A comparison of submicrometer particle dose between Australian and Italian people

G. Buonanno[a], L. Morawska[b], L. Stabile[a], L. Wang[c], G. Giovinco[a]

[a]Department of Civil and Mechanical Engineering, University of Cassino and Southern Lazio, via Di Biasio 43, 03043 Cassino, Italy

[b]International Laboratory for Air Quality and Health, Queensland University of Technology, Brisbane, Australia

[c] Tongji University, Shanghai, P.R. China

Corresponding author:

Giorgio Buonanno, Ph.D.
University of Cassino - School of Engineering
Department of Mechanics, Structures and Envirnonment (DiMSAT)
via G. Di Biasio, 43
03043 - Cassino (FR) Italy
phone: +39 0776 2993669
mobile: +39 388 9585444
fax: +39 0776 2994002
e-mail: buonanno@unicas.it

Abstract (150 words)

Alveolar and tracheobronchial-deposited submicrometer particle number and surface area data received by different age groups in Australia are shown. Activity patterns were combined with microenvironmental data through a Monte-Carlo method. Particle number distributions for the most significant microenvironments were obtained from our measurement survey data and people activity pattern data from the Australian Human Activity Pattern Survey were used.

Daily alveolar particle number (surface area) dose received by all age groups was equal to 3.0×10^{10} particles (4.5×10^{2} mm^2), varying slightly between males and females. In contrast to gender, the lifestyle was found to significantly affect the daily dose, with highest depositions characterizing adults. The main contribution was due to indoor microenvironments.

Finally a comparison between Italian and Australian people in terms of received particle dose was reported; it shows that different cooking styles can affect dose levels: higher doses were received by Italians, mainly due to their particular cooking activity.

Keywords: Tracheobronchial particle deposition, Alveolar particle deposition, Ultrafine particle exposure, Time activity pattern, Monte Carlo method.

Capsule: Alveolar and tracheobronchial-deposited submicrometer particle doses, in terms of number and surface area, were evaluated through a Monte Carlo method for different age groups population in Brisbane, Australia and compared to previously published Italian data.

1. Introduction

Scientific interest in ambient aerosols has increased significantly in the past few years since epidemiological and toxicological studies indicated that inhalation and subsequent deposition of particles into the lungs induced adverse health effects (Pope and Dockery, 2006; Schmid *et al*., 2009). Indeed, the harmful potential of particles is related to their ability in crossing human respiratory system, depositing in its deepest and most defenseless regions of the lung and carrying with them a number of toxic compounds. Furthermore, particles are produced by several indoor and outdoor sources leading to large doses in every kind of people's lifestyle.

In order to perform an exhaustive assessment of particles' impact on human health, both medical and air-quality expert contribution is required as different aspects need to be better investigated. In particular, epidemiological researchers are focused on finding correlations amongst particulate matter (PM) concentrations and increased morbidity and mortality (Salvi, 2007), whereas toxicologists are performing either experimental *in vivo* and *in vitro* exposure tests of various (mostly respiratory tract) cells or tissues to diverse types of PM (Brown *et al*., 2005; Phalen *et al*., 2006). Moreover, air-quality experts are either investigating particle formation phenomena and characterizing particle concentration levels in several indoor and outdoor microenvironments (Cass et al., 2000; See and Balasubramanian, 2006). Results of such research should be able to better clarify which particle size, assumption rate, and chemical component is mainly related to negative effect on human health, although at present, no definitive results have been reported. In terms of particle size, the scientific interest is moving from particle mass concentrations (PM_{10} or $PM_{2.5}$) to surface area (Giechaskiel *et al*., 2009) and particle number (Franck *et al*., 2011) concentrations whose prevalent contribution is due to submicrometer and ultrafine particles (UFPs). Concerning the chemical composition, a number of studies used to relate particles' toxicity to the presence of metals and compounds surrounding the particle (Eiguren-Fernandez *et al*., 2010), nonetheless, other studies are mainly focused on the carbonaceous core effect (Soto *et al*., 2008, Janssen *et al*., 2011). Finally, as regard the assumption rate, a number of authors is more confident that short term fluctuations aerosol concentrations can increase human morbidity and mortality (Brugge *et al*., 2007; Strak *et al*., 2010), whereas other researchers showed that mortality is mainly due to long term chronic exposure (Miller *et al*., 2007).

Dose-response relationship represents one of the main goal of toxicological study (Sayes *et al.* 2007) which could determine a threshold particle dose value; therefore, in order to compare personal particle dose to such threshold, a representative dose evaluation (approaching as much as possible the actual exposure) needs to be carried out. This is a crucial aspect, which could be ideally solved only through personal samplings able to measure particle concentrations (for all the particle metrics: number, surface area and mass) received by people in every resided microenvironment during a typical day. Actually, from a regulatory point of view, the only approach for estimating human exposure to airborne particles in the Western countries is the measure of a daily average mass-based concentration (PM_{10}, $PM_{2.5}$) at an outdoor fixed sampling point (FSP). The number and position of such FSPs is only recommended as a function of the number of people, without any link to geographic and microclimatic characteristics; therefore, measurement data of a FSP should be representative for the entire population living nearby (Directive 2008/50/EC; NEPC 1998, 2003; US EPA, 2006). Nonetheless, the actual exposure evaluation represents a more complex problem because: a) FSP data are not representative of a real outdoor exposure because of the high particle concentration decay with respect to distance to the source (Buonanno *et al*., 2011a); b) outdoor exposure represents only a fraction of personal integrated exposure since individuals also move through multiple indoor microenvironments (Buonanno *et al*., 2009); c) no air quality standards considering other particle metrics (number and surface area) are defined. In conclusion, basic information on air quality monitoring data and time activity patterns are not sufficient to policy-makers in developing accurate exposure profile, identifying the major contributors to human exposure, recognizing the people's groups at highest risk, and developing appropriate risk reduction measures. Thus, the integrated exposure or integrated dose of the people was not successfully estimated.

In our previous works (Buonanno *et al.*, 2011b), daily alveolar- and tracheobronchial-deposited particle number and surface area concentrations for Italian and Australian people of different age groups by developing a numerical methodology based on Monte Carlo method were independently evaluated. Moreover, exposure profiles of people as function of different commuting and behavior patterns were also performed. This work represented a specific population based study, so the results would be very different when considering people living in other countries showing a completely different lifestyle.

Therefore, the aim of the present paper was to apply the methodology proposed in Buonanno *et al.*, 2011b to different population age groups in Brisbane, Australia. Actually, preliminary results of the Australian case-study were reported in the Metrology Society of Australia Conference Proceeding (Buonanno *et al.*, 2011c). Therefore, in the present paper the study was widened and deepened in order to: i) provide quantitative information on the levels of sub-micrometer particles in terms of particle number and surface area concentrations in 25 smoke-free microenvironments in Brisbane, Australia; ii) estimate the daily alveolar- and tracheobronchial-deposited particle number and surface area dose for people of different age groups on the basis of the Australian time activity patterns (Australian Bureau of Statistics, 2010); iii) identify the activities having the highest important contribution to the global average daily dose; iv) compare sub-micrometer particle dose received by people having different lifestyles as Italian and Australian ones.

2. Methodology

In order to estimate the daily tracheobronchial- and alveolar-deposited fraction of airborne particles, a statistical procedure was performed. It is based on the following aspects: i) matching the locations where each exposed person spent time, in particular average time spent in each location (microenvironment) has to be identified; ii) verifying particle number size distributions whom people are exposed to in each location; iii) determining the proper inhalation rates as a function of the age and specific activity levels of the exposed population; iv) estimating the fraction of inhaled particles deposited in the respiratory track.

As regard the evaluation of the Australian daily time activity patterns, data were obtained on the basis of a customized report of the Australian Bureau of Statistics (2010).

In the indirect exposure assessment approach (Klepeis, 2006), the daily number (*N*) or surface area (*S*) alveolar-deposited dose for each age group ($\delta_{A,x}$) can be evaluated using the following equation:

$$\delta_{A,x} = \sum_{j=1}^{n} \left\{ IR_{activity} \left[\int_0^{\infty} \varphi_A \left(IR_{activity}, D \right) \cdot \frac{dx(D)}{dD} \cdot dD \right] T_j \right\} \quad (1)$$

where *x* stands for particle number (*N*) or surface area (*S*) concentration, $IR_{activity}$ is the inhalation rate of each age group depending on the human activity, $\varphi_A(IR_{activity},D)$ is the fractional alveolar deposition depending on inhalation rate and particle diameter, $dx(D)/dD$ is the particle number size distribution for each microenvironment (also termed location hereinfater) and T_j is the time spent for an activity in a defined location. The same methodology can be applied to evaluate the daily number or surface area tracheobronchial-deposited dose for each age group ($\delta_{TB,x}$) by considering the corresponding fractional tracheobronchial deposition $\varphi_{TB}(IR_{activity},D)$.

Thus, the eq. (1) is applied to the different daily activities (j=1…n) carried out by each age group (male/female 15-18 years, 19-40 years, 41-65 years and older than 65 years): the authors point out that different activities can be performed in the same microenvironment.

In order to evaluate the second term of eq. (1) a Monte Carlo-based statistical approach was applied (details are reported in our previous work Buonanno *et al.*, 2011b), in particular, the following inputs are required by the algorithm: a) inhalation rates applied for the different activities and age groups; b) fractional deposition in regions of the respiratory tract, for each microenvironment; c) number-based particle distributions, for each microenvironment.

Inhalation rates for the different activities and age groups were adopted on the basis of the US EPA approach (US EPA, 2009): they range from 0.3 $m^3 h^{-1}$ (children and young people during sleeping and resting) to 2 $m^3 h^{-1}$ (adults during sport activities). Details are reported in Buonanno *et al.*, 2011b.

Particle properties, airways dimensions, and breathing patterns represent the parameters allowing for evaluating the fraction of inhaled particles deposited in the respiratory system. The International Commission on Radiological Protection dosimetry model (ICRP, 1994) was applied by the authors to estimate the alveolar and tracheobronchial deposition. To determine the amount of particle number and/or surface area deposited per cubic centimeter of air inhaled, particles' number and/or surface area were multiplied by the deposited fraction (DF) (ICRP, 1994) evaluated for the midpoint diameter of each d*logD* interval. In order to obtain the functional relationship between particle diameter and alveolar and tracheobronchial deposition, the authors interpolated the data from (ICRP, 1994), in the form of piecewise cubic Hermite interpolating polynomials (Kahaner et al., 1988) of $\varphi_A(IR_{activity},D)$ versus *logD*, for each activity selected. In particular, for the evaluation of the fractional depositions in regions of the respiratory tract, normal nose breathing was considered.

A further information needed to estimate the dose is the number-based particle size distribution characteristics of the different microenvironments whom different age groups are exposed to. In order to apply eq.(1), we use the number based particle size distributions limited to the range 5-1000 nm, without considering the coarse fraction. In Table 1, lognormal distribution parameters (mode, standard deviation, total particle number) for each microenvironment are reported, as well as the maximum (N_{max}) and a minimum (N_{min}) total particle number concentration value. Highest particle number concentration (and, hence, distribution) values were measured during cooking activities, some working activities and transportation. In Table 1, our measurement data are compared to the ones found by other researchers.

Through these inputs, the authors performed a Monte Carlo simulation (Hammersley and Handscomb, 1964) to generate both particle size number distributions and daily time activity patterns; in particular:

- for each activity, a sample of 100 particle number distributions was generated accordingly to a random distribution between the minimum and maximum values for the corresponding microenvironment;
- for each age group, a sample of 10^6 daily time activity pattern combinations were generated following a Gaussian distribution. Among these combinations, a sub-sample was chosen with the constraint that the total daily time was equal to 24±0.5 hours. Then, each sample activity time combination belonging to the sub-sample was normalized to 1440 min (major details concerning the normalization method are reported in Buonanno et al., 2011b);
- a random sample of 10^6 combinations of the generated particle size number distributions and of the daily time activity patterns was obtained.

On the basis of the 10^6 different generated combinations, the daily alveolar, $\delta_{A,x}$, and tracheobronchial, $\delta_{TB,x}$, number or surface area deposited doses for each age group were finally evaluated.

3. Results

3.1 Normalized daily time activity patterns

In Table 2 normalized daily time activity patterns for Brisbane, and the corresponding standard deviations for each age group and gender are reported. The 25 considered activities were categorized according to eight "macro-activities" as function of the microenvironment (location) were they were performed. Firstly, the survey data show that the total time spent during indoor activities (referenced in Table 2 as indoor evening, indoor day, cooking, eating, working) by all age groups considered varied only slightly and was greater than 92%. Time spent at home is comparable to the one measured in Germany (942 min, 65%; Brasche and Bischof, 2005), US (940 min, 65%; Leech *et al.*, 2002), Canada (950 min, 66%; Leech *et al.*, 2002) as well as Italy (1000 min, 69%; Buonanno *et al.*, 2011b). For the Australian case, the average value, evaluated by considering the activities 1, 2, 3, 4, 5, 7, 14, 21, 22 (see to the identification number defined in the caption of Table 1 and 2) was 1024 min (71%), with women spending more time indoors (generally at home) than men. The time spent on transportation (referenced in Table 2 as pedestrian & bikes and car & buses activities) for adults (19-40 and 41-65 years) was lower than 2%. The surveyed age groups engaged mainly in different primary activities and for the 15-18 age group, the main activities were sleeping and resting (1), audio/visual media activities (7), communication associated with recreation and leisure (17) and education activities (20). For 19-40 and 41-65 year olds, the contribution from studying decreased whereas working time increased.

3.2 Alveolar and tracheobronchial particle number and surface area deposited dose

Figure 1 presents the average daily alveolar- and tracheobronchial-deposited particle in terms of number and surface area, along with the corresponding standard deviation, according to age group and gender. The daily alveolar particle number (surface area) deposited for all age groups was $2.8 \times 10^{10} \pm 1.4 \times 10^{10}$ particles ($4.1 \times 10^2 \pm 1.9 \times 10^2$ mm^2) for males and $3.2 \times 10^{10} \pm 2.2 \times 10^{10}$ particles ($4.8 \times 10^2 \pm 2.2 \times 10^2$ mm^2) for females.

In terms of tracheobronchial deposition, the daily particle number (surface area) deposited from all age groups was $1.4 \times 10^{10} \pm 6.9 \times 10^9$ particles ($1.9 \times 10^2 \pm 9.2 \times 10^1$ mm^2) for males and $1.4 \times 10^{10} \pm 4.7 \times 10^9$ particles ($2.1 \times 10^2 \pm 9.2 \times 10^1$ mm^2) for females. The average dose is only slightly higher for females, even if the difference between the two genders was lower than the corresponding standard deviations and, therefore, was considered not to be significant. Otherwise, more noteworthy is the general increase in dose with increasing age (from 15 to 65 years), and the subsequent decrease for the elderly (>65 years old). By comparing the dose received by people of different ages, an important difference (as example, 40% and 54% in terms of alveolar-deposited particle number for females and males, respectively), was found between teenagers (age 15-18) and adults (age 19-40; which was the group mainly exposed), as well as between seniors (>65 years old) and adults (20% and 74% in terms of alveolar-deposited particle number for females and males, respectively). The main reason of such differences turned out to be the different lifestyle of people during their life, or, more precisely, the different microenvironments where they spend time. In fact, the differences between the inhalation rates for the different age groups itself cannot explain such remarkable differences: by normalizing the data with respect to mean inhalation rates as a function of activities for all age groups (0.64, 0.66, 0.74, and 0.73 m^3 h^{-1}, respectively), these differences did not change significantly: for example, the difference between teenager (age 15-18) and adults (age 19-40) in terms of alveolar-deposited particle number turn into 38% and 52% for females and males, respectively.

Dose trends as function of gender and age are similar to the one present in Italy (Buonanno *et al*., 2011b), however, the actual dose received by people living in Brisbane, Australia is quite different to the dose received by Italians. For example, in the Italian case-study daily alveolar particle number (surface area) deposited for all age groups was $1.4 \times 10^{11} \pm 1.5 \times 10^{10}$ particles ($2.3 \times 10^3 \pm 4.2 \times 10^2$ mm^2) for males and $1.4 \times 10^{11} \pm 1.5 \times 10^{10}$ particles ($2.5 \times 10^3 \pm 4.1 \times 10^2$ mm^2) for females, respectively.

Dose values for the Australian and Italian case-study clearly show that adults receive a higher particle number and surface area deposition in their lungs with respect to other ages. In particular, the Italian case study (where data for people younger than 15 years old are also reported) show that children receive lower dose levels. This could be considered a positive aspect since physiological research has shown that particle exposure of developing lungs can permanently affect the lungs themselves, in particular early life exposure to UFPs can result in persistent alterations in distal airway architecture that is characterized by an initial decrease in airway cell proliferation (Lee *et al.*, 2010). Nevertheless, absolute dose could be a misleading parameter when a comparison amongst age groups showing different the air-tissue interface (alveolar surface area exposed to air) in the alveolar region of the lung are considered. In fact, after their birth children's alveolar surface area keeps growing (from 2.8 m^2 at birth) reaching a maximum value at the age of 20 (when it is about 75 m^2) (Dunnill, 1962; Thurlbeck, 1982). Therefore, a lower absolute particle dose in children can anyhow lead to a higher deposited particle "density" in the alveolar region. To this purpose in Figure 2 the average daily doses (in terms of alveolar-deposited particle number and surface area) as a function of age group and gender, for both Italian and Australian case-study, normalized to the air-tissue interface data obtained from Dunnill (1962) and Thurlbeck (1982) are reported. Figure 2 data clearly show that whatever the metrics (number *vs*. surface area) and the gender (male *vs*. female) were considered, the deposition trend normalized to the actual available air-tissue interface is completely different from the absolute one: in particular, infants received the highest "specific" particle number deposition among the considered population age groups and a "specific" particle surface area deposition higher or equal to the one experienced by working adults (age 19-65). Summarizing, infants (and children) are exposed to the high normalized doses (deposited particle "density") in the period of their life during which it could be more dangerous from a physiological point of view.

Concluding, Figure 2 also confirms the aforementioned higher dose received by Italian people with respect to the Brisbanians. By comparing time activity patterns typical of Italian (see Buonanno *et al*., 2011b) and Australian, differences not sufficient to justify the significantly different doses were found. Therefore, the main reason of such significant difference can be addressed to the different exposure levels in Italian and Australian microenvironments; in particular, Italian particle concentration levels significantly higher than the Australian ones were measured during eating, cooking and working activity (see Buonanno *et al*., 2011b). As example, looking at cooking activity, the total concentration values measured by He *et al*., 2004 (see Table 1) for the Australian case-study range between 0.4×10^5 and 2.7×10^5 part. cm^{-3}, whereas for the Italian case-study minimum and maximum concentrations of 1.0×10^5 and 6.9×10^5 part. cm^{-3} were considered, respectively (Buonanno *et al*., 2011b). Such difference can be addressed to the different cooking methods, since in Australia are typically used electric stoves whose particle emission factor is lower than gas stove ones (He *et al*., 2004; Buonanno *et al*., 2009).

3.3 Contributions to the alveolar and tracheobronchial particle number and surface area dose

In Figure 3 the contribution to the average daily dose of different activities carried out by each age group is reported. For example, the average contributions to alveolar deposited number and surface area from indoor microenvironments were equal to 85% ± 1.7% and 90% ± 2.6%, respectively. In order to better discuss such contributions, the authors also refer to the "dose intensity" parameter (introduced by Wang *et al*., 2011), defined as the ratio of the daily dose contribution and the daily time contribution. When analyzed in terms of dose intensity, contributions to alveolar deposited number and surface area from indoor microenvironments ranged between 0.9 ± 0.03 and 1.0 ± 0.04: such average dose intensity of indoor microenvironments is quite low, clearly highlighting that the long duration of time spent in these environments accounts for the high contribution to daily total deposition. As example, particle number and surface area alveolar dose intensities for the age groups investigated are reported in Figure 4. Here is clearly shown how other significant microenvironments in terms of dose contribution are the transportation ones: in fact, even though the average contribution to alveolar deposited number and surface area was quite low, the dose intensity varied between 5.3 ± 3.7 and 2.9 ± 1.7, which is higher than the one received in indoor microenvironments.

As regards the contribution of single human activities to overall dose, the age group effect was also recognized. For 15-18 years, the following activities contributed to alveolar particle number deposition by more than 10%: sleeping (16%), eating/drinking (after cooking) (14%) and audio/visual media time (15%). Similar values were found for tracheobronchial number deposition. In terms of alveolar and tracheobronchial surface area deposition, the highest contribution came from the cooking and eating combined (44%). These values show that particles generated from cooking activities represent a critical exposure, with a dose intensity higher than 10. Similar values were measured for people >65 years, with cooking and eating contributing 34% and 36% to alveolar and tracheobronchial particle number deposition, and 32% and 31% for alveolar and tracheobronchial surface area deposition, respectively.

4. Conclusions

In order to give an exhaustive answer about how much the lifestyle can affect the dose received by people, a population based study was performed on different age groups in Brisbane (Australia) and compared to our previous results regarding Italian people. In particular, alveolar and tracheobronchial-deposited (dose) particle number and surface area received by people were evaluated through a Monte Carlo method simulation taking into account activity pattern data and micro-environmental data (human activities and particle number distributions).

Results concerning alveolar and tracheobronchial dose values in terms of particle number and surface area (evaluated on daily basis) show that females receive higher doses than males. This difference should be not addressed to the “gender effect”, but it can be explained through the different lifestyle between female and male: females spend more time in indoor environments where higher exposure levels are experienced.

As regards the age, we found that adults (in particular, people age 19-40) received considerably higher doses than teenagers (age 15-18) and seniors (>65 years old). Anyway, such “age effect” is completely ascribable to the different lifestyle too, since the different inhalation rates, characteristics of the different age groups and performed activities, were found to have a negligible effect on doses.

The reason of the significant of the “lifestyle effect” on received particle doses is due to the different particle exposure levels experienced in different microenvironments. In particular, highest dose intensities were found during cooking activities and transportations (both indoor, car and bus, and outdoor, pedestrian and bike). The effect of the particle exposure levels on doses received is also highlighted by the comparison between Italian and Australian particle deposition: higher doses are received by Italian people with respect to the Australians mainly because in Italy particle concentration levels are significantly higher than the Australian ones in particular during eating, cooking and transportation activities.

Finally, we point out that the absolute dose values can be misleading in the evaluation of a particle dose-response relationship. In fact, when the analysis of the particle deposition as function of the available air-tissue interface for different age groups is considered, infants and children (typically receiving a lower absolute dose) turned out to be exposed to normalized doses (deposited particle "density") higher than the ones experienced by working adults. This could represent a critical aspect since such high exposure coincides with the period of their life during which it could be more dangerous from a physiological point of view.

References

Australian Bureau of Statistics, 2010. Customised report. Cat. no. 4430.0, Australian Bureau of Statistics, Canberra.

Berghmans, P., Bleux, N., Int Panis, L., Mishra, V.K., Torfs, R., Van Poppel, M., 2009. Exposure assessment of a cyclist to PM_{10} and ultrafine particles. Science of the Total Environment 407 (4), 1286-1298.

Brown, J.S., Wilson, W.F., and Grant, L.D., 2005. Dosimetric comparisons of particle deposition and retention in rats and humans. Inhalation Toxicology 17, 355–385.

Brugge, D., Durant, J.L., Rioux, C., 2007. Near-highway pollutants in motor vehicle exhaust: a review of epidemiologic evidence of cardiac and pulmonary health risks. Environmental Health 6, 23.

Buonanno, G., Stabile, L., Morawska, L., 2009. Particle Emission Factors During Cooking Activities, Atmospheric Environment 43(20), 3235-3242.

Buonanno, G., Fuoco, F.C., Stabile, L., 2011a. Influential parameters on particle exposure of pedestrians in urban microenvironments. Atmospheric Environment 45, 1434-1443.

Buonanno, G., Giovinco, G., Morawska, L., Stabile, L., 2011b. Tracheobronchial and alveolar dose of submicrometer particles for different population age groups in Italy, Atmospheric Environment 45, 6216-6224.

Buonanno, G., Giovinco, G., Morawska, L., Wang, L., 2011. Submicrometer particle dose for different population age groups in Brisbane, Australia. Metrology Society of Australia Conference, A Climate for Better Measurement Deakin Management and Convention Centre, Geelong (VIC), 19-21 October 2011.

Buonanno, G., Morawska, L., Stabile, L., 2011d. Exposure to welding particles in automotive plants. Journal of Aerosol Science 42, 295–304.

Cass, G.R., L.A. Hughes, P. Bhave, M.J. Kleeman, J.O. Allen, and L.G. Salmon. 2000. The chemical composition of atmospheric ultrafine particles. Philos. Trans. R. Soc. Lond. A 358:2581–2592.

Dennekamp, M., Mehenni, O.H., Cherrie, J.W., Seaton, A., 2002. Exposure to ultrafine particles and PM2.5 in different micro-environments. Annals of Occupational Hygiene 46 (S1), 412e414.

Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008 on ambient air quality and cleaner air for Europe.

Dunnill, M.S., 1972. Postnatal growth of the lung. Thorax 17, 239-333.

Eiguren-Fernandez, A., Shinyashiki, M., Schmitz, D.A., Di Stefano, E., Hinds, W., Kumagai, Y., Cho, A.K., Froines, J.R., 2010. Redox and electrophilic properties of vapor- and particle-phase components of ambient aerosols. Environ. Res. 10, 207–212.

Elihn, K., and Berg, P., 2009. Ultrafine Particle Characteristics in Seven Industrial Plants, Ann. Occup. Hyg. 53, 475–484.

Franck, U., Herbarth, O., Röder, S., Schlink, U., Borte, M., Diez, U., Krämer, U., Lehmann, I., 2011. Respiratory effects of indoor particles in young children are size dependent. Science of the Total Environment 409(9), 1621-1631.

Fromme, H., Twardella, D., Dietrich, S., Heitmann, D., Schierl, R., Liebl, B., Rüden, H., 2007. Particulate matter in the indoor air of classroomsdexploratory results from Munich and surrounding area. Atmospheric Environment 41, 854-866.

Giechaskiel, B., Alföldy, B., Drossinos, Y., 2009. A metric for health effects studies of diesel exhaust particles. Journal of Aerosol Science 40, 639-651.

Hammersley, J.M., Handscomb, D.C., 1964. Monte Carlo Methods. Chapman and Hall, London & New York.

He, C., Morawska, L., Hitchins, J., Gilbert, D., 2004. Contribution from indoor sources to particle number and mass concentrations in residential houses, Atmospheric Environment, 38, 3405–3415

Hitchins, J., Morawska, L., Wol, R., Gilbert, D., 2000. Concentrations of submicrometre particles from vehicle emissions near a major road. Atmospheric Environment 34, 51-59.

International Commission on Radiological Protection (ICRP), 1994. Human Respiratory Tract Model for Radiological Protection: A Report of a Task Group of the International Commission on Radiological Protection. Elsevier Science Ltd., Oxford, U.K., pp. 1-482.

Janssen, N., Simic-Lawson, M., Hoek, G., Fischer, P., Brunekreef, B., Atkinson, R., and Cassee, F., 2011. Black Smoke as an Additional Indicator to Evaluate the Health Benefits of Traffic-related Policy Measures: A Systematic Review of the Health Effects of Black Smoke Compared to PM Mass. Epidemiology 22(1), S199-S200.

Kahaner, D., Moler, C., Nash, S.,1988. Numerical Methods and Software. Prentice Hall.

Kaur, S., Nieuwenhuijsen, M.J., Colvile, R., 2007. Fine particulate matter and carbon monoxide exposure concentrations in urban street transport microenvironments. Atmospheric Environment 41, 4781-4810.

Klepeis, N.E., 2006. Modeling human exposure to air pollution. In: Ott, et al. (Eds.), Human Exposure Analysis. CRC Press.

Lee, D., Wallis, C., Wexler, A.S., Schelegle, E.S., Van Winkle, L.S., Plopper, C.G., Fanucchi, M.V., Kumfer, B., Kennedy, I.M., Chan, J.K., 2010. Small particles disrupt postnatal airway development. Journal of Applied Physiology 109(4), 1115-1124.

Mejìa, J.F., Wraith, D., Mengersen, K., Morawska, L., 2007. Trends in size classified particle number concentration in subtropical Brisbane, Australia, based on a 5 year study. Atmospheric Environment 41, 1064-1079.

Miller, K.A., Siscovick, D.S., Sheppard, L., Shepherd, K., Sullivan, J.H., Anderson, G.L., Kaufman, J.D., 2007. Long-term exposure to air pollution and incidence of cardiovascular events in women. The New England Journal of Medicine 365, 447-458.

Morawska, L., Thomas, S., Gilbert, D., Greenaway, C., 1999. A study of the horizontal and vertical profile of submicrometer particles in relation to a busy road. Atmospheric Environment 33, 1261-1274.

Morawska, L., He, C., Hitchins, J., Gilbert, D., Parappukkaran, S., 2001. The relationship between indoor and outdoor airborne particles in the residential environment. Atmospheric Environment 35, 3463-3473.

Morawska, L., Jayaratne, E.N., Mengersen, K., Jamriska, M., Thomas, S., 2002. Differences in airborne particle and gaseous concentrations in urban air between weekdays and weekends, Atmospheric environment, 36, 4375–4383.

Morawska, L., He, C., Hitchins, J., Mengersen, K., Gilbert, D., 2003. Characteristics of particle number and mass concentrations in residential houses in Brisbane, Australia, Atmospheric Environment, 37, 4195–4203

Morawska, L., Keogh, D.U., Thomas, S.B., Mengersen, K.L., 2008. Modality in ambient particle size distributions and its potential as a basis for developing air quality regulation. Atmospheric Environment 42(7), 1617–1628.

Morawska, L., He, C., Johnson, G., Guo, H., Uhde, E., Ayoko, G., 2009a. Ultrafine Particles in Indoor Air of a School: Possible Role of Secondary Organic Aerosols. Environmental Science and Technology 43, 9103–9109.

Morawska, L., Jamriska, M., Guo, H., Jayaratne, E.R., Cao, M., Summerville, S., 2009b. Variation in indoor particle number and PM2.5 concentrations in a radio station surrounded by busy roads before and after an upgrade of the HVAC system. Building and Environment 44, 76–84.

NEPC 1998, National Environment Protection Council. National Environment Protection Measure and Impact Statement for Ambient Air Quality, National Environment Protection Council, Adelaide.

NEPC 2003, National Environment Protection Council. Variation to the National Environment Protection (Ambient Air Quality) Measure, NEPC, Adelaide.

Phalen, F.R., Oldham, J.M., Nel, E.A., 2006. Tracheobronchial Particle Dose Considerations for In Vitro Toxicology Studies. Toxicological Sciences 92, 1, 126-132.

Pope, C.A., and Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. Journal of the Air & Waste Management Association 56, 709-742.

Salvi, S., 2007. Health effects of ambient air pollution in children. Paediatric Respiratory Reviews 8, 275–280.

Sayes, C.M., Reed, K.L., Warheit, D.B., 2007. Assessing toxicity of fine and nanoparticles: comparing in vitro measurements to in vivo pulmonary toxicity profiles. Toxicol Sci. 97, 163-80.

Schmid, O., Möller, W., Semmler-Behnke, M., Ferron, G.A., Karg, E., Lipka, J., Schulz, H., Kreyling, W.G., Stoeger, T., 2009. Dosimetry and toxicology of inhaled ultrafine particles. Biomarkers 14, S1, 67-73.

See, S.W., Balasubramanian, R., 2006. Physical characteristics of ultrafine particles emitted from different gas cooking methods. Aerosol Air Qual. Res. 6, 82–92.

Shi, J.P., Khan, A.A., Harrison, R.M., 1999. Measurements of ultrafine particle concentration and size distribution in the urban atmosphere. The Science of the Total Environment 235, 51-64.

Soto, K.F., Garza, K.M., Shi, Y., Murr, L.E., 2008. Direct contact cytotoxicity assays for filter-collected, carbonaceous (soot)nanoparticulate material and observations of lung cell response. Atmospheric Environment 42, 1970-1982.

Strak, M., Boogaard, H., Meliefste, K., Oldenwening, M., Zuurbier, M., Brunekreef, B., Hoek, G., 2010. Respiratory health effects of ultrafine and fine particle exposure in cyclists. Occupational and Environmental Medicine 67 (2), 76-77.

Thurlbeck, W.M., 1982. Postnatal human lung growth. Thorax 37, 564-571.

US EPA, 2006. U.S. Environmental Protection Agency 40 CFR Part 50, 2006. National Ambient Air Quality Standards for Particulate Matter, Part II. Final Rule.

US EPA, 2009. Environmental Protection Agency. Metabolically derived human ventilation rates: a revised approach based upon oxygen consumption rates, National Center for Environmental Assessment, Office of Research and Development, EPA/600/R-06/129F.

Wang, L., Morawska, L., Jayaratne, E.R., Mengersen, K., Heuff, D., 2011. Characteristics of airborne particles and the factors affecting them at bus stations, Atmospheric Environment 45 (3), 611-620.

Zhu, Y., Hinds, W.C., Krudysz, M., Kuhn, T., Froines, J., Sioutas, C., 2005. Penetration of freeway ultrafine particles into indoor environments. Aerosol Science 36, 303-322.

Table 1 – Maximum and minimum particle number distributions, in terms of lognormal functions parameter (mode, standard deviation, and total concentration), applied in the different microenvironments were the 25 activities were performed.
Activity identification numbers: Sleeping (1), Personal hygiene (2), Eating/drinking (3), Housework (4), Food and drink preparation/cleanup (5), Purchasing goods and services (6), Audio/visual media (7), No activity (8), Car (9), Bus (10), Walking or bicycle (11), Motorcycle (12), Grounds/animal care (13), Child care activities (14), Home maintenance + Household management (15), Games/hobbies/arts/crafts (16), Communication associated with recreation and leisure (17), Main job (non sedentary job) (18), Other job + job search (sedentary job) (19), Education activities + Attendance at educational courses (20), Homework/study/research (21), Domestic activities (22), Sport and outdoor activity (23), Voluntary work and care activities (24), Social and Community interaction (25).

Microenvironemnt (*activities*)	$Mode_{max}$ ($Mode_{min}$) nm	Standard deviation σ_{max} (σ_{min})	N_{max} (N_{min}) part. cm^{-3}	Our measurement survey data	Other references (average particle number concentration, part. cm^{-3})
Indoor evening & night *(1)*	55 (70)	2.0 (2.2)	8.0×10^3 (4.0×10^3)	Morawska *et al*., 2001; Morawska *et al*., 2003	Zhu *et al.*, 2005 (9.0×10^3)
Indoor day *(2, 4, 6, 7, 8, 14, 15, 16, 17, 20, 21, 22, 24)*	41 (48)	1.8 (2.0)	1.2×10^4 (8.0×10^3)	Morawska *et al*., 2001; Morawska *et al*., 2003; Morawska *et al*., 2009a	Fromme *et al*., 2007 (1.2×10^4)
Outdoor day *(13, 23, 25)*	35 (48)	1.7 (2.0)	1.5×10^4 (8.0×10^3)	Morawska *et al*., 2001; Morawska *et al*., 2002	Shi *et al*., 1999 (2×10^4); Mejìa *et al*., 2007 (1×10^4)
Cooking *(5)*	65 (70)	1.9 (2.0)	2.7×10^5 (4.0×10^4)	He *et al*., 2004	See and Balasubramanian, 2006 (7.7×10^5);
Eating *(3)*	95 (100)	1.7 (1.9)	1.0×10^5 (2.0×10^4)	He *et al*., 2004	Dennekamp *et al*., 2002 (6×10^4)
Working *(18, 19)*	35 (50)	1.8 (2.2)	8.0×10^4 (1.1×10^4)	Buonanno *et al*., 2011d Morawska *et al*., 2009b	Elihn and Berg, 2009 (1.0×10^5)
Pedestrian & bikes *(11, 12)*	30 (45)	1.7 (1.9)	9.0×10^4 (3.0×10^4)	Hitchins *et al.*, 2000; Morawska *et al*., 1999	Berghmans *et al*., 2008 (4×10^4); Kaur *et al*., 2007 (8×10^4)
Car & Buses *(9, 10)*	35 (50)	1.8 (2.0)	7.2×10^4 (2.5×10^4)	Hitchins *et al.*, 2000; Morawska *et al*., 1999	Kaur *et al*., 2007 (6×10^4)

Table 2 - Daily time activity patterns (min), normalized to 1440 min, and corresponding standard deviations for each age group and gender, by considering the 25 activities classified in eight microenvironments.
Activity identification numbers: Sleeping (1), Personal hygiene (2), Eating/drinking (3), Housework (4), Food and drink preparation/cleanup (5), Purchasing goods and services (6), Audio/visual media (7), No activity (8), Car (9), Bus (10), Walking or bicycle (11), Motorcycle (12), Grounds/animal care (13), Child care activities (14), Home maintenance + Household management (15), Games/hobbies/arts/crafts (16), Communication associated with recreation and leisure (17), Main job (non sedentary job) (18), Other job + job search (sedentary job) (19), Education activities + Attendance at educational courses (20), Homework/study/research (21), Domestic activities (22), Sport and outdoor activity (23), Voluntary work and care activities (24), Social and Community interaction (25).

	FEMALE				*MALE*			
Microenvironment (*activities*)	Age 15-18	Age 19-40	Age 41-65	Age >65	Age 15-18	Age 19-40	Age 41-65	Age >65
Indoor evening & night *(1)*	504±62	403±16	409±21	456±27	541±82	434±12	436±13	488±22
Indoor day *(2, 4, 6, 7, 8, 14, 15, 16, 17, 20, 21, 22, 24)*	741±187	729±81	677±86	717±97	678±207	572±57	558±52	664±76
Outdoor day *(13, 23, 25)*	57±34	42±23	56±25	74±30	65±38	45±23	57±25	98±35
Cooking *(5)*	14±2	46±2	64±4	78±5	8±1	20±1	26±1	49±2
Eating *(3)*	83±12	72±3	90±5	113±7	90±16	72±2	91±3	119±6
Working *(18, 19)*	32±20	130±7	129±8	3±2	47±30	264±9	244±8	19±12
Pedestrian & bikes *(11, 12)*	3±0	5±0	5±0	0	3±1	10±0	9±0	1±0
Car & Buses *(9, 10)*	5±1	9±0	8±0	0	6±1	18±1	16±1	3±0

Figure captions

Figure 1 - Average daily dose with the corresponding standard deviations as a function of age group and gender: a) alveolar and tracheobronchial-deposited particle number, b) alveolar and tracheobronchial-deposited surface area.

Figure 2 – Comparison between Italian and Australian case-study in terms of average daily dose (and corresponding standard deviations) as a function of age group and gender normalized to the air-tissue interface (alveolar surface area, m^2): alveolar-deposited particle number (part. m^{-2}), b) alveolar -deposited surface area (mm^2 m^{-2}).

Figure 3 - Contributions to daily activity patterns, average daily alveolar and tracheobronchial particle number and surface area deposited of the different human activities carried out by the age groups investigated.
Activity identification numbers: Sleeping (1), Personal hygiene (2), Eating/drinking (3), Housework (4), Food and drink preparation/cleanup (5), Purchasing goods and services (6), Audio/visual media (7), No activity (8), Car (9), Bus (10), Walking or bicycle (11), Motorcycle (12), Grounds/animal care (13), Child care activities (14), Home maintenance + Household management (15), Games/hobbies/arts/crafts (16), Communication associated with recreation and leisure (17), Main job (non sedentary job) (18), Other job + job search (sedentary job) (19), Education activities + Attendance at educational courses (20), Homework/study/research (21), Domestic activities (22), Sport and outdoor activity (23), Voluntary work and care activities (24), Social and Community interaction (25).

Figure 4 - Alveolar deposited particle number and surface area dose intensity received by the age groups investigated in the eight microenvironment: a) alveolar deposited particle number dose intensity; b) alveolar deposited particle surface area dose intensity.
Activity identification numbers: Sleeping (1), Personal hygiene (2), Eating/drinking (3), Housework (4), Food and drink preparation/cleanup (5), Purchasing goods and services (6), Audio/visual media (7), No activity (8), Car (9), Bus (10), Walking or bicycle (11), Motorcycle (12), Grounds/animal care (13), Child care activities (14), Home maintenance + Household management (15), Games/hobbies/arts/crafts (16), Communication associated with recreation and leisure (17), Main job (non sedentary job) (18), Other job + job search (sedentary job) (19), Education activities + Attendance at educational courses (20), Homework/study/research (21), Domestic activities (22), Sport and outdoor activity (23), Voluntary work and care activities (24), Social and Community interaction (25).