

Theoretical analysis of the influence of aerosol size distribution and physical activity on particle deposition pattern in human lungs

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Objectives A theoretical comparison of modeled particle depositions in the human respiratory tract was performed by taking into account different particle number and mass size distributions and physical activity in an urban environment.

Methods Urban-air data on particulate concentrations in the size range 10 nm–10 µm were used to estimate the hourly average particle number and mass size distribution functions. The functions were then combined with the deposition probability functions obtained from a computerized ICRP 66 deposition model of the International Commission on Radiological Protection to calculate the numbers and masses of particles deposited in five regions of the respiratory tract of a male adult. The man's physical activity and minute ventilation during the day were taken into account in the calculations.

Results Two different mass and number size distributions of aerosol particles with equal (computed) <10 µm particle mass concentrations gave clearly different deposition patterns in the central and peripheral regions of the human respiratory tract. The deposited particle numbers and masses were much higher during the day (0700–1900) than during the night (1900–0700) because an increase in physical activity and ventilation were temporally associated with highly increased traffic-derived particles in urban outdoor air.

Conclusions In future analyses of the short-term associations between particulate air pollution and health, it would not only be important to take into account the outdoor-to-indoor penetration of different particle sizes and human time-activity patterns, but also actual lung deposition patterns and physical activity in significant microenvironments.

Key terms modeling, particulate matter, pulmonary deposition, urban aerosol.

Epidemiologic studies have shown consistent associations between the mass concentrations of outdoor-air particulate matter with an aerodynamic diameter of <10 µm (PM₁₀) or <2.5 µm (PM_{2.5}) and respiratory and cardiovascular morbidity and mortality (1–4). There have also been independent associations between the number concentration of ultrafine particles (aerodynamic diameter <0.1 µm) and the respiratory health of asthmatic adults and children (5, 6). Although the causative factors and mechanisms of these health effects are not known, one of their primary determinants must be the deposition of the particles (ie, the initial contact with

the surfaces of the respiratory tract). A commonly used rough estimate of population exposure has been the 24-hour average PM₁₀ concentration measured at a central urban site, but this estimate does not account for the penetration of particles indoors, human activity patterns, and indoor sources of particles, all influencing personal exposures to particles especially in different indoor microenvironments like the home, the workplace, vehicles, and the like (7). Nor does this estimate give any information about the amounts of deposited particles or how they are distributed into the different regions of the human lower respiratory tract. The latter information may

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be important for health risk assessment in different susceptible population groups (eg, elderly subjects with heart disease versus young asthmatics).

One more problem is that the information on immediate (eg, hourly) associations between particulate exposure and health is lost (8, 9).

The deposition pattern of inhaled particles is a key factor in assessments of the association between lung dose and health effects in future epidemiologic studies, although the estimation of such patterns is a complicated issue. Several approaches have been used to estimate particle deposition in different regions of the human respiratory tract (10–12), and mathematical models have been constructed for predicting the fractions of particles deposited in the different regions as a function of particle size (13–15).

A commercial LUDEP (lung dose evaluation program) computer program has been developed on the basis of the lung deposition model of the International Commission on Radiological Protection (ICRP) to evaluate the deposition pattern of a mono-disperse or log-normally distributed aerosol (16, 17). However, the aerosol number and mass size distribution of indoor and outdoor aerosols cannot usually be described accurately with this model, and consequently the deposition patterns calculated using LUDEP may be inaccurate.

The objective of our study was to compare modeled particle depositions in the human lower respiratory tract theoretically, when different particle size distributions and physical activity were taken into account. For simplicity and the lack of an adequate database, the analysis did not include separate information from several outdoor and indoor microenvironments, where people usually spend their time.

Material and methods

Particle number and mass in inhaled air

Inhaled air always contains suspended solid and liquid particles that enter the airways and deposit on the surfaces of the upper and lower respiratory tract. The deposition probability is highly dependent on the physical properties of the particles (eg, size, density, shape, hygroscopicity), and also on the subject's breathing pattern and the anatomic structure of the airways, as all these factors affect regional flow profiles. For simplicity, we assumed, in the modeling, that the particles in the different size ranges were nonhygroscopic unit-density spheres.

When particle deposition patterns are evaluated, it is essential to define the regional deposition probability functions, $DE_r(d_p)$, that express the basic probability as a function of the particle diameter (d_p) in region r of the respiratory tract. The deposited amounts depend on these functions and on the particle number or mass size

distribution functions. The number distribution function $f(d_p)$ describes how the number of aerosol particles per unit of gas volume is distributed over a given size range, and $f(d_p)dd_p$ is the number concentration of particles belonging to the size range $[d_p, d_p + dd_p]$. In real-life environments, the number and mass size distribution functions vary with time, but in this computation we assumed that the distributions were time-invariant during each hour and denoted them as $f(d_p)$ and $f_m(d_p)$, respectively. The number of particles (in the size range $[d_p, d_p + dd_p]$) penetrating into the human airways each hour was then $V_h f(d_p) dd_p$, where V_h was the hourly ventilation. The rate of deposition of particles in the size range $[d_p, d_p + dd_p]$ into the region was $V_h DE_r(d_p) f(d_p) dd_p$. By integration, we obtained the following total number flux into region r :

$$\dot{n}_r = \int_{d_{p,\min}}^{d_{p,\max}} V_h DE_r(d_p) f(d_p) dd_p,$$

where $d_{p,\min}$ and $d_{p,\max}$ were the lower and upper limits of the particle size range, respectively. This was the general form for the number flux into region r , and it should be noted that the preceding equation was valid for number size distributions of any form. The corresponding mass flux into region r depended on the mass size distribution function $f_m(d_p)$ as follows:

$$\dot{m}_r = \int_{d_{p,\min}}^{d_{p,\max}} V_h DE_r(d_p) f_m(d_p) dd_p.$$

As only the particle number size distribution function $f(d_p)$ could be estimated from the previously collected data, it was used to calculate the mass fluxes. The mass size distribution function depends on the shape and density of the particles. In the case of spherical particles of constant density ρ , the particle mass size distribution function was

$$f_m(d_p) = \left(\rho \frac{\pi}{6} d_p^3 \right) f(d_p).$$

If the temperature of the ambient air (T) differs from body temperature (T_b), the volumes of inhaled and exhaled air are not equal, as the air changes in volume when its temperature changes during passage through the upper airways. According to the ideal-gas law, the volume of ambient air corresponding to tidal volume (V_T) is $V = (T/T_b)V_T$. Thus we corrected the integrals in our modeling by the factor T/T_b .

In order to compute estimates for the number and mass fluxes of particles, one must have time-related estimates for the number and mass distribution functions. Since these functions cannot be measured directly, several computational methods have been proposed for their reconstruction from measurements in multiple size ranges (18, 19). In our modeling, we inverted data according to the principles of Dubovik et al (20).

Lung deposition model and particle measurements

The human lung deposition model ICRP 66 published by the International Commission on Radiological Protection is widely used for predicting the regional deposition of inhaled particles (17). It has been validated by means of particle deposition measurements in humans under controlled exposures with radiolabeled particles to assess the regional deposition in different lung compartments. The observed data have been in good agreement with the predictions given by the model. The ICRP 66 model incorporates specific information related to the subject (eg, gender, age, ventilation rate, breathing pattern). The respiratory tract in the model is divided into the following five main deposition regions: the anterior nose (ET1), the main extrathoracic region (ET2, including the posterior nasal region, mouth, pharynx and larynx), the bronchial region (BB, consisting of trachea and bronchi), the bronchiolar region (bb, consisting of bronchioles), and the alveolar region (AI, consisting of alveolar ducts and sacks).

The principal criteria of the ICRP 66 model have been adopted in LUDEP (16), which predicts regional particle deposition in each lung compartment for particle diameters from 0.6 nm to 100 μm . Therefore, this program offers a useful means for determining the regional deposition probability functions in the human respiratory tract during different physical activities. The deposition probability functions were calculated for three selected activity levels (sleeping, sitting, and light exercise) of an adult person. The following daily schedule was assumed: sleeping from 2300 to 0700, light exercise from 0700 to 1900, and sitting from 1900 to 2300. The activity-related breathing parameters are shown in table 1.

Three regional deposition probability functions for an adult male performing light physical exercise are shown in figure 1.

The particle number size distribution data were obtained from a monitoring campaign carried out in the city of Kuopio in eastern Finland on 19 March–24 April 1995 (21). Particles outside the size range 10 nm–10 μm were neglected in our computations due to the limitations of the measurement methods.

Results

The modeling was made by utilizing previously collected data on outdoor-air particulate number size distributions and the ICRP 66 lung deposition model. The calculations did not account for the filtering of particles by building ventilation systems and the allocation of human life activities between different outdoor and indoor microenvironments, which would have modified the results in real-life exposures.

Effects of particle size distribution on lung deposition

The numbers and masses of particles deposited in the five regions of the respiratory tract of an adult male were calculated as 1-hour averages on the assumption that the number and mass size distributions in inhaled air were stable during each hour. The 1-hour average total

Table 1. Selected ventilation parameters for three activity levels in an adult male.

Activity level	Hourly ventilation (m ³ /h)	Breathing frequency (times/min)	Tidal volume (cm ³)	Volumetric flow rate (cm ³ /s)	Fraction breathed through nose
Sleeping	0.45	12	625	250	1.0
Sitting	0.54	12	750	300	1.0
Light exercise	1.5	20	1250	833	0.8

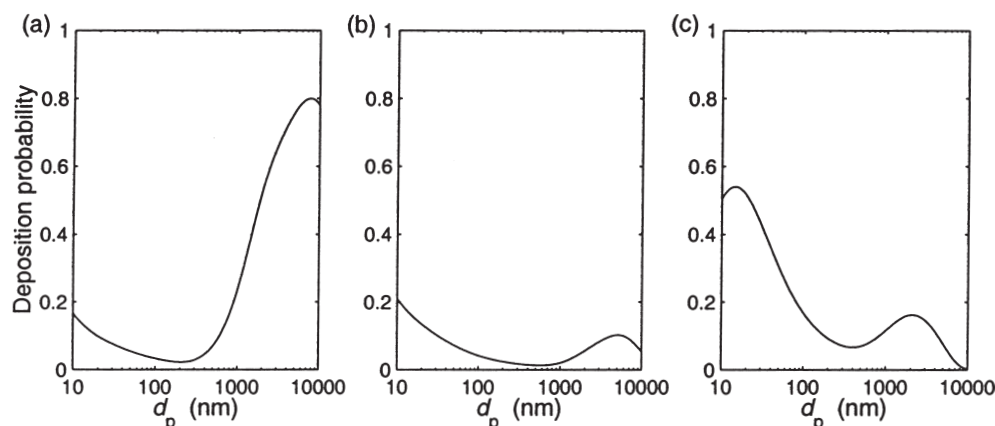


Figure 1. Three regional deposition probability functions in relation to particle size (d_p) for an adult male performing light exercise. The activity-related parameters are shown in table 1. [a = extrathoracic region (ET1+ET2), b = tracheobronchial region (BB+bb), and c = alveolar region (AI)]

number concentration of outdoor air particles in the size range 10 nm–10 µm varied from $2.23 \times 10^3 \text{ cm}^{-3}$ to $1.38 \times 10^5 \text{ cm}^{-3}$ during the measurement period. The 1-hour number concentration was highest in the size range 10–100 nm of ultrafine particles, while the mass concentration was highest in the size range 1–10 µm of coarse particles.

The ultrafine particles appeared in high numbers and low mass, and they had the highest deposition probability in the alveolar region. In contrast, the coarse particles appeared in low numbers and large mass, and they were mostly cleared from inhaled air in the extrathoracic airways, as shown in figure 1. The fractions of the total number and mass of deposited particles in the five airway regions on 20 March–23 April 1995 are shown in table 2. The first and last day of the measurement period were neglected in the computation since they did not contain full 24-hour data.

Figure 2 shows two 1-hour average mass size distributions of different shapes, which were selected and normalized so that the PM_{10} concentrations computed from the mass size distributions were equal in both cases. The mass size distributions were calculated on the basis

Table 2. Theoretical calculation of the relative particle numbers and mass deposited in the five regions of the human respiratory tract over the 5-week period.

Region	Number (%)		Mass (%)	
	Case A	Case B	Case A	Case B
Anterior nose (ET1)	6.46	0.080	35.75	0.114
Main extrathoracic region (ET2)	8.32	0.108	47.84	0.157
Bronchial region (BB)	2.65	0.030	5.65	0.022
Bronchiolar region (bb)	18.18	0.216	2.74	0.011
Alveolar region (Al)	64.39	0.890	8.02	0.040

of the number size distribution functions. The estimated PM_{10} mass concentration was 21.3 µg/m^3 , while the corresponding total particle number concentrations were $15.4 \times 10^3 \text{ cm}^{-3}$ (case A) and $9.5 \times 10^3 \text{ cm}^{-3}$ (case B). The respective particle number and mass deposition rates for the five regions of the respiratory tract in an adult male performing light physical exercise are given in table 3. The deposition rates, in terms of particle numbers in all regions of the respiratory tract, were 1.85–2.21 times higher for case A than those for case B. In terms of the particulate mass only, the ratio of case A to case B was 1.35–1.37 for the extrathoracic and bronchial regions, 1.0 for the bronchiolar region, and 0.8 for the alveolar region.

Effects of diurnal physical activity on lung deposition

Figure 3 presents the estimated number and mass of particles deposited in the five regions of the respiratory tract for each hour during two consecutive spring days. Both the number and mass of deposited particles increased

Table 3. Deposition rates of number and mass in the five respiratory regions for two different particulate number and mass size distribution functions with equal PM_{10} mass concentrations as shown in figure 2.

Region	Number ($10^9/\text{min}$)		Mass ($\text{µg}/\text{min}$)	
	Case A	Case B	Case A	Case B
Anterior nose (ET1)	0.148	0.080	0.154	0.114
Main extrathoracic region (ET2)	0.200	0.108	0.215	0.157
Bronchial region (BB)	0.056	0.030	0.030	0.022
Bronchiolar region (bb)	0.407	0.216	0.011	0.011
Alveolar region (Al)	1.966	0.890	0.032	0.040

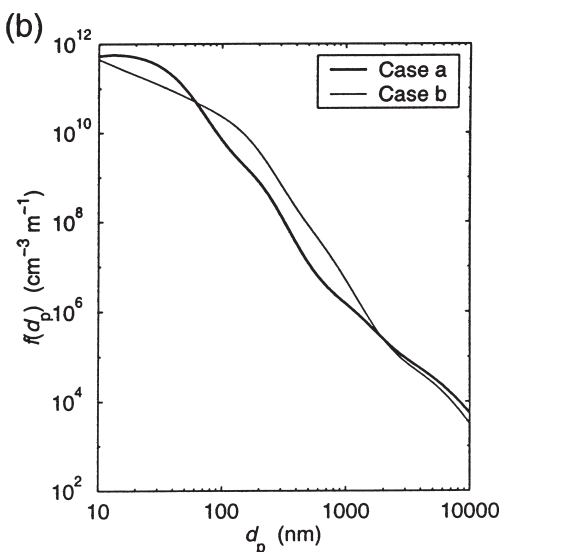
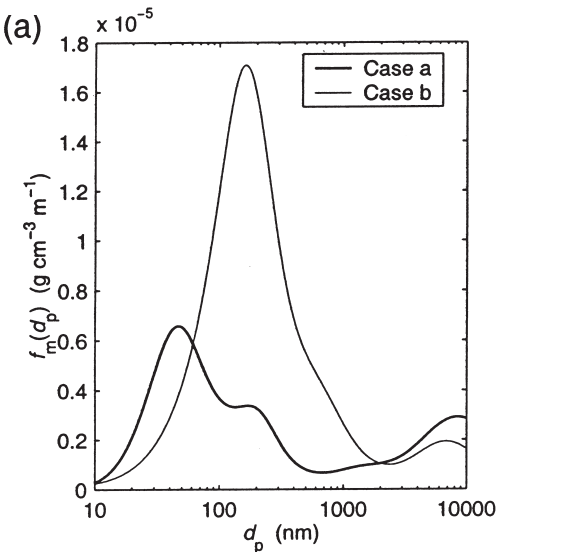


Figure 2. Two 1-hour average particulate mass size distributions with equal PM_{10} mass concentration ($\text{PM}_{10}=21.3 \text{ µg/m}^3$) (a) and the corresponding particle number size distributions (b).

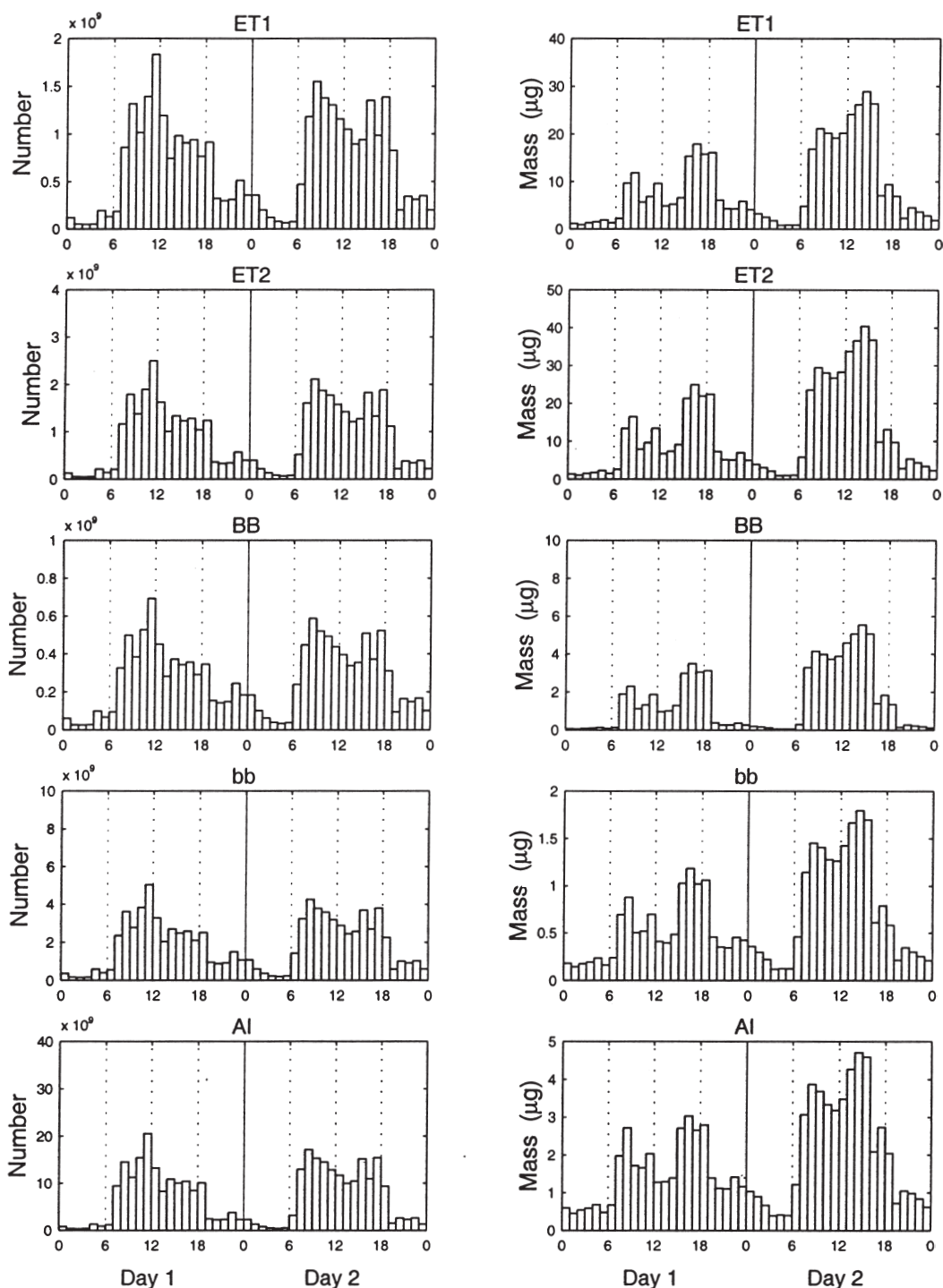


Figure 3. Number and mass of particles deposited in the five regions of the respiratory tract of an adult male during each hour of two consecutive spring days. (ET1 = anterior nose, ET2 = main extrathoracic region, BB = bronchial region, bb = bronchiolar region, AI = alveolar region)

rapidly after the awakening of the model person in the mornings. This increase was mostly due to the threefold increase in hourly ventilation (table 1) because there were no drastic differences in the deposition probabilities between sleeping and light exercise. The large increase in the number of deposited particles in the mornings was also influenced by the morning rush hours in traffic,

which produced large numbers of primary combustion particles in the ultrafine size range. After the morning rush hours, the traffic density and the total number concentration of particles in ambient air decreased (data not shown), and the decrease resulted in a corresponding decrease in the number of deposited particles in late mornings and afternoons. At the same time, the mass of

deposited particles still increased from the values during rush hours; this finding reflected the time-dependent change in the particle number size and mass size distributions in outdoor air (data not shown). After 1900, both the number and mass of deposited particles in all airway regions decreased due to the simultaneous declines in outdoor air particle concentrations and physical activity of the model person (figure 3).

The total number of particles deposited on the surfaces of the whole respiratory tract during the daily light-exercise periods (0700–1900) varied from 6.33×10^{10} to 4.38×10^{11} . The corresponding masses of deposited particles varied from 0.078 to 1.486 mg. The total number of deposited particles during the daily less-active period (1900–0700) varied from 2.19×10^{10} to 1.61×10^{11} , while the corresponding masses of deposited particles varied from 0.025 to 0.382 mg.

Discussion

In this study, we have described a method for estimating the numbers and masses of particles deposited in the different regions of the human respiratory tract. The method allows the inclusion of data on both the diurnal variations in particle number size and mass size distributions and the person's diurnal physical activity. However, the model simplified the real-life exposures to a large extent because we used outdoor-air data on particle concentrations and did not account for the influence of some other major factors on the quality of breathing air [eg, filtering by the building ventilation system (22, 23) and the allocation of human-time activities between different outdoor and indoor microenvironments (7)].

The results showed that two different particulate number and mass size distributions with equal (computed) PM_{10} mass concentration in outdoor air gave significantly different number and mass deposition rates for the human lung (table 3). The differences in the deposition rates could not be due to other reasons, because the breathing patterns and the anatomic and physiological properties of the person, a healthy adult male, were the same in both cases. This finding reveals an important limitation in the dosimetry of particulate air pollutants. The current use of defined mass concentrations (eg, PM_{10} , $PM_{2.5}$, etc) should be complemented with information on the variations in the size distribution.

In our theoretical calculations, we showed a large difference in the deposited particle numbers and masses between the physically active (0700–1900) and inactive (1900–0700) periods of the day (figure 3). The difference was affected by the fact that the increase in physical activity and ventilation were temporally associated with highly increased traffic and traffic-derived

small combustion particles in outdoor air. However, the deposited number of particles in the respiratory tract somewhat declined after the morning rush hours, whereas the corresponding deposited mass of particles still increased in the afternoon, due to a diurnal shift in the particle number and mass size distributions in the atmosphere. In our analysis, we also showed that, during the 5-week campaign period, 84% of the total deposited particulate mass was distributed into the extrathoracic airways, while 83% of the total particulate numbers was distributed into the peripheral airways (ie, the bronchial and alveolar regions) (table 2).

In all the calculations, the particles were assumed to be nonhygroscopic unit-density spheres. Consequently, their diameters were not expected to change due to the high humidity inside the respiratory tract. If there had been information on the physicochemical properties of the inhaled particles, also the hygroscopicity could have been taken into account (17). Another methodological issue that would have improved the real-life relevance of our analysis would have been the use of either measured (23) or modeled (22, 24) aerosol size distributions in relevant microenvironments, where the person used in the model spent his time.

In conclusion, the number and mass size distributions of aerosol particles in breathing air and the physical activity of the person greatly affected the amounts of particles deposited in the different regions of the human respiratory tract. In future analyses of the short-term associations between particulate air pollution and health, it would not only be important to take into account the outdoor-to-indoor penetration of different particle sizes and the human time-activity patterns, but also the actual lung deposition patterns and physical activity in significant microenvironments.

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