The smallest spread was encountered for Cu; they are 22%, 20% and 19% for the male, female and child, respectively. For a given location, the deposition for the male, for instance, changes between 12–45% at the KFKI campus, between 16–62% at the Lágymányos campus, between 24–68% at the Széna Square and between 49–75% within the tunnel. Extrathoracic deposition for typically anthropogenic elements at the most polluted location (tunnel) approaches the deposition of the soil-derived elements. All this suggest that the size distribution (location) and chemical species have the most important influence on the extrathoracic deposition, and that the role of the gender is also significant though to a lesser extent.

Table 2
Deposition fractions, means and standard deviations (SD, all in %) of some typically anthropogenic elements (group 2) in the extrathoracic region (ET), tracheobronchial tree (TB) and acinar region (Aci) for an adult male under sitting 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 (group 1) are also displayed

Sampling site	KFKI campus			Lágymányos campus			Széna Square			Castle District Tunnel		
Element	ET deposition	TB	Aci	ET deposition	TB	Aci	ET deposition	TB	Aci	ET deposition	TB	Aci
S	18	3.0	7.7	16	3.1	8.0	24	3.1	7.3	49	3.9	6.9
Cl	45	3.9	7.3	62	3.9	6.0	68	3.9	5.6	71	4.3	6.2
V	38	4.0	8.4	49	3.6	6.6	48	3.5	6.5	75	3.9	5.3
Ni	40	3.8	7.8	56	3.9	6.8	58	4.0	6.5	70	4.4	6.6
Cu	41	4.2	8.5	50	4.6	8.3	59	4.9	8.2	63	5.0	8.1
Zn	31	3.6	8.6	46	3.8	7.7	52	3.8	7.1	65	4.3	6.8
As	35	4.0	8.7	55	3.5	6.1	53	3.7	6.4	71	4.0	5.9
Se	13	2.9	8.4	37	3.5	7.2	42	3.5	6.6	67	3.6	5.1
Br	21	3.2	8.0	28	3.3	7.5	32	3.5	7.5	56	3.8	6.7
Pb	12	2.9	8.0	30	3.7	8.5	38	3.7	7.6	59	4.0	6.9
Mean		3.6	8.1		3.7	7.3		3.8	6.9		4.1	6.5
SD		0.5	0.5		0.4	0.9		0.5	0.7		0.4	0.9
Soil-derived elements												
Mean	69	4.3	6.6	76	3.9	5.4	79	3.7	4.8	79	3.9	5.0
SD	3	0.1	0.5	3	0.1	0.5	3	0.2	0.7	3	0.2	0.6

Deposition in the tracheobronchial tree is much smaller than the extrathoracic deposition. In contrast to the extrathoracic region, however, the tracheobronchial deposition for the male seems to be slightly smaller than for the female by a factor of 0.96 ± 0.03. It is worth noting that the difference has an increasing tendency with increasing relative mass of the coarse mode in the size distributions. For the soil-derived elements, for instance, a mean deposition ratio of 0.88 ± 0.02 was obtained, which is already statistically significant. Tracheobronchial deposition for the female is larger than for the child by a mean factor of 1.49 ± 0.08 (it is 1.35 ± 0.02 for the soil-derived elements). The tracheobronchial deposition for the downtown sites and tunnel relative to that for the urban background is larger and is increasing more rapidly for the child (from 1.13 to 1.48) than for the male (from 1.03 to 1.16) or for the female (from 1.07 to 1.30) in the order of sampling locations given. The relative standard deviation (coefficient of variation) of the mean tracheobronchial deposition also shows an increasing tendency for the male, female and child. This all may indicate that deposition in the tracheobronchial tree of the child is more influenced by the differences in the size distributions (different locations) than that of the female or male. As shown in Fig. 4, it is the particles with a diameter of approximately 4 μm EAD that exhibit maximal deposition of about 5% in the size interval studied. For the female and child, the maximum is slightly shifted toward larger diameters of up to 6 μm EAD.

Deposition in the acinar region is lower than in the extrathoracic region but higher than that in the tracheobronchial tree. Acinar deposition is decreasing rapidly for the male, female and

Table 3
Deposition fractions, means and standard deviations (SD, all in %) of some typically anthropogenic elements (group 2) in the extrathoracic region (ET), tracheobronchial tree (TB) and acinar region (Aci) for an adult female under sitting 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 (group 1) are also displayed

Sampling site	KFKI campus			Lágymányos campus			Széna Square			Castle District Tunnel		
Element	ET deposition	TB	Aci	ET deposition	TB	Aci	ET deposition	TB	Aci	ET deposition	TB	Aci
S	17	2.8	5.3	16	2.8	5.4	22	3.0	5.0	46	4.1	5.4
Cl	42	4.1	5.5	58	4.2	4.8	64	4.4	4.6	66	4.8	5.2
V	35	4.1	6.1	46	3.8	5.0	45	3.7	5.0	70	4.5	4.5
Ni	37	3.8	5.8	52	4.2	5.3	54	4.3	5.2	65	4.8	5.4
Cu	37	4.2	6.4	45	4.7	6.4	54	5.2	6.5	57	5.4	6.6
Zn	27	3.5	6.1	42	3.9	5.6	48	4.0	5.4	60	4.7	5.5
As	31	4.0	6.4	52	3.7	4.7	49	4.0	5.0	66	4.5	4.9
Se	12	2.6	5.6	34	5.5	5.3	40	3.6	4.9	63	4.1	4.2
Br	19	3.0	5.7	26	3.2	5.3	30	3.5	5.4	52	4.0	5.2
Pb	11	2.5	5.4	27	3.6	5.9	35	3.8	5.6	55	4.2	5.4
Mean		3.5	5.8		3.8	5.4		3.9	5.2		4.5	5.2
SD		0.7	0.4		0.5	0.5		0.6	0.5		0.4	0.6
Soil-derived elements												
Mean	64	4.8	5.4	71	4.5	4.5	74	4.3	4.1	74	4.5	4.4
SD	3	0.1	0.3	3	0.1	0.4	4	0.2	0.5	3	0.2	0.4

child. It also has a decreasing tendency with increasing relative mass of the coarse mode in the size distribution for the male and female, as expected. For the child, however, the acinar deposition does not seem to depend on the size distribution (sampling location), and a mean deposition of $(1.9 \pm 0.02)\%$ was obtained. The relative standard deviation of the mean deposition is approximately 10% for all locations and for both groups of the elements. Maximal acinar deposition for the adult male occurs for particles of approximately 2 μm EAD as displayed in Fig. 4. For smaller particles, the deposition mechanisms first become less efficient, so deposition fraction decreases until it reaches 8–9% at 0.4–0.5 μm EAD. The regional deposition fractions for particles with a diameter below 0.4 μm are increasing again as a result of the increased deposition by Brownian motion (diffusion). For the female and child, the maximum of the acinar deposition is shifted toward larger diameters of up to 3 μm EAD. It is worth noting as well that the diameter for the maximal acinar depositions fortuitously corresponds to the separation value between the coarse and accumulation modes in the mass size distributions (at 2–2.5 μm EAD). It means that, in general, there is a local minimum in the atmospheric mass concentration of typically bimodal aerosol constituents at this diameter, which has an advantageous effect on the deposited amount in the acinar region.

With respect to total deposition ($D_{\mathrm{tot}} = D_{\mathrm{ET}} + D_{\mathrm{TB}} + D_{\mathrm{Aci}}$ or relative respiratory intake), a very considerable fraction, i.e., 43–88% for the male, 38–83% for the female, and 31–76% for the child of the mass of an atmospheric aerosol species can be deposited in the whole human respiratory system. The total deposition follows the tendencies derived from the superposition of

Table 4
Deposition fractions, means and standard deviations (SD, all in %) of some typically anthropogenic elements (group 2) in the extrathoracic region (ET), tracheobronchial tree (TB) and acinar region (Aci) for a 5-year-old child under sitting 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 (group 1) 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	16	1.6	1.7	15	1.7	1.7	21	1.8	1.6	44	2.8	1.9
Cl	39	2.8	1.9	56	3.0	1.8	61	3.2	1.7	63	3.5	2.0
V	33	2.6	2.1	44	2.6	1.8	44	2.5	1.7	67	3.3	1.8
Ni	35	2.5	1.9	49	2.9	1.9	51	3.0	1.8	62	3.5	2.0
Cu	35	2.8	2.1	42	3.2	2.3	51	3.6	2.3	54	3.8	2.4
Zn	26	2.2	1.8	40	2.6	1.9	45	2.8	1.8	57	3.4	2.1
As	29	2.6	2.1	50	2.6	1.6	48	2.7	1.7	64	3.3	1.8
Se	11	1.5	1.6	33	2.3	1.8	38	2.4	1.7	61	3.0	1.6
Br	18	1.8	1.7	25	2.0	1.8	29	2.2	1.8	50	2.8	1.8
Pb	10	1.4	1.6	26	2.3	1.9	33	2.5	1.8	52	2.9	1.9
Mean		2.2	1.9		2.5	1.8		2.7	1.8		3.2	1.9
SD		0.5	0.2		0.5	0.2		0.5	0.2		0.3	0.2
Soil-derived elements												
Mean	61	3.4	2.0	68	3.3	1.8	72	3.2	1.6	71	3.3	1.7
SD	3	0.1	0.1	3	0.1	0.1	4	0.1	0.1	3	0.1	0.2

the regional depositions. It is worth noting that their ratios for male and child or for female and child have a decreasing tendency with increasing relative mass of the coarse mode in the size distribution in that extrathoracic deposition for the child is increasing more rapidly than for the male or female. Deposition in the lung as represented by the thoracic region ($D_{\mathrm{Thor}} = D_{\mathrm{TB}} + D_{\mathrm{Aci}}$) makes up only 10% of the total deposition for the soil-derived elements. For the anthropogenic elements, approximately 17–45% of the total deposition takes place in the lung of the adults, while it is 10–23% for the child. The deposition pattern of typically anthropogenic elements is reminiscent of the corresponding deposition curve of Pb displayed in Fig. 3.

5. Discussion

The stochastic morphometric lung model employed in the present study refers to an individual adult lung, normalized to the average functional residual capacity (see Table 1, ICRP66, 1994). However, experimental studies with different human test subjects exposed to the same aerosol, exhibited significant variations of individual particle deposition fractions (Heyder et al., 1982, 1988), commonly termed “intersubject” variability. Deposition computations based on different lung models suggest that volumetric and structural differences of lung morphologies among different individuals are primarily responsible for the experimentally observed variability of total and regional particle depositions (Hofmann, Bergmann, & Ménache, 1998; Asgharian, Hofmann, & Bergmann, 2001). Hence, the deposition patterns computed in the present study represent population-averaged values that may significantly vary in specific exposed individuals, in addition to the systematic differences caused by gender and age already considered here.

In the present study, the biological response to airborne particles is assumed to be related to the amount of matter deposited in the different compartments of the human respiratory tract. However, the initially deposited fraction of the inhaled aerosol as computed in the present study will readily be modified by the action of several clearance mechanisms operating with different magnitudes in the various regions, such as mucociliary clearance in the bronchial tree or macrophage transport in the acinar region (ICRP66, 1994). Consequently, intersubject differences of clearance fractions and half-times will contribute to any intersubject variability of biological response, in addition to the above discussed intersubject variations of particle deposition.

The primary target of inhaled atmospheric aerosols in the human body with respect to health effects is the respiratory system. Nevertheless, most of the deposited mass appears eventually in the extrathoracic region of the respiratory system as also indicated by the present paper. From this region, the deposited particles generally enter into the gastrointestinal tract so that they can be absorbed there. Numerous complex and involute factors influence the absorption processes (Ferguson, 1990 and the references therein, Ruby et al., 1999), and, therefore, the calculations and discussion of the order of the uptake together with some implications of the results to potential health effects are to be dealt with in a separate paper. The absorbed amount can be redistributed in the body stimulating some biological response, stored or accumulated causing an increased burden or even overload, or eventually be eliminated.

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