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Reduction potential of urban $PM_{2.5}$ mortality risk using modern ventilation systems in buildings

Abstract Urban $PM_{2.5}$ (particulate matter with aerodynamic diameter smaller than 2.5 μm) is associated with excess mortality and other health effects. Stationary sources are regulated and considerable effort is being put into developing low-pollution vehicles and environment-friendly transportation systems. While waiting for technological breakthroughs in emission controls, the current work assesses the exposure reductions achievable by a complementary means: efficient filtration of supply air in buildings. For this purpose infiltration factors for buildings of different ages are quantified using Exposures of Adult Urban Populations in Europe Study (EXPOLIS) measurements of indoor and outdoor concentrations in a population-based probability sample of residential and occupational buildings in Helsinki, Finland. These are entered as inputs into an evaluated simulation model to compare exposures in the current scenario with an alternative scenario, where the distribution of ambient $PM_{2.5}$ infiltration factors in all residential and occupational buildings are assumed to be similar to the subset of existing occupational buildings using supply air filters. In the alternative scenario exposures to ambient $PM_{2.5}$ were reduced by 27%. Compared with source controls, a significant additional benefit is that infiltration affects particles from all outdoor sources. The large fraction of time spent indoors makes the reduction larger than what probably can be achieved by local transport policies or other emission controls in the near future.

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Practical Implications
It has been suggested that indoor concentrations of ambient particles and the associated health risks can be reduced by using mechanical ventilation systems with supply air filtering in buildings. The current work quantifies the effects of these concentration reductions on population exposures using population-based data from Helsinki and an exposure model. The estimated exposure reductions suggest that correctly defined building codes may reduce annual premature mortality by hundreds in Finland and by tens of thousands in the developed world altogether.

Introduction

Epidemiologists have shown that urban fine particulate matter ($PM_{2.5}$: particulate matter with aerodynamic diameter smaller than 2.5 μm) concentration is associated with increased risk of premature mortality (e.g. Pope et al., 2002). The observed risk ratios translate to hundreds of thousands of annual excess deaths in the developed world at the prevailing $PM_{2.5}$ levels. Although successful restrictions have been set on industrial and energy production emissions and a lot of work has been done in developing low-emission motor vehicles to reduce exposures to particles from these sources, significant exposures still remain. Besides the remaining emissions from these sources, particles are generated by sources that are more difficult to control by local policies, like natural sources and distant sources contributing to long-range transport. In Helsinki it has been estimated that up to 76% of ambient $PM_{2.5}$ originates from long-range transport (Karppinen et al., 2004; Koistinen et al., 2004; Vallius et al., 2003).

Many studies have shown that personal PM exposures correlate poorly with ambient concentrations (Koistinen et al., 2001; Pellizzari et al., 1999) and that indoor sources make remarkable contributions to personal exposures (Clayton et al., 1993; Koistinen et al., 2004; Wallace, 1996). The health effects observed in the epidemiological studies, however, must be caused by ambient PM (or some factor closely associated with it), and not by exposures to indoor-generated particles, which do not correlate with the ambient pollution levels (Wilson et al., 2000). The additional personal exposures caused by individual behavior and independent indoor sources may, of course, be responsible for additional health effects that are not associated with ambient concentrations.

It has been suggested that ventilation systems in buildings could protect people from ambient particles (Fisk et al., 2002). In the warm and humid climate areas in the US, where sealed and air conditioned buildings are most common, the dose–response rate for PM_{10}-induced morbidity was found to be lower than in the milder climate areas, where open windows are used more for ventilation, indicating a safety factor created by the sealed building envelopes (Janssen et al., 2002). Similarly, in Canada residents of new energy efficient homes experienced less air quality-related symptoms than the control group members (Leech et al., 2004). People in developed countries spend a majority of their time indoors (Clayton et al., 1993; Hänninen et al., 2003) and thus filtration of ambient pollution by building envelopes can be expected to be an important exposure modifier. In residential buildings, where mechanical ventilation systems have been rare, outdoor particles penetrate indoors very efficiently (penetration factors close to unity) (Özkaynak et al., 1996; Wallace, 1996), but in buildings with two-way mechanical ventilation particle removal by supply air filters has been identified as the most significant particle removal process (Thornburg et al., 2001). Indoors particles are slowly removed from the air due to deposition and other decay processes even in houses with no supply air filtering (Hänninen et al., 2004; Wallace, 1996). In mechanical ventilation systems particle removal can be accelerated by recirculating indoor air through the filters (Fisk et al., 2002).

In Helsinki metropolitan area $<1\%$ of homes built before 1990 have supply air filters, but these are becoming increasingly common in new buildings. The recently renewed National Building Code of Finland (section D2, 2003) requires mechanical ventilation with heat recovery and efficient fine particle filtration of supply air in urban areas. Since 2000 a majority of single-family houses have been equipped with mechanical supply and exhaust ventilation system with supply air filtration. Mechanical supply and exhaust ventilation system with supply air filtration was used in 78% of the existing office buildings in Helsinki already in 1990 (Jaakkola and Miettinen, 1995) and 83% of office employees were working in such buildings. Since then all new office buildings have been equipped with mechanical supply and exhaust air ventilation systems.

Fisk et al. (2002) estimated performances of various supply air filters on indoor particle concentrations using a mass-balance model. According to their results, up to 80% reductions in indoor concentrations of ambient fine particles can be achieved with realistic filter efficiencies and flow rates. Such a modeling study, however, is based on assumptions on filter efficiencies, air leaks, particle penetration rates through the building envelopes (Airaksinen et al., 2004), and indoor particle decay rates. In reality also the behavior of the inhabitants affects the indoor concentrations; efficiency of even the best filtration system is reduced when windows or doors are kept open. Therefore the theoretical estimates calculated by Fisk et al. (2002) must be validated by using real life observations.

The objective of the current work is to compare the theoretical reductions estimated by Fisk et al. (2002) with the values observed in the Helsinki metropolitan area building stock in the Exposures of Adult Urban Populations in Europe Study (EXPOLIS) (Hänninen et al., 2004a; Jantunen et al., 1998). In addition, to support air pollution exposure control policy optimizations, a probabilistic simulation model is used to estimate how much the mechanical ventilation systems with supply air filtration, if assembled to the whole building stock, residential and occupational, could reduce population exposure to ambient $PM_{2.5}$.

Material and methods

The conceptual exposure model used in this work is shown in Figure 1. The adult population in Helsinki metropolitan area spends on average 87% of their time in indoor environments; approximately 8% in traffic (including walking) and only 5% in non-traffic outdoor environments. Therefore decreasing infiltration of particles indoors significantly reduces overall exposure levels to particles of ambient origin.

Scenarios

The current work defines two exposure scenarios. The current scenario is based on the prevailing situation in 1996–97 when the population-based EXPOLIS study was conducted in the Helsinki metropolitan area. A random sample of adults was drawn and exposures and concentration in the residences and workplaces of the subjects were measured. Infiltration factors for the ambient $PM_{2.5}$ were calculated using indoor and outdoor measurements of $PM_{2.5}$ concentrations and corresponding PM-bound elemental sulfur levels (Hänninen et al., 2004). In the alternative scenario the infiltration properties of the future building stock of the 21st century are approximated by using the infiltration factors observed in the newest occupational buildings built in the 1990s, which were captured in the EXPOLIS workplace sample, i.e. existing buildings that all use mechanical ventilation systems with F7 or F8 class supply air fine particle filters with 80–95% collection efficiencies for 0.4 μm particles. A probabilistic simulation model (Hänninen et al., 2003, 2005;

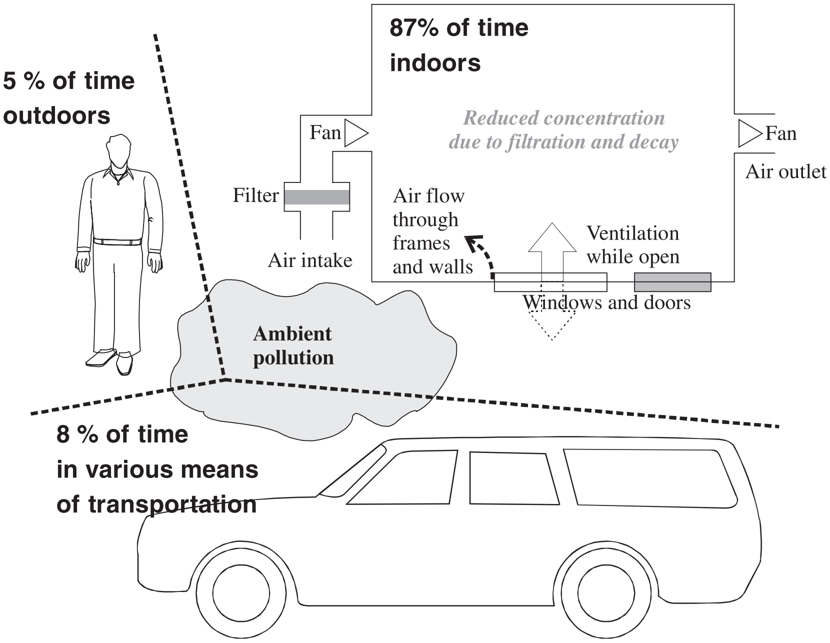

Fig. 1 Schematic diagram of the exposure model used in this study: a major fraction of the population exposure to ambient $PM_{2.5}$ occurs indoors. The effect of supply of air filtration, which is an efficient means to reduce these exposures, is quantified for the existing building stock in Helsinki

Kruize et al., 2003) is applied to estimate the population distributions of 48-h exposures for these two scenarios.

Simulation model

The simulation model used is based on microenvironment approach (Duan, 1982; Letz et al., 1984; Ryan et al., 1986) and probabilistic simulation (Law et al., 1997; Ott et al., 1988). The model defines personal exposure level (E) as the time-weighted average concentration (C) over the microenvironments (indexed by i) visited. According to Equation 1, time weighting is done using personal time activities as fractions of time (f_i) spent in each microenvironment, implicitly defining the averaging time:

$$E = \sum_i f_i \times C_i. \tag{1}$$

The simulation model has been validated for $PM_{2.5}$ exposures in two steps. First, the model was used in microenvironment mode, where the concentrations in the microenvironments are directly defined with parameters of log-normal distributions (Hänninen et al., 2003). In the second step the indoor microenvironment concentrations (C_i) were modeled from ambient concentration according to Equation 2:

$$C_i = F_{\mathrm{inf}} \times C_{\mathrm{a}} + \sum_j C_{Sj}, \tag{2}$$

where F_{inf} is the infiltration factor and C_{a} the ambient $PM_{2.5}$ concentration. The additional concentrations (C_{Sj}) caused by various sources (indexed by j) within the microenvironment are then added to the concentration of ambient origin ($F_{\mathrm{inf}} \times C_{\mathrm{a}}$). Infiltration factor can be estimated as the slope of indoor–outdoor concentration regression (Hänninen et al., 2005).

The simulations were run using four microenvironments: (i) residential indoors, (ii) workplace indoor (working subpopulation only), (iii) in traffic, and (iv) all other environments grouped together (Hänninen et al., 2005).

Input data

The model inputs were calculated from the EXPOLIS database (Hänninen et al., 2002). EXPOLIS study was conducted in seven European cities in 1996–2000, including Helsinki, Finland. Fine PM exposures, corresponding residential and occupational concentrations and exposure-related characteristics of the residences, workplaces and time activities of the subjects were measured from a random sample of the adult urban populations. The study design has been described by Jantunen et al. (1998), the collection of the PM data by Koistinen et al. (1999), the X-ray-induced fluorescence analysis of the $PM_{2.5}$ samples by Mathys et al. (2001) and the calculation of the infiltration factors by Hänninen et al. (2004). Elemental sulfur had no notable indoor sources (i.e. indoor–outdoor ratios above unity) in the data and the sulfur indoor–outdoor ratio was assumed to represent the effective infiltration factor for those fine particles that have a similar size distribution as the sulfur-containing particles. The sulfur infiltration factors were corrected for the slightly different size distribution of $PM_{2.5}$ particles using the ratio of corresponding indoor–outdoor regression coefficients (Hänninen et al., 2004). For occupational buildings simultaneous outdoor sulfur measurements were not available; these data were substituted with corresponding residential outdoor concentrations. It was assumed that as a secondary long-range transported pollutant the sulfur concentrations do not have significant spatial or diurnal patterns and that the two-night average residential concentration is a reasonable estimate for the 2-day occupational outdoor concentration.

Distribution of the ambient $PM_{2.5}$ concentration was formed from hourly ambient $PM_{2.5}$ concentrations, monitored by the Helsinki Metropolitan Area Council (YTV). The 6854-h time series data was measured during the study field phase at Vallila monitoring station, located approximately 3.5 km north-east from the Helsinki downtown area, using β-radiation absorption-based Eberline FH 62 I-R analyzer. Non-positive data (182 h) were discarded before fitting the log-normal distribution to the concentration data using method of matching moments (i.e. using mean and standard deviation values). Indoor concentrations in residences and workplaces were probabilistically modeled using the ambient concentration distribution and Equation 2. Residential and occupational concentrations of indoor sources were estimated from the EXPOLIS data and modeled assuming log-normal distributions (Hänninen et al., 2004, 2005). Log-normal traffic concentration distribution was simulated using the 37 in-transport measurements conducted during the EXPOLIS study and the population time activities (Hänninen et al., 2005). The ambient concentration distribution described above was used directly for the other microenvironment. The model input values are listed in Table 1.

Time activities of the working and non-working adult populations were modeled separately. The time activity data for the 11 microenvironments in the EXPOLIS Helsinki database for 434 subjects was grouped into four microenvironment categories and transformed into fractions of time spent in each during the 48-h diary collection period. In the model time activity values were sampled from beta distributions for each microenvironment and scaled for the sum of unity for each simulated individual.

Four simulation models were run. For the current scenario a model was run for the total $PM_{2.5}$ exposures, including exposures from non-ETS (environmental tobacco smoke) indoor sources (model 1) and for the exposures to ambient $PM_{2.5}$ (model 2). Similar models were run for the alternative scenario (models 3 and 4 respectively). The total non-ETS exposures for the current scenario (model 1) were simulated for validation purposes and compared with the personal exposure distribution observed in the EXPOLIS study.

Table 1 Model input distributions and parameters used in the simulations. Models columns indicate in which models (1–4) each input was used

		Parameters			Models			
Input category	Data distribution	Mean	s.d.	Obs[a] (n)	1	2	3	4
Time-activity (fractions of time, %)								
Working subpopulation (86.2%)								
Home indoors	beta	57	8	374	×	×	×	×
Workplace	beta	28	9	374	×	×	×	×
Traffic	beta	8	6	374	×	×	×	×
Others	beta	6	7	374	×	×	×	×
Non-working subpopulation (13.8%)								
Home indoors	beta	85	13	60	×	×	×	×
Traffic	beta	9	13	60	×	×	×	×
Others	beta	7	7	60	×	×	×	×
$PM_{2.5}$ concentrations ($\mu g/m^3$)								
Ambient 1-h	log-normal	9.6	6.8	7036	×	×	×	×
Traffic	log-normal	17.2	13.9	37	×	×	×	×
Infiltration factors (fractions)								
Current building stock scenario								
Homes	beta	0.64	0.20	98	×	×		
Workplaces	beta	0.47	0.24	94	×	×		
Building stock 1990s scenario								
Homes[b]	beta	0.35	0.12	n/a			×	×
Workplaces	beta	0.35	0.12	9			×	×
Indoor sources for $PM_{2.5}$ ($\mu g/m^3$)								
General home source	log-normal	2.48	3.18	78	×		×	
General work source	log-normal	4.18	4.98	41	×		×	

[a] Number of observations used in parameter estimation.

[b] Workplace data used also for residences.

The natural negative autocorrelations of time fractions and correlation between the ambient concentration and concentration experienced while in traffic were modeled using the rank correlation technique provided by the @Risk software (Palisade, Newfield, NY). The rank correlation values varying between −0.1 and −0.7 for time fractions and between 0.2 and 0.7 for concentrations were analyzed from the EXPOLIS data and have been reported in detail earlier (Hänninen et al., 2005).

Results

The infiltration factors for ambient $PM_{2.5}$ in the residential buildings are higher (mean ± s.d.: 0.64 ± 0.20) than those in the occupational buildings (0.47 ± 0.24, Figure 2, Table 2). More efficient filtration of ambient particles in the occupational buildings is presumably caused by the facts that supply air filtering is more common in office buildings and that ventilation by opening windows is more common in residential buildings. The 90-day running averages (Figure 2) show a slight seasonal pattern for both types of buildings, following the average seasonal temperatures. For both building types there are some outliers above the theoretical upper limit of 1.0, caused by (i) indoor sources of sulfur (especially in two workplaces with $PM_{2.5}$ infiltration values of 2.8 and 3.6, which were excluded from the analysis), (ii) time delay from outdoor PM via infiltration to indoor levels, (iii) by

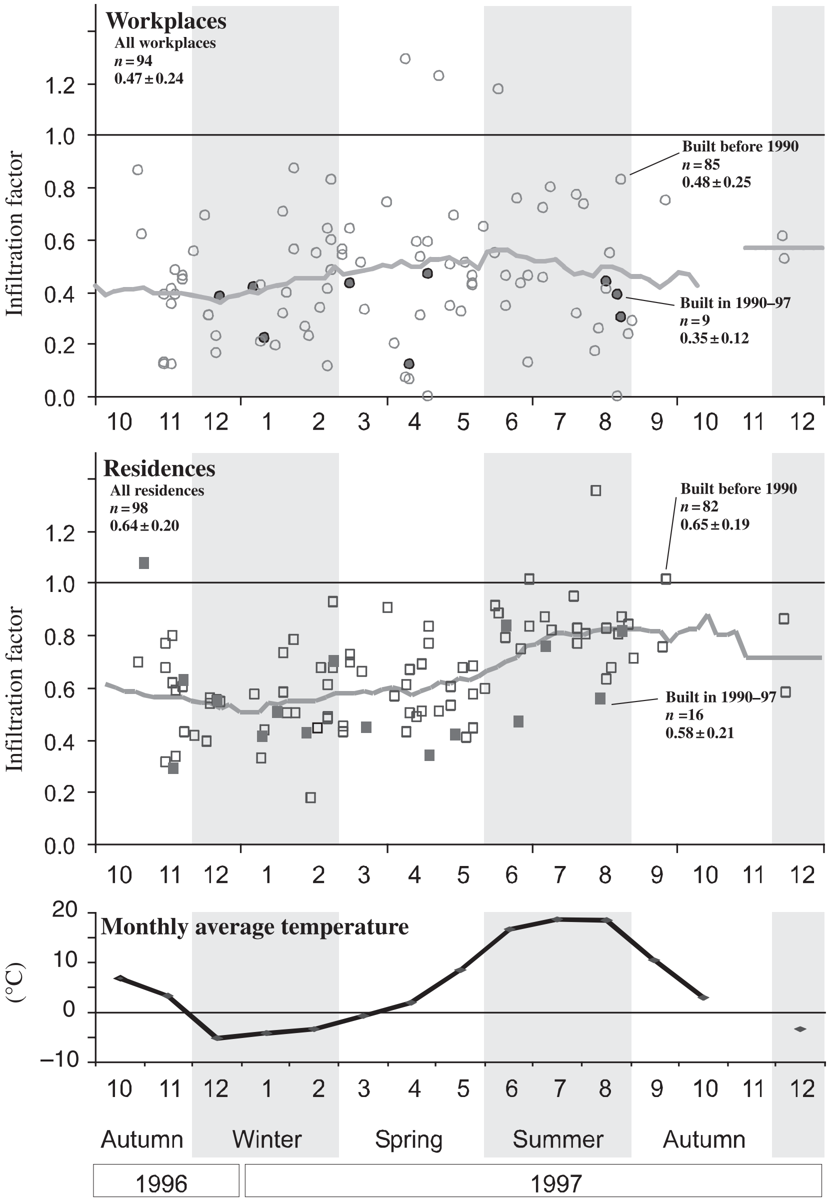

Fig. 2 Comparison of $PM_{2.5}$ infiltration factors for workplaces and residences (mean ± s.d.). Solid markers indicate newer buildings built between 1990 and the study field phase in 1996–97. The gray solid lines represent 90-day running averages for all buildings. Monthly average temperatures are shown in the bottom chart as an important modifier for building ventilation adjustments

Table 2 Infiltration factors observed in different EXPOLIS building categories and values used to describe scenarios

	Construction before 1990		Construction 1990–97		
	Filtering prevalence (%)	Observed infiltration (fraction)	Filtering prevalence (%)	Observed infiltration (fraction)	Reduction (%)
Residences	<1	0.65	n/a	0.58	11
Workplaces	78	0.48	100	0.35	27
	(1) No filtering used		(2) Filtering in all buildings		
Scenario values	<1	0.65	100	0.35	46

n/a, not available.

measurement errors, and (iv) PM concentration difference between the outdoor monitoring site and actual air intake location. Despite of these minor shortcomings, the overall distributions of infiltration factors are plausible.

A log-normal fit to the observed ambient fixed monitoring station concentration data was used in the simulations (Figure 3). The adjusted coefficient of determination (R^2) calculated from the observed concentration data using values from the fitted log-normal function with identical z-score values, was 0.98, i.e. 98% of the observed variation in the ambient concentration could be modeled indicating a very good fit. The same ambient concentration model was used for both scenarios.

Besides the building infiltrations, population time activity is the most important factor affecting the exposure reduction potential modeled here. The more people spend time in indoor environments, the larger effect the building filtration properties have on their exposures. On individual level the time activity is very variable, as can be seen in Figure 4a. The histograms in these charts describe the distribution of the observed fractions of time spent indoors, outdoors, and in traffic according to the 434 time activity diaries collected in the EXPOLIS study in Helsinki. The population average for the fraction of time spent in indoor environments is 87%. The overlaid beta distribution in each chart depicts the technique used to model the time activity distributions in the simulations; in the simulations the number of microenvironments was four for the working and three for the non-working subpopulations (totaling seven time activity classes; parameters of these distributions are listed in Table 1).

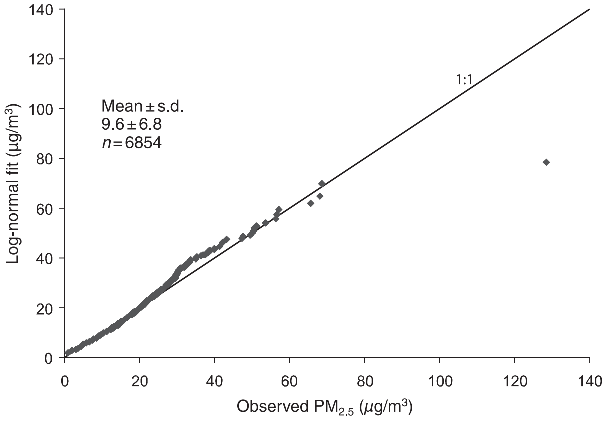

Fig. 3 Hourly ambient $PM_{2.5}$ concentrations in Helsinki and the fitted log-normal distribution (calculated based on z-scores; adjusted $R^2 = 98.0$)

From the point of view of generalizing the Helsinki results to other cities in Europe or elsewhere, it is important to look at the differences in the state of the art of building construction and ventilation technology for residential and occupational buildings, including the infiltration properties, and the population time activity patterns. To demonstrate that the time use differences between urban populations in Europe are small, the population averages for indoors, outdoors and in traffic fractions of times observed in the EXPOLIS study are compared in Figure 4b. The average fraction of time spent indoors varies from 0.86 in Athens (Greece) to 0.89 in Grenoble (France) and Milan (Italy), being thus nearly constant. Therefore it can be concluded that if there are differences between geographical areas in the efficiency of the suggested approach to reduce exposures, they must be driven by the differences in buildings and occupant behavior.

Simulated total exposures in current scenario (model 1) compare well with the observations (Figure 5a). For the highest percentiles the model underestimates the levels slightly. The observed mean exposure level is 9.8 $\mu g/m^3$ and simulated 9.3 $\mu g/m^3$. Thus the overall underestimation is 0.5 $\mu g/m^3$, or 5%. The corresponding standard deviation values were 6.4 and 4.7 $\mu g/m^3$, respectively, having larger underestimation in both absolute and relative terms. This could be expected, because standard deviation of a skewed distribution is more sensitive to underestimation of the high-tail values and consequently is not a very stable statistic for such distributions. The overall match between the two distributions is reasonable: the model is capable of catching 95% of the population exposures and can thus be considered valid for the following analyses.

Modeled mean exposure levels to ambient $PM_{2.5}$ were 6.9 and 5.0 $\mu g/m^3$ for the current and alternative

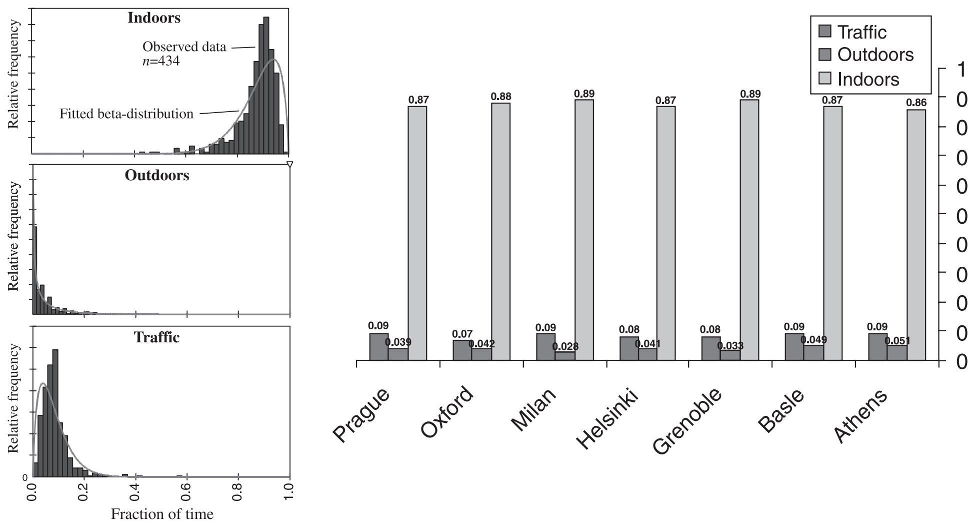

Fig. 4 Histograms of population variability of time-activity in Helsinki (a) and comparison different EXPOLIS cities (b). While the within city variability between individuals is significant, the differences in city averages are almost negligible, especially for the time fraction spent indoors. For the other two categories the difference is relatively larger

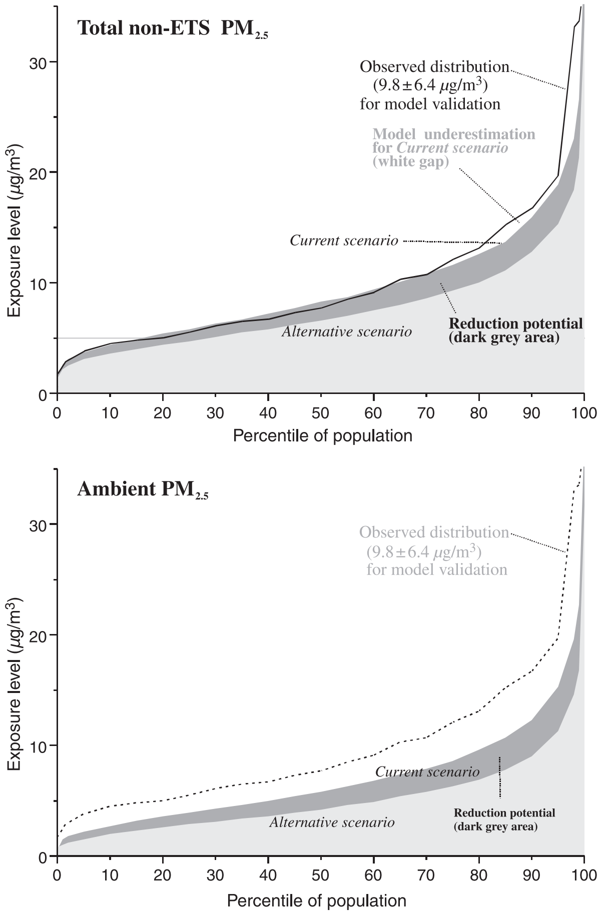

Fig. 5 The observed non-ETS $PM_{2.5}$ exposure distribution, corresponding simulated exposure, and estimated exposure reduction potential (a) and same for the exposures to ambient $PM_{2.5}$ particles (b). Dark gray area represents the reduction potential; the top edge of the gray area is the model result for the current and the bottom edge for the alternative scenario

scenarios, respectively, indicating a 27% reduction potential (Table 3). This main result of the current work is graphically depicted in Figure 5b, where the difference between the scenarios is shown in darker shade of gray. As both axes are printed on linear scales, the areas under the curves are proportional to the corresponding risks. Reduction affects all percentiles as can be expected, but the absolute reduction is largest around the 70th to 90th percentiles, i.e. where the exposure levels are rather high. This can be considered as an advantage: exposures can be reduced efficiently by using filtration systems in buildings in polluted areas. For the highest percentiles the effectiveness gets smaller, corresponding to relatively rare personal activities that lead into high exposures.

Current approach assumes that concentrations of indoor-generated particles would not be affected in the alternative scenario. While this assumption is reasonable when focusing on the ambient exposures to which health effects have been mostly associated, the indoor-generated concentrations can also be lowered with changes in the ventilation system, e.g. by using indoor air recirculation through filters. Simultaneously with

Table 3 Simulated mean population exposures to ambient, indoor-generated and total $PM_{2.5}$, and the corresponding risk reduction estimates (%) based on the linear exposure-response factor

Exposure fractions	Current scenario ($\mu g/m^3$)	Alternative scenario ($\mu g/m^3$)	Exposure reduction (%)
Ambient $PM_{2.5}$	6.9	5.0	–27
Indoor sources	2.5	2.5	0
Total $PM_{2.5}$ exposure	9.3	7.5	–20
Indoor % of ambient	36	49	–

the lowering ambient exposures in alternative scenario, the relative magnitude of indoor-generated non-ETS exposure increases from 36 to 49% (Table 3). If the indoor-generated particles turn to be toxic at all, their role in the PM question will become more important as the ambient part is alleviated.

The simulated exposure results can be translated to reduction in the ambient $PM_{2.5}$-associated health risks by using the generally adopted no-threshold linear dose–response relationship (WHO, 2000). This assumption suggests that a reduction in the health risk, e.g. mortality, is proportional to the reduction in the exposure. When looking at the main focus of the current work, the ambient exposures, the current scenario exposure level 6.9 $\mu g/m^3$ reduces to 5.0 $\mu g/m^3$ in the alternative scenario, a 27% reduction in the exposure and thus potentially a similar risk reduction. Taking the World Health Organization estimate that the annual number of deaths associated with ambient $PM_{2.5}$ levels in Europe is 102,000–368,000 (WHO, 1999), the estimated reduction would turn to be in the order of 27,000–100,000 deaths per year in Europe.

Discussion

To compare the theoretical reductions of ambient $PM_{2.5}$ in indoor air obtainable with supply air filters as estimated by Fisk et al. (2002) with respective observations, the buildings in the EXPOLIS sample were classified into two age categories divided by construction before or after 1 January 1990. The technical specifications of ventilation systems of the EXPOLIS buildings were not collected, but over three quarters of office buildings constructed before 1990 already had mechanical ventilation with supply air filtration (Jaakkola and Miettinen, 1995). Some of the EXPOLIS workplaces were not located in office buildings, so it can be expected that the prevalence of supply air filtering in the EXPOLIS workplaces is somewhat lower. Less than 1% of residences built before 1990 use supply air filtering. Residences built in the 1990s started to introduce mechanical ventilation with supply air filters and all office buildings built in 1990s were designed with mechanical ventilation with supply air filters. Consequently, the old residences (built before 1990) represent a reference building stock, where filtration systems are practically absent. The old occupational buildings (built before 1990) and the newer residences built in 1990s represent mixed building stocks, and in the occupational buildings built in 1990s a vast majority uses mechanical ventilation with supply air filtration.

In the EXPOLIS Helsinki sample there were nine occupational buildings built after 1 January 1990 and 16 corresponding residential buildings. For both building types the newer buildings had smaller infiltration factor values than the pre-1990 buildings, but the difference was much larger for the workplace buildings (Table 2). Fisk et al. (2002) estimated that the levels of ambient $PM_{2.5}$ could be reduced approximately by 23, 51 and 80% when using fine particle filters with classification ASHRAE 45, 65 and 85% (efficiencies as defined in standard ASHRAE, 1992), respectively, compared with ventilation without filter. In their base case they assumed 1 h^{-1} mechanical outside air ventilation, 0.25 h^{-1} unfiltered ventilation and 4 h^{-1} indoor air recirculation through the filters, representing a North American one-family house with forced air heating system. The estimate for ASHRAE 65% class filters (51%) is close to the observed reduction of 46% for the building categories 'all with filters' versus 'none with filters' (Table 2). Out of this reduction potential, the current building stock in 1996–97 had already established reductions of 2 and 28% for residences and workplaces, respectively, calculated as the proportion of current building stock infiltration values to that of the reference building stock of old residences. In comparison, the theoretical maximum of 80% reported by Fisk et al. (2002) indicates that with the building technology to be developed in the 21st century, significant benefits remain to be achieved.

The $PM_{2.5}$ fraction responsible for the observed excess mortality has not been identified conclusively yet regardless of the significant effort put to study this problem. $PM_{2.5}$ is composed of fractions including long-range transported particles of different types, tail-pipe particles from local traffic, combustion particles from local stationary sources, crustal particles generated and/or re-suspended by road traffic and natural processes, salt particles associated both with natural processes as well as road de-icing in colder climates. In the current situation the mean population exposure level to ambient fine particles, observed as $PM_{2.5}$ mass concentration, is still the most widely accepted health-relevant PM measure. Primary combustion-generated particles from local sources are very small, typically smaller than 100 nm in diameter These ultrafine particles behave differently in the filtering and ventilation systems. Especially their removal rate in indoor air is lower than that for the larger particles which comprise a majority of $PM_{2.5}$ mass. It has been suggested that the ultrafine particles have health effects different from those of $PM_{2.5}$; it should be noted that the results obtained here for $PM_{2.5}$ particles are not representative for the ultrafines.

Filtration by the building envelopes reduces exposures to particles from all ambient sources. The filters in mechanical ventilation systems are capable of removing $PM_{2.5}$ particles with high efficiency. When windows or doors are kept open, suspended particles of all sizes penetrate indoors with equal efficiency (~100%). Only when outdoor air penetrates indoors through small cracks, holes, and fibrous insulation materials in the building envelope does the infiltration result in particle size-dependent losses. For larger particles the dominant mechanisms are sedimentation and impaction, for the smallest interception and diffusion. Accumulation mode particles have the highest penetration efficiency (Kulmala et al., 1999; Raunemaa et al., 1989; Tung et al., 1999). The same physical phenomena reduce the PM concentrations after they have penetrated into indoor spaces. When the air leaks are minimized, the exposure reduction affects particles of all sizes and a risk reduction can be expected regardless of future findings of the role of different $PM_{2.5}$ fractions in causing the premature mortality associated with ambient $PM_{2.5}$.

The current work simulated the exposure reduction for the active working age population. The suggested approach, however, affects the exposures of all residents without any behavioral changes. Susceptible population groups, like the newborns and the elderly, spend more of their time indoors and less in traffic compared with the working age population; thus they would benefit the most from exposure reduction affecting indoor environments. Because buildings are designed, built, and renewed one by one, the ventilation system specifications reducing $PM_{2.5}$ exposures can be targeted to selected buildings, geographical areas, and population groups.

Renewing of the urban building stock is expensive and occurs gradually along the natural renovation and re-construction process. The same, however, is more or less true also for most local outdoor source control alternatives. People concerned about air pollution can act accordingly and select residences in sealed building envelopes and with good filtration systems. To support this, information on the filtration properties of houses should be made available. However, ventilation systems themselves can become sources of pollution (Pasanen et al., 1994) and therefore it is important also to maintain the ventilation systems properly.

Enhancements of city transportation system and changes of local traffic emissions and population time activity affect mainly exposures to local traffic particles. Based on published data (Koistinen et al., 2004; Vallius et al., 2003) we estimate that in Helsinki particles from local traffic contribute approximately 10–20% to the total $PM_{2.5}$ exposures. Compared with the exposure reduction potential estimated in the current work, the tailpipe $PM_{2.5}$ emissions from local traffic should be totally eliminated to obtain similar reductions in the total $PM_{2.5}$ exposures. Battery- or fuel cell-operated vehicles might eliminate traffic tailpipe emissions in the decades to come, but even then exposure to re-suspended soil particles and to industry and energy production-generated long-range particles would not be affected. In contrast, filtration by building envelope affects particles from local and regional sources as well as long-range transport, and its potential is not limited to our simulation results, which only reflect the ongoing business as usual policy.

The risk reduction potential is estimated using data from Helsinki, a city with northern location and population of 1 million. Because of the northern climate, triple glazing is standard in most buildings and the current building stock may also be in other ways tighter than buildings e.g. in the Mediterranean area, Central Europe or Southern states in the US. Thus it can be expected that the infiltration of $PM_{2.5}$ is similar or larger in most parts of the developed world and that the reduction potential could thus be even larger. Janssen et al. (2002) looked at the relationships between the health outcomes, including chronic obstructive pulmonary disease, cardiovascular disease and pneumonia, associated to ambient PM_{10} and prevalence of air conditioning systems in 14 cities in the US. In comparison with open window ventilation, a sealed building with air-conditioning considerably reduces PM infiltration. Consequently they found out that the prevalence of air conditioning reduced the concentration–response slope, especially for cardiovascular diseases, suspected to be the most common primary cause of premature death linked to PM. This result indicates that the reduced exposures in mechanically ventilated sealed buildings indeed do reduce morbidity and mortality, and supports the idea that the building envelope and ventilation system design can be used to reduce $PM_{2.5}$ risks also in warmer climates than Helsinki.

Slower air exchange rates lead to decreased infiltration due to the longer air residence times and particle decay processes. However, it is known that low air exchange rates lead to poor indoor air quality caused by indoor sources of CO_2 and other compounds (Lin and Deng, 2003; Thornburg et al., 2004; Wong and Huang, 2004). The concentrations caused by indoor sources are proportional to the air exchange rate and would be increased if air exchange rates would be reduced. Although the exposures to pollution of ambient origin would be reduced due to lower infiltration rates in such situation, the net effect could be worsening of total exposures and potentially increasing health risks. Moreover, poorly designed building structures can lead to moisture condensation and consequent mold problems, having both economical and health consequences. All these issues must be carefully considered when planning exposure reduction policies.

Conclusions

Engineering buildings and their ventilation systems in a way that minimizes the infiltration of fine particles indoors is an efficient way to reduce population exposures to PM and corresponding health risks. In the EXPOLIS Helsinki data the $PM_{2.5}$ infiltration efficiencies for the residential and office buildings built after 1990 were clearly lower than for the older buildings and especially for the occupational buildings, where the mechanical ventilation systems with supply air filters became standard in 1990s. If the non-ETS-exposed working age population in Helsinki lived and worked in buildings with similar filtration efficiencies as the occupational buildings built after 1990, their $PM_{2.5}$ exposures would be reduced by 27% in comparison with the current situation.

Advantages of filtration by ventilation systems compared with other local exposure reduction alternatives include:

- Exposures to particles from all ambient sources are reduced;
- The reduction can be targeted to susceptible sub populations;
- Making building filtration property information available so that people can select their residences according to their concern for air pollution;
- The benefits of reducing ambient air concentrations indoors can be further amplified by indoor air recirculation.

Based on the generally accepted no-threshold linear dose–response model for the ambient $PM_{2.5}$, any exposure reduction will lead to a proportional reduction in $PM_{2.5}$-induced mortality and other health effects. The public health benefit potential can be tens of thousands saved lives per year in both Europe and North America. Improvement of the ambient air quality, however, is necessary and the primary means to reduce these exposures in the long run.

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