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Seasonal Variations of Children's Personal Exposure to Ultrafine Particles in Different Microenvironments in Bhutan

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Abstract: ***The health impacts of air pollution are driven by exposure to pollutants, which is a function of time spent and pollutant concentrations in different microenvironments. There are only a handful of studies on exposure assessment to ultrafine particles (UFP > 0.1 µm), particularly in developing countries. Available studies on human exposure to air pollution have mostly focused on particle mass and relied on data from fixed monitoring stations and area measurements. While such studies may be useful, it can lead to gross miscalculation of exposure. Real-time personal monitoring combined with individual's time activity patterns provide an accurate assessment of exposure and identification of high-risk microenvironments. This study characterized children's daily personal exposure to UFP using real-time personal monitors, during wet and dry seasons in rural Bhutan. 45 village children, with age range of 9 to 13 years and attending two primary schools participated in the study. All children carried personal monitors attached to their waists for 24 hours and air was sampled continuously from the breathing zone. An activity diary was used to track children's activity patterns and time spent in different microenvironments. Children received higher daily UFP exposure during the dry season (mean = 4.19 × 10^4 particles/cm^3) than wet season (mean = 1.13 × 10^4 particles/cm^3), respectively. The highest UFP exposure resulted during cooking/eating, contributing to 51% of the total daily exposure during the wet season and 73% during the dry season. This is despite children spending only 7% (during the wet season) and 13% (during the dry season) of the total daily time in the microenvironment where this activity was conducted. The lowest UFP exposures were during the hours that children spent outdoors at schools. Results of this study highlight substantial contribution of household air pollution to children's personal exposure, thus potentially presenting a significant environmental health hazard.***

Key words: Exposure, Children, Ultrafine particles, Rural, Bhutan

1. Introduction

The concept of human exposure was first described by Ott (1982) as an event when a person comes in contact with a pollutant of certain concentration. Studies have established that exposure to air pollution results in several adverse health outcomes. In particular, exposure to particles has been associated with alveolar inflammation, leading to acute respiratory illness (Hussein, et al., 2005), cardiovascular disease and lung cancer (Fullerton, et al., 2008, Pope III and Dockery, 2006). To date, there is limited understanding of health outcomes of ultrafine particles (UFP < 0.1 µm). However, toxicological studies have established greater health effects from UFP compared to particle mass (WHO, 2005), which is attributed to their high alveolar deposition rate, large surface area and potential to translocate into the blood stream (Buonanno, et al., 2012).

Most studies on exposure assessment have relied on data from fixed monitoring stations, and indoor and outdoor area measurements (Morawska, et al., 2013). This approach does not account for the spatial variations of pollutant concentrations (Buonanno, et al., 2012, Hinwood, et al., 2014, Mazaheri, et al., 2014, Sarnat, et al., 2005). The degree of variability over time and space is more pronounced for UFP, which has been shown to vary by orders of magnitude between different indoor and outdoor environments (Buonanno, et al., 2011). Exposure estimated from indirect methods assume that each person is exposed to a same level of a given pollutant, based on mean values obtained (Buonanno, et al., 2013). Therefore, indirect assessment does not provide accurate and representative exposure profile and can result in gross miscalculation of exposure (Buonanno, et al., 2013, Clark, et al., 2013, Dionisio, et al., 2012, Kaur, et al., 2007, Saarela, et al., 2003).

In contrast, direct exposure assessment which involves use of monitoring device that can be carried by participants provide accurate exposure experienced by an individual (Morawska, et al., 2013). Personal sampling is a term used when exposure is measured directly from the person's breathing zone (Cattaneo, et al., 2010). Depending on the instrumentation, time-integrated and real-time approaches can be used to assess the personal exposure (Clark, et al., 2013). The time integrated method provides average exposure for the duration of measurement, without accounting for peak concentrations and temporal distributions (Baumgartner, et al., 2011, Bruce, et al., 2004). Real-time approach coupled with time-activity data have been used to assess short-term peaks, contributions from different activities/microenvironments, and temporal variations in exposure (Buonanno, et al., 2012, Mazaheri, et al., 2014).

Children are more vulnerable to health effects of air pollution compared to adults. This is because of their formative system presenting minimal defense against foreign bodies and breathing more air relative to their body size (Buonanno, et al., 2013). Most personal exposure studies on children relate to particle mass, with only limited studies done on ultrafine particles, for example (Buonanno, et al., 2012, Mazaheri, et al., 2014, Wangchuk, et al., 2015). In particular, children's personal exposure to UFP in rural areas of developing countries, where high levels of household air pollution (HAP) is prevalent is essentially nonexistent, perhaps (possibly) the first one ever reported was from Bhutan by Wangchuk, et al. (2015). In light of this knowledge gap, this study characterized children's personal exposure to UFP in rural locations in Bhutan. The specific aims of the study were to: (1) examine the seasonal variations of children's daily personal UFP exposure and (2) identify the dominant activity and microenvironment contributing to personal exposure.

2. Materials and Methods

2.1 Study area

The study was conducted in Kanglung under Trashigang district in eastern Bhutan (Figure 1), which is one of the largest and the most densely populated districts in the country. People in Kanglung are mostly subsistence farmers, residing in villages and depending mostly on seasonal crops for livelihood. There are no obvious differences in housing types and livelihood between villages. People live in traditional houses made of mostly wood, stone and mud. Although villages have access to electricity, biomass fuels are extensively used for cooking and space heating.

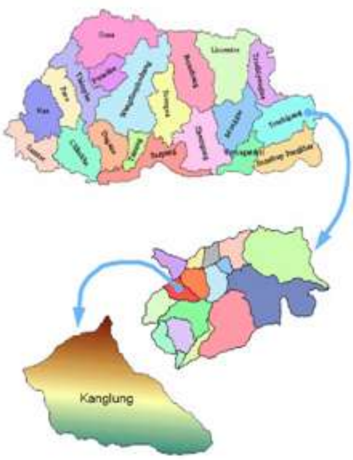

Figure 1: Location of study site

2.2 Instrumentation and quality assurance

This study used two real time portable particle counters, Philips Aerasense NanoTracer (NT) to measure personal exposure to UFP. NT measures particle number (PN) concentrations up to 1×10^6 particles/cm^3 in the size range of 10-300 nm, and operates on two modes: (i) Advanced mode, which measures both PN and mean particle diameter; and (ii) Fast mode, which measures PN concentration only. The Advanced mode was used in the present study; however, results of particle diameter are not reported in the present study. The instrument has an internal reachable battery but also can be operated using the mains power supply.

The NT was calibrated by running side by side with a TSI 3787 condensation particle counter (CPC). The correction factors were derived using the equation 1.

$$CF_n = \frac{C_{CPC}}{C_{NT_n}} \quad (1)$$

where, C_{CPC} and C_{NTn} refer to the concurrent total particle number concentrations in the ambient air, as measured by the CPC and the NT.

The NT's time stamp was synchronized to the local time using the NanoReporter software prior to each measurement.

2.3 Children participants

45 children, with age range of 9 to 13 years and attending two primary schools (S1 and S2) from two different villages (V1 and V2) in Kanglung participated in the study in 2013. Measurements for children attending S1 were done during the wet season (May to June), while measurements for S2 children were done during the dry season (October to November). The two schools had similar characteristics in terms of building types and materials used for construction, and had similar curriculum. Likewise, both villages where children resided had similar characteristics, such as housing types and lifestyle, and geographical features, including similar altitudinal range of ~1500 to 1800 m above the sea level. An informed consent for the study was obtained from the participating children, their parents and the school authority.

2.4 Personal exposure measurement

All children carried NT attached to their waists for 24 hours and air was sampled continuously from the breathing zone, except during sleeping and playing, where children have been instructed to keep the instrument in the proximity. All children were trained to maintain their time activity diary for the duration of measurement. A total of six distinct microenvironments/activities have been considered: (1) school indoor (2) school outdoor (3) home cooking/eating (4) home sleeping (5) home others and (6) commuting.

Personal UFP exposure (particles/cm^3) due to specific activity over the total personal monitoring period was derived using Equation 2.

$$\vec{E}_x = \frac{\sum_{i=1}^{n} \Delta C_{x_i} \times \Delta t_{x_i}}{24 \text{ hours}} \quad (2)$$

where $\vec{E}_x$ is average personal exposure due to the specific activity (x) for each child, ΔC_{x_i} is average UFP concentration (particles/cm^3) due to the specific activity, Δt_{x_i} is activity duration and i = (1- n) is the frequency of activity during the day.

3. Results and Discussion

3.1. UFP concentrations

Of the 45 children measurements, only 35 with full 24 hours data were used for analyses. Missing data resulting from power failure and from children failing to charge NTs properly have been excluded from analyses. The time series data from all the children presented distinct peak concentrations during morning and evening hours, which largely corresponded with the cooking and eating time at homes (Figure 2). The peak concentrations were the result of firewood combustion during cooking and heating, and children simultaneously spending time indoors. It should be noted that firewood is the primary fuel used for cooking and heating in village homes in the study area.

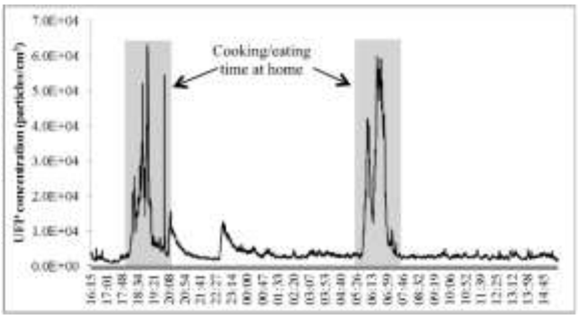

Figure 2: A typical time series UFP concentration measured during the wet season from one of the children

3.2. UFP personal exposure

Figure 3 presents personal UFP exposure received by children in different microenvironment/activities, computed using Equation 2. Daily mean UFP exposure was four times higher during the dry season ($4.19 \times 10^4 \pm 3.74 \times 10^4$ particles/cm^3) than the wet season ($1.13 \times 10^4 \pm 6.64 \times 10^3$ particles/cm^3). Likewise, median concentrations also presented a marginal difference with 2.6×10^4 particles/cm^3 for the dry season and 1.1×10^4 particles/cm^3 for the wet season, respectively. At the time of this study, the author has not come across any comparable study on UFP from similar geographical location to which this study can be compared with. With slightly different particle size fraction (PM < 4µm), Balakrishnan, et al. (2004), reported mean 24 hour exposures ranging from 80 to 573 µg/m^3 in rural areas in South India. A meta study of particle number concentrations in different ambient environments worldwide reported concentrations (particles/cm^3) ranging from of 2.61×10^3 for clean background to 1.08×10^4 for urban, and 4.21×10^4 for street canyon to 1.68×10^5 for tunnel environment, respectively (Morawska, et al., 2008). Therefore, children in this study received total daily UFP exposure that was comparable to typical concentration in urban areas during the wet season, and street canyon concentration during the dry season.

Children received the lowest UFP exposure in schools, with comparable exposures in both wet and dry seasons. This was expected since two schools did not have any primary combustion source in the campus. Both schools at the time of monitoring were day-schools, with no cooking done on the campus, unlike in boarding schools where meals for children are cooked in the school campus, using (mostly) firewood. All children who participated in the study carried lunch pack from their homes.

Overall, children received highest exposure in home environment, with 7 times higher than school environment during the wet season (particles/cm^3 = 9.30×10^3 home, 1.39×10^3 school), and 20 times higher during the dry season (particles/cm^3 = 3.67×10^4 home, 1.84×10^3 school). A significantly high contribution was made by cooking/eating at home, when children were present indoors, with exposure (particles/cm^3) of 5.57×10^3 in the wet season and 2.94×10^4 during the dry season. Higher exposure during cooking/eating time was due to use of firewood for cooking using traditional cookstove, without a chimney and inadequate space ventilation. Likewise, exposure during sleeping time and "home others" (range of other activities at home), including commuting were higher during the dry season than wet season. It should be noted that dry season in the study area is characterized by a cool and windy weather. This meant that children spent more time indoors, where more firewood is used for heating than in the warm, wet season. This explains why the mean exposures for home activities were much higher during the dry season.

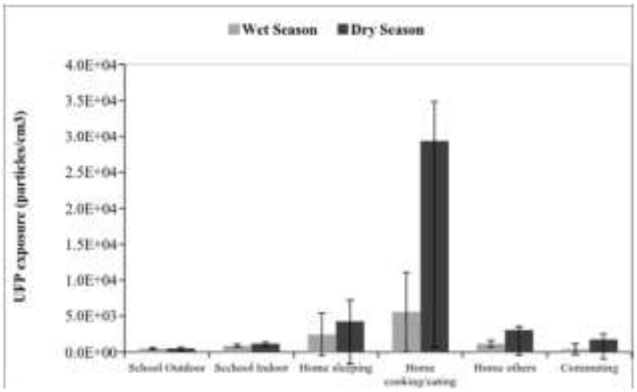

Figure 3: UFP personal exposure for different activities. Error bar presents standard deviation

3.3. Relative contribution to personal exposure

Table 1 presents relative contributions from different microenvironments/activities to children's daily UFP personal exposure. The "home cooking/eating" made the highest contribution with 51% and 73%, during the wet and dry season, respectively. This is despite children spending only 7% and 13% of their time indoors during cooking at homes. This indicates that children received intense short-term exposure from biomass cooking fuels at homes. The lowest contributions were made by school microenvironments, with classrooms contributing higher than the school outdoor environment. This was because children spent more time inside classrooms, even though UFP concentrations were marginally higher in the school outdoor environment.

Table 1: Relative contribution of UFP exposure

Microenvironments	Wet Season (n = 22)		Dry Season (n = 13)	
	Exposure Contribution (%)	Average Time Spent (%)	Exposure Contribution (%)	Average Time Spent (%)
School outdoor	4	11	1	8
School indoor	8	23	3	23
Home sleeping	22	36	11	40
Home cooking/eating	51	7	73	13
Home others	11	17	8	13
Commuting	4	6	4	3

4. Conclusion

This study characterized children's personal exposure to ultrafine particles in rural location in Bhutan. UFP exposure has strong association with seasonal variations, with dry season contributing to higher exposure compared to the wet season. Home environments and activities were associated with high UFP exposure, with highest contributions during cooking/eating time, when children were indoors, which was attributed to emissions from biomass fuels used for cooking and heating. Results of this study are consistent with other studies from developing countries inferring that HAP in rural residence present a potential health risk to occupants. It further highlights a significant contribution to exposure from short-term peak concentrations.

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