Daily submicron particle doses received by populations living in different low- and middle-income countries

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Abstract

In the present study, the daily dose in terms of particle surface area received by citizens living in different low- and middle-income countries, characterized by different lifestyles, habits, and climates, was evaluated. The level of exposure to submicron particles and the dose received by the populations of Accra (Ghana), Cairo (Egypt), Florianopolis (Brazil), and Nur-Sultan (Kazakhstan) were analyzed. A direct exposure assessment approach was adopted to measure the submicron particle concentration levels of volunteers at a personal scale during their daily activities. Non-smoking adult volunteers performing non-industrial jobs were considered. Exposure data were combined with time-activity pattern data (characteristic of each population) and the inhalation rates to estimate the daily dose in terms of particle surface area.

The received dose of the populations under investigation varied from 450 mm^2 (Florianopolis, Brazil) to 1300 mm^2 (Cairo, Egypt). This work highlights the different contributions of the microenvironments to the daily dose with respect to high-income western populations. It was evident that the contribution of the Cooking & Eating microenvironment to the total exposure (which was previously proven to be one of the main exposure routes for western populations) was only 8%-14% for low- and middle-income populations. In contrast, significant contributions were estimated for Outdoor day and Transport microenvironments (up to 20% for Cairo, Egypt) and the Sleeping & Resting microenvironment (up to 28% for Accra, Ghana), highlighting the effects of different site-specific lifestyles (e.g. time-activity patterns), habits, socioeconomic conditions, climates, and outdoor air quality.

Keywords: airborne particles; dose; lung-deposited surface area; personal monitoring; submicron particles; ultrafine particles.

Capsule: A direct exposure assessment approach was adopted to measure the particle concentrations whose people is exposed to and to estimate the dose of sub-micron particles received by people living in low and middle-income countries. The contribution of the microenvironments and lifestyles on the total daily dose was assessed.

1 Introduction

Several scientific studies reported a relationship between inhalation (and consequent deposition in the respiratory tract) of airborne particles and adverse effects for human health, including respiratory diseases and inflammation (Schmid et al., 2009), cardiovascular diseases (Buteau & Goldberg, 2016), diabetes (Brook et al., 2008), higher systolic blood pressure and pulse pressure (Auchincloss et al., 2008), decreased cognitive function (Power et al., 2011), heart rate increase (Rizza et al., 2019), changes in the brain wave pattern (Naseri et al., 2019), and lung cancer (Beelen et al., 2014; International Agency for Research on Cancer, 2013). Recently, the scientific community has shifted its interest from super-micrometric particles (characterized in terms of the mass concentrations of particles smaller than 10 μm and 2.5 μm, i.e. PM_{10} and $PM_{2.5}$, respectively) to submicron and ultrafine particles (UFPs, particles smaller than 100 nm), which are usually characterized in terms of particle number and surface area concentrations instead of mass concentration (Franck et al., 2011; Giechaskiel et al., 2009; Kumar et al., 2014). In particular, the surface area of the particles deposited in the lungs was recognized the most appropriate aerosol metrics when evaluating the effect of UFPs on human health (Sager & Castranova, 2009; Schmid & Stoeger, 2016; Stoeger et al., 2006).

Nonetheless, particle-phase pollutants and air quality standards worldwide are still defined in terms of outdoor PM_{10} and $PM_{2.5}$ levels; moreover, the outdoor sampling sites are limited to a certain number of fixed sampling points (FSPs), then not representing the effective citizen exposure to PM fractions due to the lacking of proper links to climate or population lifestyle (Buonanno et al., 2010; European Parliament and Council of the European Union, 2008; Rizza et al., 2017). Moreover, due to the different dynamics (e.g. dilution, deposition) and sources among supermicron and submicron particles, the measurements of PM fractions through FSPs cannot be considered proxies for the exposure to submicron and ultrafine particles (Kaur et al., 2005; Kumar et al., 2011; Neft et al., 2016). Additionally, the outdoor concentration levels are often uncorrelated with the indoor ones; thus, exposure assessment based on outdoor FSP measurements (i.e. city scale or outdoor scale approaches) could significantly underestimate the exposure in an indoor environment, which represents the environment where the population spends most of the day (Scungio et al., 2020). Therefore, to obtain a better representativeness of the complete human exposure to submicron and ultrafine particle measurements at a personal scale, personal monitoring approaches should be adopted (Pacitto et al., 2020; Scungio et al., 2020).

Along with exposure data, information on the sort of activity is additionally needed to estimate the inhalation and consequent deposition of particles in several regions of the lungs (International Commission on Radiological Protection, 1994) as well as the time-activity pattern data (i.e. time spent in each indoor or outdoor environment). Indeed, as shown in previous studies, people's different lifestyles lead to significantly different exposures to airborne particles (Bekö et al., 2015; Pacitto et al., 2018; Schweizer et al., 2006). As an example, in a previous study the daily dose received by different high-income western populations was estimated applying a direct exposure assessment approach, i.e. characterizing the exposure to airborne particles through personal monitoring, then evaluating the daily dose received by the typical population whose time-activity pattern is known. The study highlighted significant differences among the five western world populations investigated in terms of the daily dose received, highlighting the influence of the lifestyle (e.g. massive use of particle sources indoors as well as outdoors) and ventilation of the indoor environment (e.g. widespread use of mechanical ventilation systems) (Pacitto et al., 2018). Thus, previous studies opened questions on the effect of lifestyle and geographical location (e.g. climate, outdoor concentration) on airborne particle doses received by the populations. Nonetheless, the amount of studies on this subject are still limited and, typically, they consider populations in developed and high-income countries characterized by a stronger sensitivity towards air quality topics (Fernández-Iriarte et al., 2020; Moreno et al., 2019; Pacitto et al., 2019; Scungio, Rizza, Stabile, Morawska, & Buonanno, 2020; Tomassetti et al., 2020). In contrast, in low- and middle-income countries the race for industrialization tends to overshadow air quality-related aspects, such as the utilization of highly emitting cooking fuels and fewer efficient vehicles (Mehta et al., 2013; Puzzolo et al., 2019). Therefore, the evaluation of the exposure to submicron particles and the daily dose in these countries is crucial because it could help in detecting the principal activities and environments contributing to the daily dose of the populations under investigation. This might lead to more detailed knowledge of the factors that contribute to possible adverse health effects and outcomes and of related prevention or mitigation strategies that may be adopted.

To this end, in the present work we carried out personal exposure field campaigns in four major cities in low- and middle-income countries: Greater Cairo (Egypt), Greater Accra (Ghana), Florianopolis (Brazil), and Nur-Sultan (Kazakhstan). In particular, a direct UFP exposure assessment approach was applied to estimate the daily dose received by the typical populations of those cities in relation to the activity patterns and inhalation rates typical of those populations. The obtained data were compared to those of a previous work focused on the UFP exposure of the populations of western and high-income countries. The main influence parameters affecting the dose of the different populations were determined and discussed.

2 Methodology

2.1 Study area

Measurements were carried out in Greater Cairo (Egypt), Greater Accra (Ghana), Florianopolis (Brazil), and Nur-Sultan (Kazakhstan). The choice of the cities was based on the existing research collaboration network capable of supporting the study. A brief description of the cities under investigation is provided below to characterize their climatic conditions and main indoor and outdoor airborne particle sources. Indeed, the climate and location of the cities investigated affect the outdoor particle concentration levels and the resulting contribution to the populations' daily dose. Because much of the daily dose is typically contributed to by indoor environments, information on possible indoor sources (Morawska et al., 2013; Scungio et al., 2017) and building ventilation (Bakó-Biró et al., 2012; Stabile et al., 2017; Stephens & Siegel, 2012) are useful as they can affect the exposures and doses of the people living/residing therein (Buonanno et al., 2015b).

Greater Cairo (Cairo, Giza and Shoubra El-Kheima and their urban agglomeration) is the largest urban concentration in Africa and the Middle-East (surface area of about 1700 km^2) with approximately 20 million permanent residents; it hosts various industrial complexes and is characterized by intensive vehicular traffic with almost 3.2 million cars (CAPMAS, 2018). Similar to most of the Egyptian terrains, Greater Cairo's climate is classified as a hot desert climate (Köppen-Geiger classification) and is thus characterized by warm winters (14–22 °C on average), hot summers (20–35 °C on average), and sparse rainfall (Peel et al., 2007). The prevailing wind direction is northwesterly, although southern wind storms loaded with Saharan dust are frequent during spring. Both natural and anthropogenic sources contribute to the very high airborne particulate matter concentrations in Greater Cairo, with annual average concentrations of 161 $\mu g\ m^{-3}$ and 71 $\mu g\ m^{-3}$ for PM_{10} and $PM_{2.5}$, respectively (EEAA, 2016). The main indoor particle source is fossil-fuel combustion (including coal, natural gas, propane, and kerosene) for cooking and heating.

The Greater Accra region is located in the Republic of Ghana on the West African coast, with a surface area of about 3245 km^2 and a population of approximately 4 million permanent residents. The climate is classified as a tropical savanna climate (Köppen-Geiger classification) with an annual average rainfall of 730 mm and very little variation in temperature throughout the year (25.9–29.6 °C). The main anthropogenic sources of atmospheric air pollution in the city include vehicle emissions and combustion activities, which account for over 70% of outdoor air pollution in Accra (Arku et al., 2015), and the high percentage of old vehicles, characterized by less fuel-efficient engines, used in the city. A further outdoor source is the widespread use of biomass fuels (firewood and charcoal) for cooking in underprivileged communities. For indoor air quality, cooking and other combustion activities, such as burning of anti-mosquito coils in bedrooms at night, represent the main indoor sources; indeed, several people living in low-income countries burn coils at night to expel mosquitos (Nyarku et al., 2019).

Florianopolis is the second largest urban concentration in Santa Catarina State, located in the South of Brazil, with a surface area of 675 km^2 and a population of about 500,000 people (IBGE, 2018). The climate of Florianopolis is humid subtropical (Köppen-Geiger classification), with annual average temperature and precipitation of 20.1 °C and 1462 mm, respectively. The air quality in Florianopolis complies with the permissible limits for PM_{10}; the average concentration of PM_{10} during the period 2011–2016 was 24 $\mu g\ m^{-3}$ (Vasques et al., 2017). The main outdoor PM source is vehicular traffic since Santa Catarina has the highest vehicle density in Brazil (49.8 cars km^{-2}).

Nur-Sultan city is the capital of the Republic of Kazakhstan and is located in the center of the country and at the center of Central Asia; it has a surface area of 722 km^2 and 1 million citizens.

The climate of Nur-Sultan is humid continental (Köppen climate classification) with an average annual temperature of 3.5 °C. Indeed, Nur-Sultan has an extreme continental climate with warm summers (featuring occasional brief rain showers) and long, very cold, dry winters. The main outdoor PM sources are road traffic and two power plants, due to the widespread consumption of coal as a fuel and energy source.

2.2 Study design

To characterize and compare the submicron particle daily doses received by the populations in four low- and middle-income countries, we carried out an experimental campaign following a direct exposure assessment approach, i.e. measuring the exposure to airborne particle concentrations at a personal scale by means of handheld particle counters (Pacitto et al., 2018; Pacitto et al., 2020; Wallace & Ott, 2011). The study was limited to the non-smoking population and non-industrial working environments; the smoking population should be analyzed separately due to the large dose they typically receive, as should people working in industrial jobs characterized by specific particle sources (Fuoco et al., 2017). Thus, the volunteers considered in this study, to characterize the different environments in terms of submicron particle concentrations, were all adults (both male and female), office workers, and non-smokers.

To estimate the daily dose of submicron airborne particles received by the populations living in the cities under investigation, the following steps were applied:

- identification of the typical time-activity patterns characteristic of citizens living in each country;
- measurement of the concentrations of particle numbers and lung-deposited particle surface area to which citizens are exposed in different environments and during different activities;
- estimation of the daily dose received by the typical population living in the investigated cities.

2.2.1 Population time-activity patterns under investigation

The typical time-activity patterns characteristic of citizens living in the investigated cities were obtained from national human activity pattern surveys performed by national statistics institutes and/or research studies taking into account people living both in urban areas and country sites (Central Agency for Public Mobilization and Statistics of Egyptian Arabic Republic, 2016; 2017; Ghana Statistical Service, 2012; 2014; 2015) except for the Brazilian population. In particular, time-activity patterns of people from 19 to 65 years old were considered. A descriptive exploratory study was performed for Brazilian people due to the lack of information about the time-activity pattern characteristics of this population. Data were collected from a non-probabilistic sample by quotas and convenience in people living in the metropolitan region of Florianopolis. It was not possible to develop an epidemiological study or a probabilistic sample of the entire population of the area due to the COVID-19 pandemic. However, the significant number of participating subjects (n = 435) can be considered acceptable as a sample of the general population. The questionnaire was filled out through the Google form platform. The data were analyzed using IBM SPSS Statistics version 20.0. Data were analyzed with descriptive statistics such as mean and standard deviation.

2.2.2 Measurement of the exposure to submicron particle concentrations

The exposure to airborne particles in each environment of the four cities was obtained by performing mobile measurements of particle number (PN) concentrations, average particle sizes (D_p), and lung-deposited surface area (LDSA) concentrations through direct measurements carried out with hand-held diffusion charger particle counters. The experimental campaigns were carried out from October 2017 to December 2017 in Accra (Ghana), from December 2018 to March 2019 in Cairo (Egypt), from December 2019 to March 2020 in Florianopolis (Brazil), and from March 2020 to June 2020 in Nur-Sultan (Kazakhstan). Details of the meteoclimatic conditions in the four cities during the experimental campaigns are reported in Table 1.

To obtain a significant amount of data for each environment or activity, 60 volunteers (15 for each city) were selected. The volunteers, both males and females aged from 25 to 55 years old, lived and worked in the urban area of the city. Personal particle counters were worn by volunteers for 3 days; therefore, each volunteer contributed continuous measurements for 3 days. When volunteers were at home/office (e.g. working, studying, sleeping, etc.), the instrument was left on a close desk. In addition, the volunteers had to fill out an activity diary to take note about (i) place, (ii) time, and (iii) kind of activity, to relate the particle exposure values to the activity and the specific environments. The authors highlight that the 15 volunteers for each city were chosen in order to cover a wide range of activities and to better characterize the concentrations in the different environments, following the methodology already used in the previous study by Pacitto et al., (2018). For example, different measurements during cooking activities allow the effects of different cooking practices on the exposure levels to airborne particles to be included (such as the type of food, cooking, and stove). Additionally, several measurements in the transport environments allow different transport modes (such as metro, train, car) to be taken into account. The authors point out, that in the present study we were not interested in the volunteer per se, the volunteers just acted as mobile platforms allowing moving the instruments across the different environments. Thus, we are not really interested in completely describe the volunteers, we just avoided to enroll volunteers living in the same house or belonging to the same groups (i.e. family, friend, age, job), in order to avoid obtaining exposure data only for a very specific sub-population.

2.2.3 The daily dose of the population

The doses of submicron particles received by the population were calculated from the typical exposure to lung-deposited surface area concentrations (obtained from the experimental analysis described in section 2.2.2) and time-activity patterns. In particular, the total surface area dose ($\delta_{SA,j}$) for the j-th activity was obtained by applying the following equation (Buonanno et al., 2011; Buonanno et al., 2012):

$$\delta_{SA,j} = \boldsymbol{IR_j} \cdot \boldsymbol{LDSA_j} \cdot \boldsymbol{T_j} \qquad \textbf{(1)}$$

where IRj (m^3 h^{-1}) is the inhalation rate of the j-th activity (which depends on the age and activity level) (Buonanno et al., 2012), T_j is the time spent on each activity (as a function of the age and sex), and $LDSA_j$ is the concentration in terms of lung-deposited surface area of submicron particles during the j-activity. The information on time-activity patterns obtained from the activity diary was not used to calculate the dose because this was specific to the volunteers under investigation. The time-activity diary was simply used to relate the particle exposure values to the environments/activities in order to characterize them in terms of the particle concentration of each environment they resided in and the activities they performed. The dose $\delta_{SA,j}$ estimated through eq. (1) represents the median dose received during that activity as it was calculated considering the median LDSA concentrations and the average time.

The activities performed by the population, obtained on the basis of the typical time-activity patterns, were grouped into six main microenvironments, as reported in Table 2. The dose for each microenvironment was obtained by summing up the median doses evaluated for each activity; similarly, the daily dose was obtained as the sum of the doses received in each microenvironment. To compare the doses in different microenvironments, the dose intensity ratio (i.e. the ratio between the daily dose fraction and the daily time fraction characteristics of each activity) was also evaluated (Buonanno et al., 2014; Pacitto et al., 2018).

2.2.4 Comparison with high-income western countries

In order to compare the dose received by the low- and middle-income populations to high-income western countries we used the data reported in our abovementioned previous paper (Pacitto et al., 2018). In that paper, we applied the same methodology and instrumentation here shown to gather exposure data for five different western populations. In particular, we performed the experimental analyses in Barcelona (Spain), Cassino (Italy), Guilford (United Kingdom), Brisbane (Australia), and Lund (Sweden). For detailed information regarding the climate, location, and anthropogenic sources of these five cities please refer to Pacitto et al., (2018). For the sake of brevity, here we just summarize the measurement periods of the experimental campaigns, as they may affect the people exposure. In particular, measurements in Barcelona, Cassino, Guilford, Brisbane, and Lund were performed on Oct-Dec 2015 (average temperature and relative humidity of 18 °C and 73%), Apr-June 2016 (17 °C, 74%), Aug-Nov 2016 (17 °C, 81%), Jun-Aug 2016 (27 °C, 79%), and Sept-Dec 2016 (10 °C, 78%), respectively. A further aspect to be highlighted, as it may help in explaining the indoor exposure levels, is the widespread use of mechanical ventilation systems in Lund.

The experimental analyses in the five high income countries were carried out with the support of 15 volunteers (for each city) as we did in the current study adopting the same criteria for their enrollment. Analogously, also in the previous experimental analysis, the volunteers were asked to take note about place, time, and kind of activity in an activity diary.

The exposure data post-processing and dose estimates were carried out on the basis of the methodology reported in the present paper.

2.3 Instrumentation and quality assurance

Particle number (PN) concentrations, lung-deposited surface area (LDSA) concentrations and average particle sizes (D_p) were measured through three diffusion charger particle counters:

- the Aerasense NanoTracer XP (Oxility, partner of Royal Philips Electronics), which measures PN and LDSA concentrations and D_p in the range 10–300 nm with 10 seconds sampling time, was used in the experimental analyses performed in Ghana;
- the DiscMini (Testo), which measures PN and LDSA concentrations and D_p in the range 10–700 nm with 1 second sampling time, was used in the experimental analyses performed in Egypt and Brazil;
- the Partector 2 (Naneos Particle Solutions Gmbh), which measures PN and LDSA concentrations and the D_p in the range 10–300 nm with 1 second sampling time, was adopted in the experimental analyses performed in Kazakhstan.

The operating principle of the instruments is based on the diffusion charging technique. Specifically, the sampled aerosol is charged in a positive unipolar diffusion charger imparting an average known charge on the particles that is approximately proportional to the particle diameter of the aerosol. The number of charges, and thus the number of particles, is then detected by an electrometer (Buonanno et al., 2014; Fierz et al., 2011; Marra et al., 2010). Since over 99% of total PN concentration in urban environments is contributed by particles below 300 nm in diameter (Goel & Kumar, 2014; Kumar et al., 2013), all the instruments were able to measure total particle numbers despite their different ranges for particle diameters. On the basis of the measured values of PN concentration and D_p, the LDSA concentration was calculated by means of built-in semi-empirical correlation as reported and discussed in previous papers (Marra et al., 2010; Pacitto et al., 2018; Stabile et al., 2015).

2.3.1 Instrument intercomparison

Calibrations were performed before and after the experimental campaigns. In particular, the NanoTracer, DiscMini, and Naneos Partector 2 were compared to a CPC (model 3775, TSI Inc.) and SMPS system (model 3936, TSI Inc.) in terms of particle number concentration and particle size, respectively, before and after each experimental campaign. Calibrations were carried out at the European Accredited Laboratory of Industrial Measurements (LaMI) of the University of Cassino and Southern Lazio (Italy) while placed in a 150 m^3 room, with an ordinary mechanical ventilation system guaranteeing constant thermo-hygrometric conditions (20 ± 2 °C and 50 ± 5% relative humidity). Comparisons were performed for two different aerosols: aged indoor aerosol and freshly emitted aerosol produced by incense burning. Tests were performed by measuring for 2 h simultaneously with the diffusion charger monitors (Nanotracer, DiscMini or Naneos Partector 2), CPC 3775, and SMPS 3936. The average correction factors, in terms of particle number concentration, obtained by averaging the two aerosols investigated before and after the experimental campaign, were applied as correction factors for the entire campaigns.

2.3.2 Statistical analysis

The exposure levels to particle number and lung deposited surface area concentrations in the different microenvironments were checked in order to determine whether they were statistically different or not. In particular, we compared the nine cities, microenvironment by microenvironment; thus, nine distinct statistical analyses (one for each microenvironment) were carried out for particle number and lung deposited surface area concentrations, respectively. To this end, preliminary normality tests (Shapiro-Wilk test) were performed to check the statistical distribution of the data. Since the data did not meet Gaussian distributions, non-parametric tests and further post-hoc tests, the Kruskal-Wallis test (Kruskal & Wallis, 1952), were conducted for each microenvironment. The statistically significant result was referred to a significance level of 99% in order to reduce the probability of type I error (i.e. the data were assessed as statistical different for *p*-value lower than α=0.01). The authors point out that the population were tested just for one parameter (particle number or lung deposited surface area concentrations separately, thus no adjustments of statistical inference (type I error) were needed (Chen et al., 2017).

3 Results and Discussions

3.1 Time-activity pattern

Data on the time-activity patterns of the populations under investigation, and the contribution of the individual microenvironment for the whole day as a function of sex for the four countries, are shown in Table 3. The data clearly demonstrate that all populations, both males and females, spend the largest time fraction indoors (in a range from 84% to 96%). This finding matches with the results found in our previous studies on high-income western populations where, whatever the population (Italian, Australian, Spanish, English and Swedish) and the sex, indoor environments were those where people spend the largest daily time fraction, ranging from 88% to 95% of their time. Cooking & Eating, recognized as the most significant activities in terms of exposure (Buonanno et al., 2015b; Buonanno et al., 2017), presented here jointly a contribution ranging from 4.0% to 10.7% – lower than the range found in Pacitto et al. (2018) (from 13% to 26%) for western populations. In fact, as shown in Table 3, western populations spend more time in the Cooking & Eating microenvironment than the Egyptian, Brazilian and Ghanaian populations (but not the Kazakhstan population); as an example, the time spent in the Cooking & Eating microenvironment by Spanish people was almost three-fold that spent by Egyptian people.

Another microenvironment typically recognized as critical in terms of people exposure is the Transport microenvironment (Scungio et al., 2015; Scungio et al., 2013; Stabile et al., 2015); nonetheless, the exposure times in such microenvironments were quite short (as already recognized for western populations in our previous paper) and did not vary greatly amongst the populations investigated: they ranged from 4.3% to 6.9% (except for Kazakhstan females who spend 2.8% of the day in such microenvironments).

The Sleeping & Resting microenvironment, as expected, accounted for a third of the day; in particular, the time fraction ranges roughly from 30% (Kazakhstan females) to 40% (Egyptian females), which is quite in line with the western population. The Indoor day microenvironment, as seen in Table 3, displays huge variability as a function of nationality; in fact, the contribution of this microenvironment to the whole day varies from 11.4% to 22.1%. Comparing the Indoor day time fractions presented here to those obtained for western countries by Pacitto et al. (2018) (and not reported here for the sake of brevity), it can clearly be seen that high-income western populations spend more time in indoor microenvironments than the low- and middle-income populations analyzed here.

Finally, in the Outdoor day microenvironment, there is an evident difference between the Kazakhstan population and the other populations. In fact, the contribution to the total daily time for the Kazakhstan population varies between 1.7% and 2.6%, likely due to the severe meteoclimatic conditions characteristics of the country; whereas for the other populations the contribution is much higher (up to 10%) and also higher than those characteristic of western populations (4%-8%).

3.2 Concentration levels of submicron particles in the investigated cities

Figure 1 and Table 4 report statistics of submicron particles in terms of (i) PN concentration, (ii) LDSA concentration, and (iii) average particle size as a function of the microenvironments for the investigated populations. Moreover, data of the five western countries considered in our previous study were also reported (and are re-analyzed here accordingly) in order to perform comparisons amongst the populations.

The data from western countries, discussed in detail in our previous paper and here just summarized for the sake of brevity, highlighted that: (i) the highest PN concentrations are typically measured in the Cooking & Eating microenvironment (median values in the range 0.16–3.05 × 10^5 part. cm^{-3}), (ii) the exposure in Traffic and Outdoor day microenvironments are mostly lower than that experienced in other indoor activities, including the Indoor day microenvironment, (iii) the lowest concentrations occur in the Sleeping microenvironment (median values in the range 0.8–1.2 × 10^4 part. cm^{-3}), and (iv) the widespread use of mechanical ventilation systems indoors, including homes (see Lund exposure data, Table 4), can strongly reduce (by roughly one order of magnitude) the exposure to submicron particle concentrations in indoor environments and activities.

Exposure data characteristic of the populations investigated in the present study reveal significant differences with respect to the high-income western countries. The first clear finding concerns the comparison between the Cooking & Eating and Transportation microenvironments. Indeed, in the four cities analyzed, the exposure levels in these two microenvironments were roughly comparable; for Egyptian and Kazakhstani people, the PN and LDSA concentrations in the Transport microenvironment were even higher than in Cooking & Eating. As an example, median values of 1.73×10^5 part. cm^{-3} and 2.88×10^2 μm^2 cm^{-3} were measured for Egyptians, likely due to the intensive vehicular traffic and the particular meteoclimatic condition (e.g. no rain). The exposure levels (in terms of both PN and LDSA) in the Transport microenvironments of the Egyptian and Kazakhstani populations were also larger than those in the western populations. Similarly, in these two cities, the exposure levels in the Outdoor day microenvironment (in terms of both PN and LDSA) were significantly larger than those experienced in western countries, with median values of up to 5×10^4 part. cm^{-3}/ 1×10^2 μm^2 cm^{-3} for the Egyptian population. These data emphasize the important role of the outdoor air quality in the overall exposure of a population. Moreover, poor outdoor air quality can also affect indoor microenvironments where no other particle sources are typically in use. As an example, the data in Figure 1 and Table 4 clearly highlight that the exposure to submicron particles in the Working and Sleeping & Resting microenvironments in Cairo and Nur-Sultan reflects the outdoor conditions (likely due to particle penetration), thus resulting in concentrations typically higher than those received in the western countries previously investigated.

For the Sleeping & Resting microenvironment, high particle concentrations were measured for the population living in Accra (Ghana) (median value of 4.18×10^4 part. cm^{-3} and 9.45×10^1 μm^2 cm^{-3}). This is due to the common use of anti-mosquito products (e.g. mosquito coils) during the night in Ghana (Nyarku et al., 2019), as they have gained widespread popularity in malaria-endemic countries (Hogarh et al., 2016). This could also partly explain the higher concentrations in the Indoor day microenvironment of Ghana in relation to Egypt and Kazakhstan.

As mentioned above, the exposure in the Cooking & Eating microenvironment, which was the most critical for western countries, was mostly lower or similar to those measured in other microenvironments for the four populations analyzed in the present study. Several reasons could explain this finding, including the (unknown) emission factors of cooking activities typically performed in such countries (likely related to the type of food, cooking activity, fuel, and stoves used). Nonetheless, a further reason could be strictly related to the climatic conditions; indeed, higher outdoor temperatures would lead to better airing of the homes than in the western populations (whose data were mostly collected in periods of lower temperature), thus leading to faster particle concentration decay.

The results for Florianopolis were somewhat different from the other three populations investigated. Indeed, the concentrations were generally lower than those measured in the other three cities; indeed, the highest exposure level was measured in the Cooking & Eating microenvironment, which was actually lower than those characteristics of the western cities previously analyzed (median PN and LDSA concentrations were 1.94×10^4 part. cm^{-3} and 4.10×10^1 μm^2 cm^{-3}). This could be partly due to climatic conditions (once again the average outdoor temperature during the campaign was significantly higher than those occurring during the western population characterization) but also to the socioeconomic conditions of Santa Catarina. Although Brazil is not considered a high-income country, the state of Santa Catarina is amongst the richest and most developed areas of the country (www.atlasbrasil.org.br); therefore, no site-specific air quality issues typical of the other low- and middle-income countries typically occur. These factors could explain the lower concentrations in both indoor and outdoor environments reported in Figure 1 and Table 4.

3.3 Total daily dose received by the population

Table 5 shows the values of particle surface area doses received by the populations of the cities investigated, and of the western cities reported in our previous paper, as obtained by combining (i) exposure data (summarized in section 3.2), (ii) time-activity patterns of the typical population (summarized in section 3.1), and (iii) inhalation rates characteristic of the age and activity performed. In particular, Table 5 reports the particle surface area doses (mm^2) as a function of population, sex, and microenvironment. Additionally, the contributions to the daily dose (%) and dose intensity ratios (mm^2 min^{-1}) for each microenvironment are also reported.

The dose evaluated for western populations, as discussed in detail in our previous paper (Pacitto et al., 2018) and summarized here for the sake of brevity, highlighted that: (i) particle surface area doses were significantly larger than 1000 mm^2 for people living in Cassino (Italy) and Guilford (UK), around 700 mm^2 for those residing in Barcelona (Spain) and Brisbane (Australia), and around 100 mm^2 for Lund inhabitants (Sweden), (ii) the higher doses estimated for Cassino (Italy) and Guilford (UK) are due to the higher contribution of the Cooking & Eating microenvironment; whereas the lower doses estimated for the Lund population are due to the widespread use of mechanical ventilation systems, (iii) in general, the main contributions to the daily dose are due to the Cooking & Eating and Indoor day microenvironments (from 58% to 90% of the total daily dose) for all the investigated western populations, and (iv) the total daily dose of the western populations is not greatly affected by the outdoor air quality, indeed the contribution of the Outdoor day and Transport microenvironments is generally negligible.

For the low- and middle-income populations investigated, the total doses received vary over a wide range – approximately 1300 mm^2 for Cairo (Egypt), 1100 mm^2 for Accra (Ghana), 750 mm^2 for Nur-Sultan (Kazakhstan), and 450 mm^2 for Florianopolis (Brazil). No significant differences were found between males and females in terms of total daily dose, although some differences were recognized in some specific microenvironments due to different time-activity patterns characteristic of females and males. As an example, as was also recognized for western populations, women typically receive higher doses in the Cooking & Eating microenvironment and lower doses in the Transport and Working microenvironments.

Apart from the absolute dose values, an interesting aspect is the different contribution of each microenvironment to the total daily dose with respect to the western populations previously analyzed. The most relevant difference is related to the Cooking & Eating microenvironment, for which the contribution to the total daily dose ranges from 8% to 14%, which is much lower than those evaluated for western populations (up to > 50) due to the shorter time spent in this microenvironment (see section 3.1) and, in some cases, to the lower concentrations measured therein as discussed in section 3.2 (e.g. the possible effect of different cooking habits and of the favorable climatic conditions supporting home airing). In fact, the contribution of the Cooking & Eating microenvironment was quite similar to that of the Transportation microenvironment. In particular, the median dose received by residents of Cairo during transport activities was even larger than 200 mm^2 (contributing up to 20% of the daily dose), mostly due to the larger concentrations of people who are exposed during Transportation (Figure 1), as confirmed by the highest dose intensity ratio amongst the population analyzed (2.96 mm^2 min^{-1}). A high dose intensity ratio in the Transportation microenvironment (> 1 mm^2 min^{-1}) was also recognized in Nur-Sultan (Kazakhstan) due to the abovementioned high concentrations, although the shorter time spent performing such activities led to a limited dose contribution.

In section 3.2 we highlighted the role of the outdoor air quality in the overall exposure of residents of Cairo and Nur-Sultan, which also affects some indoor microenvironments where no other particle sources are typically adopted. This can also be partly recognized in terms of doses: people in Cairo also received significant doses in the Sleeping & Resting microenvironment (about 200 mm^2), the Outdoor day microenvironment (> 200 mm^2), and the Working microenvironment (up to > 300 mm^2). A similar situation was recognized for people in Nur-Sultan, except for the Outdoor day contribution which was reduced by the short time spent outdoors. The absolute doses received in the Indoor day microenvironment were lower than 200 mm^2 (with the exception of Accra) and lower than the typical doses received by western populations (once again the authors point out that Lund should be dealt with separately due to the widespread adoption of ventilation systems). This is mainly due to the shorter time spent indoors in low- and middle-income countries in comparison with the high-income western populations (section 3.1). As mentioned above, the Accra (Ghana) situation is quite different; indeed, the doses received both in the Sleeping & Resting (about 300 mm^2) and Indoor day (> 400 mm^2) microenvironments are significantly larger than those received by the other low- and middle-income populations. This is due to high exposure related to the use of anti-mosquito products indoors. The dose fraction received by the Accra population in these two microenvironments is roughly 70%, whereas the contribution of each of the other microenvironments is lower than 10%.

Finally, for the Florianopolis population, the above-discussed low exposure in all the microenvironments (likely related to both favorable climatic conditions and good outdoor air quality) resulted in very low absolute dose values both in indoor- and outdoor-related microenvironments.

Summarizing, the data shown provide an important insight into the exposure to submicron particles and the related dose received by non-western populations that are characterized by different lifestyles, habits, socioeconomic conditions, climates, and outdoor air quality. The data revealed that, despite their higher air quality awareness and socioeconomic status, populations in some western countries receive particle doses larger than non-western populations. This is strongly related to the time spent indoors and to the adoption of inadequate ventilation practices. In contrast, in the warmer low- and middle-income countries analyzed in this study, where the populations spend less time indoors and home airing is likely allowed by favorable climatic conditions, the indoor contribution is reduced. Low- and middle-income countries present their own site-specific concerns; for example, the dose of some populations is significantly affected by outdoor air quality and transport microenvironments, and the use of anti-mosquito products in Accra (Ghana) highlighted an unpredicted huge contribution to the night time exposure dose. Thus, the dose data provided here importantly highlight some critical exposures not easily recognizable through typical outdoor air quality measurements, and thus provide the opportunity to search for solutions. Additionally, dose data could be combined with particle chemical composition data to perform a-priori estimates of the lung cancer risk of the population as performed in our previous paper on the Italian population (Buonanno et al., 2015a).

In order to properly use the data here shown the authors want to point out some limitations of the study that should be consider when generalizing the results or transferring them to other contexts. Since the study aims at providing a population-based dose (i.e. a dose characteristics of the entire population), a key question is “how the concentrations measured in the experimental campaigns are representative of the typical exposures of the populations?” We tried to cope with this problem enrolling volunteers with different habits in order to obtain exposure data in very different situations, microenvironment by microenvironment; nonetheless, no one knows if all the possible exposure situations were covered. This critical aspect could have minimized enrolling a huge number of volunteers, but this would have been not workable for both practical and economic reasons. Further aspects to be contemplated are the possible effects on the exposures of (i) the urban development (e.g. the outdoor exposure in small towns could be different from main cities), and (ii) the season (colder or warmer periods would have increased or reduced the exposure in some microenvironments). These critical aspects related to the selection of a representative sample should be handled in future studies along with further technical issues, e.g. the uncertainty of the portable counters, in order to provide the uncertainty budget of the dose values. Nonetheless, such limitations do not undermine the importance and significance of the findings here obtained, since for the very first time the particle dose received by several populations were determined (including non-western world countries) and the contribution of each microenvironment, habit, lifestyle, and climate were highlighted.

Conclusions

In the present study, the daily doses in terms of particle surface area received by four low- and middle-income populations were assessed and compared to those characteristics of high-income western populations obtained in our previous study. In particular, the total daily doses received by populations living in Greater Cairo (Egypt), Greater Accra (Ghana), Florianopolis (Brazil), and Nur-Sultan (Kazakhstan) were estimated based on submicron particle concentration measurements at a personal scale (i.e. direct exposure assessment method), time-activity patterns (obtained from national statistics institutes) and inhalation rates. The contribution of the main microenvironments was also investigated.

The total doses received by the low- and middle-income populations here investigated were roughly 1300 mm^2 for Egyptians, 1100 mm^2 for Ghanaians, 750 mm^2 for Kazakhstanis, and 450 mm^2 for Brazilians. The different concentration levels with respect to the western populations, along with different time-activity patterns (e.g. generally low- and middle-income populations spend less time indoors), resulted in different contributions of the microenvironments to the daily dose. Indeed, the Cooking & Eating microenvironment contributed just 8%–14% to the daily dose for the four populations analyzed (for western populations it contributed up to > 50%), whereas the outdoor-related microenvironments increased their contributions (e.g. the Transportation microenvironment reached up to 20% for Egyptians). Finally, in contrast with the other populations, the main contribution to the total daily dose for Ghanaians came from the Sleeping & Resting and Indoor day microenvironments, possibly because of the use of anti-mosquito products indoors.

To summarize, the different dose values and relative contributions amongst the populations analyzed clearly highlight the effect of the lifestyle of the populations; indeed, the different time-activity patterns and site-specific habits strongly affected the dose data. The study also showed that, in contrast with the western population study, outdoor air quality (and consequently the climate) can also play a role in the total daily dose received by low- and middle-income populations.

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Tables

Table 1 Main meteoclimatic parameters characteristic of the cities under investigation during the experimental campaign: data are expressed as maximum (max) average (avg) and minimum (min) values (Meteorology, 2019).

City	Temperature (°C)			Humidity (%)			Wind speed (m/s)	Precipitation (mm)
	Max	Avg	Min	Max	Avg	Min	Avg	Total
Cairo (Egypt)	20	16	12	73	53	33	7	0
Accra (Ghana)	32	29	24	95	78	23	1	54
Florianopolis (Brazil)	33	25	16	92	74	30	2	24
Nur-Sultan (Kazakhstan)	39	13	-8	93	53	13	2	Not available

Table 2 Classification of the activities performed by citizens in the six main microenvironments.

Microenvironment	**Activities**
Transportation	Trip and use of time not specified, round-trip to work
Working	Non-industrial workplaces, Profitable work, Main and secondary job, Working-connected activities, Studying, School, Institute or University, Voluntary job and meetings, Voluntary work in an organization
Cooking & Eating	Eating and drinking (including home and restaurant), Cooking
Outdoor day	Gardening and animal care, Construction and restoration, Sport and outdoor activities, Physical workout, Productive exercise, Sports-connected activities, Collecting firewood, Fetching, Running errands, Collecting food from the garden
Indoor day	Personal care, Other personal care, Studying not specified, Studying in free time, Activities for home and family not specified, Housework, Clothes care and folding, Purchasing goods and services, Home maintenance, Baby care, Helping adult family members, Helping other family members, Active activities, Social activities and entertainment, Social life, Entertainment and culture, Inactivity, Hobbies and computer science, Art and hobbies, Computing, Playing, Media, Reading, Watching TV, DVD or videos, Listening to the radio or recording
Sleeping & Resting	Sleeping and resting

Table 3 Time-activity pattern data (daily time spent, in minutes, for each microenvironment expressed as mean values) and the contribution of single microenvironments to the total daily time (expressed in percentages) of the investigated populations as a function of sex.

Parameter	Microenvironment	Greater Cairo (Egypt)		Greater Accra (Ghana)		Nur-Sultan (Kazakhstan)		Florianopolis (Brazil)	
		Male	Female	Male	Female	Male	Female	Male	Female
Time (min)	Sleeping & Resting	541	576	490	524	517	499	476	444
	Indoor day	177	188	318	311	163	295	253	287
	Outdoor day	116	145	107	120	37	24	132	112
	Transport	87	62	73	70	80	40	98	99
	Working	462	396	379	318	505	427	396	392
	Cooking & Eating	57	73	70	93	137	154	85	107
Time contribution (%)	Sleeping & Resting	37.6%	40.0%	34.1%	36.5%	35.9%	34.7%	33.1%	30.8%
	Indoor day	12.3%	13.1%	22.1%	21.7%	11.3%	20.5%	17.6%	19.9%
	Outdoor day	8.1%	10.1%	7.4%	8.4%	2.6%	1.7%	9.2%	7.7%
	Transport	6.0%	4.3%	5.1%	4.9%	5.6%	2.8%	6.8%	6.8%
	Working	32.1%	27.5%	26.4%	22.1%	35.1%	29.7%	27.5%	27.2%
	Cooking & Eating	4.0%	5.1%	4.9%	6.5%	9.5%	10.7%	5.9%	7.4%

Table 4 Median values and 5th-95th percentile ranges of particle number (PN) and lung-deposited surface area (LDSA) concentrations, and average particle size (D_p) to which the nine populations are exposed in each microenvironment. Data of the four cities investigated in the present paper (Cairo, Accra, Florianopolis, and Nur-Sultan) and of the five western cities (Barcelona, Cassino, Guilford, Brisbane, and Lund) investigated in our previous paper (Pacitto et al., 2018), and here re-adapted accordingly, are summarized.

Population	**City**	**Parameter**	**Microenvironments**					
			Sleeping & Resting	Indoor day	Outdoor day	Transport	Working	Cooking & Eating
Low- and middle-income populations; this study	Cairo (Egypt)	PN (part. cm^{-3})	1.83×10^{4} (0.33-5.75×10^{4})	2.61×10^{4} (0.45-13.7×10^{4})	5.14×10^{4} (0.47-48.8×10^{4})	17.3×10^{4} (1.96-162×10^{4})	4.31×10^{4} (1.30-37.6×10^{4})	14.5×10^{4} (2.16-174×10^{4})
		D_p (nm)	53 (29-81)	43 (22-70)	32 (15-52)	30 (18-49)	39 (26-56)	33 (16-64)
		LDSA (µm^2 cm^{-3})	5.87×10^{1} (0.61-18.2×10^{1})	6.83×10^{1} (0.68-39.7×10^{1})	10.9×10^{1} (0.51-85.9×10^{1})	28.8×10^{1} (0.41-216×10^{1})	9.23×10^{1} (0.23-88.6×10^{1})	25.9×10^{1} (0.49-270×10^{1})
	Accra (Ghana)	PN (part. cm^{-3})	4.18×10^{4} (1.36-10.2×10^{4})	2.94×10^{4} (1.18-18.5×10^{4})	1.04×10^{4} (0.57-10.9×10^{4})	2.06×10^{4} (0.68-16.6×10^{4})	0.99×10^{4} (0.53-10.1×10^{4})	4.53×10^{4} (1.65-40.4×10^{4})
		D_p (nm)	43 (29-56)	48 (38-75)	55 (42-66)	49 (39-67)	55 (39-73)	47 (34-60)
		LDSA (µm^2 cm^{-3})	9.45×10^{1} (3.74-25.3×10^{1})	8.90×10^{1} (3.50-39.7×10^{1})	3.80×10^{1} (1.67-37.6×10^{1})	8.14×10^{1} (2.09-58.1×10^{1})	3.68×10^{1} (1.35-31.7×10^{1})	14.4×10^{1} (4.69-99.7×10^{1})
	Florianopolis (Brazil)	PN (part. cm^{-3})	0.983×10^{4} (0.78-1.82×10^{4})	1.21×10^{4} (0.89-2.60×10^{4})	1.31×10^{4} (0.89-2.71×10^{4})	1.33×10^{4} (0.86-7.21×10^{4})	1.18×10^{4} (0.9-2.78×10^{4})	1.94×10^{4} (0.98-38.5×10^{4})
		D_p (nm)	53 (29-56)	42 (29-56)	44 (29-56)	39 (29-56)	44 (29-56)	37 (29-56)
		LDSA (µm^2 cm^{-3})	3.11×10^{1} (1.9-4.82×10^{1})	2.94×10^{1} (2.0-5.19×10^{1})	3.26×10^{1} (1.81-6.33×10^{1})	3.25×10^{1} (1.72-10.6×10^{1})	3.26×10^{1} (2.17-6.63×10^{1})	4.10×10^{1} (1.98-50.7×10^{1})
	Nur-Sultan (Kazakhstan)	PN (part. cm^{-3})	1.10×10^{4} (0.27-51.0×10^{4})	2.13×10^{4} (0.31-17.6×10^{4})	1.98×10^{4} (0.31-20.9×10^{4})	5.93×10^{4} (0.43-52.9×10^{4})	3.55×10^{4} (0.30-28.8×10^{4})	4.13×10^{4} (0.58-47.4×10^{4})
		D_p (nm)	55 (20-123)	50 (19-86)	41 (18-74)	37 (19-64)	45 (13-73)	39 (16-78)
		LDSA (µm^2 cm^{-3})	3.52×10^{1} (0.91-151×10^{1})	5.01×10^{1} (1.10-28.5×10^{1})	3.94×10^{1} (1.01-43.7×10^{1})	11.8×10^{1} (1.35-70.9×10^{1})	6.94×10^{1} (0.92-31.6×10^{1})	8.31×10^{1} (1.47-89.9×10^{1})
Western populations; data adapted from Pacitto et al. (2018)	Barcelona (Spain)	PN (part. cm^{-3})	0.66×10^{4} (0.38-2.25×10^{4})	1.51×10^{4} (0.65-7.75×10^{4})	0.93×10^{4} (0.47-2.20×10^{4})	2.79×10^{4} (1.43-9.46×10^{4})	1.42×10^{4} (0.32-1.84×10^{4})	3.37×10^{4} (0.99-28.2×10^{4})
		D_p (nm)	50 (40-57)	48 (40-57)	59 (40-79)	65 (44-108)	49 (46-59)	44 (36-53)
		LDSA (µm^2 cm^{-3})	1.70×10^{1} (1.05-6.54×10^{1})	4.10×10^{1} (1.05-6.54×10^{1})	3.05×10^{1} (1.62-6.63×10^{1})	11.2×10^{1} (5.30-30.4×10^{1})	3.87×10^{1} (1.06-4.94×10^{1})	8.19×10^{1} (3.49-6.54×10^{1})
	Cassino (Italy)	PN (part. cm^{-3})	1.24×10^{4} (0.95-1.91×10^{4})	1.04×10^{4} (0.35-8.33×10^{4})	0.51×10^{4} (0.23-1.03×10^{4})	1.02×10^{4} (0.35-5.38×10^{4})	0.57×10^{4} (0.29-1.59×10^{4})	35.6×10^{4} (1.64-107×10^{4})
		D_p (nm)	61 (49-81)	62 (49-81)	110 (78-189)	88 (56-136)	97 (79-119)	49 (31-129)
		LDSA (µm^2 cm^{-3})	4.30×10^{1} (3.91-5.25×10^{1})	3.42×10^{1} (3.91-5.25×10^{1})	3.10×10^{1} (2.22-5.23×10^{1})	5.18×10^{1} (1.79-18.2×10^{1})	2.90×10^{1} (1.76-10.2×10^{1})	69.1×10^{1} (7.85-367×10^{1})
	Guilford (UK)	PN (part. cm^{-3})	0.38×10^{4} (0.16-1.71×10^{4})	3.09×10^{4} (0.62-35.9×10^{4})	1.29×10^{4} (0.52-2.20×10^{4})	1.42×10^{4} (0.31-5.55×10^{4})	6.05×10^{3} (0.28-0.89×10^{4})	6.01×10^{4} (0.41-56.5×10^{4})
		D_p (nm)	82 (63-113)	54 (30-113)	63 (33-96)	56 (27-99)	85 (65-125)	73 (27-121)
		LDSA (µm^2 cm^{-3})	1.51×10^{1} (0.93-6.74×10^{1})	9.25×10^{1} (1.97-79.1×10^{1})	4.38×10^{1} (2.03-7.21×10^{1})	4.24×10^{1} (1.10-16.1×10^{1})	2.51×10^{1} (1.31-5.59×10^{1})	18.9×10^{1} (1.63-387×10^{1})
	Brisbane (Australia)	PN (part. cm^{-3})	0.49×10^{4} (0.12-1.20×10^{4})	1.36×10^{4} (0.46-4.73×10^{4})	1.51×10^{4} (0.57-4.55×10^{4})	1.88×10^{4} (0.61-7.28×10^{4})	0.97×10^{4} (0.41-3.21×10^{4})	7.07×10^{4} (0.79-74.8×10^{4})
		D_p (nm)	59 (43-91)	43 (15-97)	38 (26-47)	40 (29-63)	54 (34-69)	66 (34-95)
		LDSA (µm^2 cm^{-3})	1.35×10^{1} (0.46-5.53×10^{1})	3.14×10^{1} (0.93-6.74×10^{1})	3.14×10^{1} (1.23-8.83×10^{1})	4.49×10^{1} (1.42-15.0×10^{1})	2.68×10^{1} (1.18-10.1×10^{1})	22.7×10^{1} (3.41-135×10^{1})
	Lund (Sweden)	PN (part. cm^{-3})	0.77×10^{3} (0.44-1.37×10^{3})	0.86×10^{3} (0.42-5.35×10^{3})	2.88×10^{3} (1.38-18.9×10^{3})	3.13×10^{3} (0.83-6.92×10^{3})	1.48×10^{3} (0.69-8.96×10^{3})	22.6×10^{3} (1.44-112×10^{3})
		D_p (nm)	72 (49-103)	62 (39-88)	47 (33-70)	55 (36-85)	58 (29-83)	35 (25-80)
		LDSA (µm^2 cm^{-3})	0.32×10^{1} (0.15-0.58×10^{1})	0.33×10^{1} (0.16-1.21×10^{1})	0.79×10^{1} (0.40-4.31×10^{1})	0.98×10^{1} (0.23-2.27×10^{1})	0.47×10^{1} (0.28-1.72×10^{1})	4.56×10^{1} (0.53-24.4×10^{1})

Table 5 Dose, dose intensity, and contribution to the daily dose as a function of the population, sex (female/male, F/M) and microenvironments for the four cities investigated in the present paper (Cairo, Accra, Florianopolis, and Nur-Sultan) and for the five western cities (Barcelona, Cassino, Guilford, Lund, Brisbane) investigated in our previous paper (Pacitto et al., 2018) (and here re-adapted accordingly).

City	**Parameter**	**Microenvironment**						**Total daily dose (mm^2)**
		Sleeping & Resting	Indoor day	Outdoor day	Transport	Working	Cooking & Eating	
Cairo (Egypt)	Dose, δ_{SA} (mm^2)	217 / 204	209 / 196	257 / 206	182 / 257	286 / 334	154 / 112	1306 / 1309
	Dose intensity ratio (mm^2 min^{-1})	0.38 / 0.38	1.11 / 1.11	1.77 / 1.77	2.96 / 2.96	0.72 / 0.72	2.11 / 1.96	
	Contribution to the daily dose (%)	17 / 16	16 / 15	20 / 16	14 / 20	22 / 25	11 / 8	
Accra (Ghana)	Dose, δ_{SA} (mm^2)	318 / 297	450 / 460	74 / 66	58 / 61	92 / 109	116 / 87	1108 / 1081
	Dose intensity ratio (mm^2 min^{-1})	0.61 / 0.61	1.45 / 1.45	0.62 / 0.62	0.83 / 0.83	0.29 / 0.29	1,25 / 1,25	
	Contribution to the daily dose (%)	29 / 28	41 / 43	7 / 6	5 / 6	8 / 10	10 / 8	
Florianopolis (Brazil)	Dose, δ_{SA} (mm^2)	89 / 95	137 / 121	59 / 70	33 / 33	100 / 101	38 / 30	456 / 450
	Dose intensity ratio (mm^2 min^{-1})	0.2 / 0.2	0.48 / 0.48	0.53 / 0.53	0.33 / 0.33	0.26 / 0.26	0.35 / 0.35	
	Contribution to the daily dose (%)	19 / 20	30 / 27	13 / 16	7 / 7	22 / 23	8 / 7	
Nur-Sultan (Kazakhstan)	Dose, δ_{SA} (mm^2)	113 / 117	241 / 133	16 / 24	48 / 97	232 / 275	105 / 94	755 / 739
	Dose intensity ratio (mm^2 min^{-1})	0.23 / 0.23	0.81 / 0.81	0.64 / 0.64	1.21 / 1.21	0.54 / 0.54	0.69 / 0.69	
	Contribution to the daily dose (%)	15 / 16	32 / 18	2 / 3	6 / 13	31 / 37	14 / 13	
Barcelona (Spain)	Dose, δ_{SA} (mm^2)	60 / 61	337 / 290	24 / 40	97 / 114	47 / 68	151 / 88	715 / 658
	Dose intensity ratio (mm^2 min^{-1})	0.12 / 0.12	0.75 / 0.75	0.53 / 0.53	1.24 / 1.25	0.30 / 0.30	0.79 / 0.63	
	Contribution to the daily dose (%)	8 / 9	47 / 44	3 / 6	14 / 17	7 / 10	21 / 14	
Cassino (Italy)	Dose, δ_{SA} (mm^2)	127 / 123	269 / 239	39 / 40	34 / 35	69 / 77	779 / 587	1317 / 1099
	Dose intensity ratio (mm^2 min^{-1})	0.29 / 0.28	0.59 / 0.56	0.50 / 0.48	0.55 / 0.53	0.26 / 0.25	5.88 / 5.21	
	Contribution to the daily dose (%)	10 / 11	20 / 22	3 / 4	3 / 3	5 / 7	59 / 53	
Guilford (UK)	Dose, δ_{SA} (mm^2)	61 / 59	585 / 452	27 / 45	30 / 36	24 / 30	683 / 497	1408 / 1188
	Dose intensity ratio (mm^2 min^{-1})	0.12 / 0.13	1.39 / 1.03	0.45 / 0.56	0.35 / 0.56	0.12 / 0.10	4.12 / 4.05	
	Contribution to the daily dose (%)	4 / 5	42 / 40	2 / 4	2 / 3	2 / 3	48 / 45	
Brisbane (Australia)	Dose, δ_{SA} (mm^2)	35 / 42	325 / 283	21 / 24	6 / 12	40 / 88	224 / 173	650 / 620
	Dose intensity ratio (mm^2 min^{-1})	0.09 / 0.10	0.46 / 0.50	0.43 / 0.47	0.44 / 0.44	0.31 / 0.34	1.64 / 1.66	
	Contribution to the daily dose (%)	5 / 7	50 / 46	3 / 4	1 / 2	6 / 14	35 / 28	
Lund (Sweden)	Dose, δ_{SA} (mm^2)	11 / 11	22 / 23	14 / 13	6 / 5	9 / 12	41 / 32	102 / 93
	Dose intensity ratio (mm^2 min^{-1})	0.02 / 0.02	0.06 / 0.06	0.14 / 0.13	0.10 / 0.09	0.04 / 0.04	0.34 / 0.30	
	Contribution to the daily dose (%)	10 / 11	22 / 23	14 / 14	5 / 5	9 / 12	40 / 35	

Figure Captions

Figure 1 Box-plots of a) particle number concentrations, and b) lung deposited surface area concentrations experienced in each microenvironment by the populations of the four cities investigated in the present paper (Cairo, Accra, Florianopolis, and Nur-Sultan, reported as yellow boxes) and of the five western cities (Barcelona, Cassino, Guilford, Lund, and Brisbane, reported as white boxes) investigated in our previous paper (Pacitto et al.,2018) (and here re-adapted accordingly). Data not statistically different amongst the different populations are also indicated ($p > 0.01$) microenvironment by microenvironment as resulting from the statistical analysis performed.