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Personal Exposure to Fine-particle Black Carbon Air Pollution Among Schoolchildren Living in Ulaanbaatar, Mongolia

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Objectives: To measure personal exposure to air pollution in children, in Ulaanbaatar, Mongolia. **Methods:** Since coal burning for domestic heating causes severe air pollution in Ulaanbaatar, we measured personal PM2.5 exposure for children aged 5-12 years during the winter 2013-2014. **Results:** Peak levels of black carbon PM2.5 exposure >200 μg/m^3 between November and March varied significantly with time of day, with the highest peak 18:00-02:00, a nadir 02:00-07:00, followed by a second peak 07:00 -12:00, with another afternoon nadir 12:00-18:00. Children living in Ger districts in a Ger or wooden house, had the highest levels of PM2.5, >500 μg/m^3, with duration of personal peak exposure in Gers 8-fold longer than in wooden houses. **Conclusion:** Peak exposures in Gers were related to going outside, fire lighting and cooking, whereas in wooden houses peak exposures were related to going outside or opening the door. The least exposure for children was in an apartment or school with the windows shut. Significant levels of personal exposure also occurred during the commute to school, outside playtime, shopping trips and car rides. Opening the window of steam heated apartments for "fresh air cooling" as well as indoor smoking also produced important levels of personal exposure.

Keywords: Particulate Matter, Child Welfare, Air Pollution

Introduction

Air pollution (AP) is a major and growing public health challenge in densely populated urban centers world wide, not only in developed countries like the USA and UK, but especially more recently in developing nations. Ulaanbaatar (UB), Mongolia, is the coldest capital city in the world, where the daily low atmospheric temperature is usually below -40 degrees Celsius/

Fahrenheit, without counting wind chill, between November and January and, mainly because of the exigency of domestic heating, also has the worst black carbon air pollution in the world during winter. Presently, about half of the 1.5 million inhabitants of UB live in densely packed neighborhoods, commonly referred to as Ger districts. Gers are the traditional portable round felt dwellings used for thousands of years by Mongolian nomads and are heated traditionally by burning biomass or, more recently, coal in a central stove with a chimney leading up and out of the dome of the Ger. Annually over 600,00 metric tons of Mongolian coal are burned in approximately >185,000 individual Ger stoves for domestic heating. Another 4.5 million metric tons are burned at 3 power stations for domestic central heating in the built housing stock (mainly apartment homes), as well as offices and businesses, by centrally piped steam, as well as for electrical power generation. Coal burning in Ger stoves causes more than 80% of the winter ground level air pollution in UB, while the contribution of vehicle exhaust is relatively minor (<15%). Thus, UB being the coldest capital city on earth and, as around half of the population rely on solid fuel use for domestic heating and cooking, UB has the highest levels of AP in winter of any capital city [1-3].

Accordingly, black carbon (BC) and PM2.5 particulate AP levels are many times in excess of both the WHO and Mongolian National Standards for clean air (<10 μg/m^3 and <25 μg/m^3, respectively for annual PM2.5), particularly in the Ger districts [1-3], largely exceeding those measured in Beijing, Los Angeles and London [1-4]. It has also previously been well established that the level and content of air pollution in UB depends on location within the city, so that residence within the Ger districts is a major determinant of ambient PM exposure, while residence next to a major road is a major determinant of ambient exposure to vehicle exhaust gases such as NO [2]. Also, seasonal variation in ambient pollution is marked, with relatively low, even WHO acceptable, ambient levels of PM during the summer months when domestic heating is not necessary [1-3].

We have recently reported a strikingly significant seasonal correlation between ambient AP levels and spontaneous abortion among pregnant women in UB [5]. Our Mongolian colleagues have also reported wide seasonal variation in other health effects, correlated with AP levels during winter including respiratory and cardiac events [1, 2].

Although ambient levels of AP in UB are documented as the world's highest in winter, personal levels of AP exposure are not yet well established. Herein we report on personal levels of exposure to the PM2.5 fraction of BC by measurements using portable serial aethalometry in school age children who resided in representative types of homes; Gers and wooden houses in Ger districts versus apartments, in UB between May 2013 and May 2014.

Materials and Methods

Ambient outdoor levels of BC particulate matter with average diameter <2.5 micrometers were measured using an AethLabs (San Francisco, CA) aethalometer with a size cut off of 2.5 microns (PM2.5) for 24-hour periods between September 2013 and May 2014. The aethalometer was mounted with a cyclone PM2.5 vortex filter at a static location with the intake pipe 4 meters above ground outside our laboratory at the National University of Mongolia (NUM) in central UB. At this site we also measured PM using a TSI DustTrak PM monitor.

Personal levels of PM2.5 exposure were measured in children over 24-hour periods using AethLabs aethalometers, mounted in a portable satchel, worn over the shoulder with the hose vortex cyclone intake pinned to the shoulder near the mouth during the day. At bed time the device was placed on a bedside table near the subject. Aethalometer sampling settings were at 1-minute interval measurements with pump suction rate set on 100 mL/min.

The human subjects research protocol for this study was approved by the Institutional Review Board of the National Center for Maternal and Child Health, Ulaanbaatar. Informed consent was obtained from the parents and informed assent was obtained in the Mongolian language from school children aged 5 to 12 years using approved consent and assent forms printed in the Mongolian language.

Children were selected to represent residents of apartments (6) versus residents of the Ger districts (6). Parents were asked to keep a diary of the children's activities during the 24-hour monitoring period, which was then reviewed with them in Mongolian immediately following the exposure period to interrogate, ascertain and confirm any significant changes in activity as suggested by changes in PM2.5 levels on the child's personal exposure recording.

Aethalometer records were downloaded to Excel and descriptive statistical analyses were applied to express continuous, maxima, minima, mean, standard deviation and range of ambient versus personal PM2.5 pollution exposure. Ambient outdoor exposure was estimated using PM2.5 and BC measurements recorded at NUM. Personal PM2.5 exposure was compared using ANOVA, regression or unpaired or paired within subject statistics and Chi square as appropriate to compare the following categories of independent variables: season of the year, time of day, ambient outdoor versus personal levels of PM2.5 exposure, location of residence and personal activities as recorded in the diary.

Results

Time series of BC and PM2.5 measured at the NUM in central UB are presented in Figure 1. BC concentrations measured between 18:00-24:00 were taken as representing the daily average concentration of BC because filter saturation occurred on the most heavily polluted days. Peak levels of BC and PM2.5 exposure in central Ulaanbaatar varied significantly with season of the year (Figure 1), ranging 100-fold from <5 to >500 μg/m^3 between May 2013 and May 2014, with the highest measured peak levels >200 μg/m^3 occurring between November 5 and March 9.

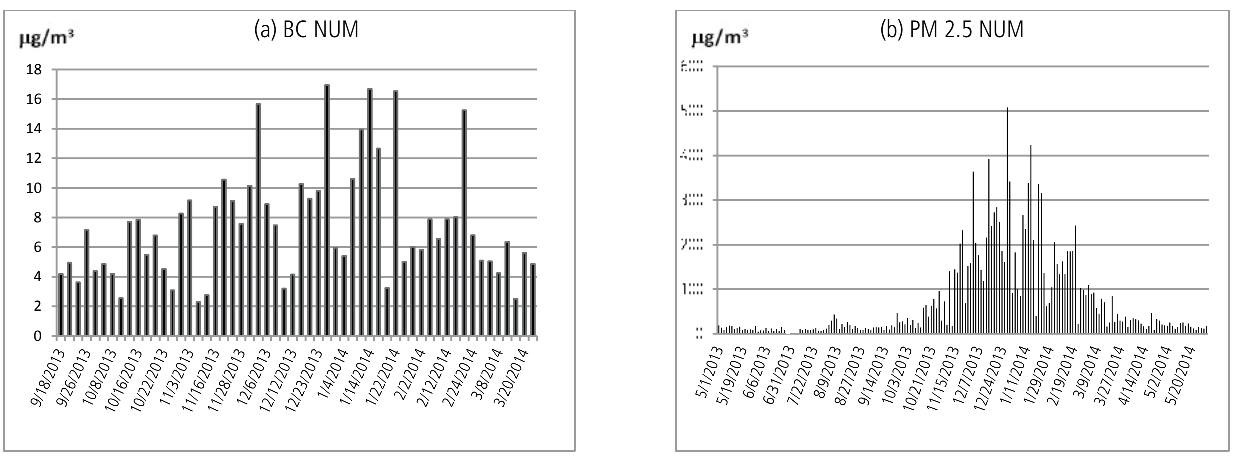

Figure 1. (a) BC and (b) PM2.5 time series measured in central UB.

The ratio of ambient BC/PM2.5 measured at the central NUM location is shown in Table 1. These data show that measuring BC alone underestimated the levels of PM2.5 by as much as 20-fold, particularly in the coldest months of the winter.

Table 1. Monthly ratio of BC/PM2.5 measured at the central Ulaanbaatar

Months	BC/PM2.5
Sep 2013	0.29
Oct 2013	0.13
Nov 2013	0.10
Dec 2013	0.05
Jan 2014	0.07
Feb 2014	0.07
Mar 2014	0.09
April 2014	0.19
May 2014	0.31

Ambient levels of PM2.5 also varied significantly with time of day. The highest peak ambient PM2.5 levels occurred between the hours of 18:00 and 02:00, while an overnight nadir occurred between 02:00 and 07:00, followed by a second peak between 07:00 and 12:00, with another afternoon nadir between 12:00 and 18:00. This diurnal rhythm of ambient AP was most pronounced during the winter months.

Representative daily time series of both PM2.5 and BC measured simultaneously in September and December, 2014 at NUM, located in central Ulaanbaatar are shown in Figure 2.

Personal exposures to PM2.5 were measured over 24 hours on 15 occasions in 12 school-aged children, aged 5 to 12 years, during the season of highest pollution between November, 2013 and February, 2014. Typical aethalometer readings representative of individual children living in a Ger in the Ger district (n = 6) versus in an apartment (n = 6) are shown in Figure 3 and summaries of these data are tabulated in Table 2.

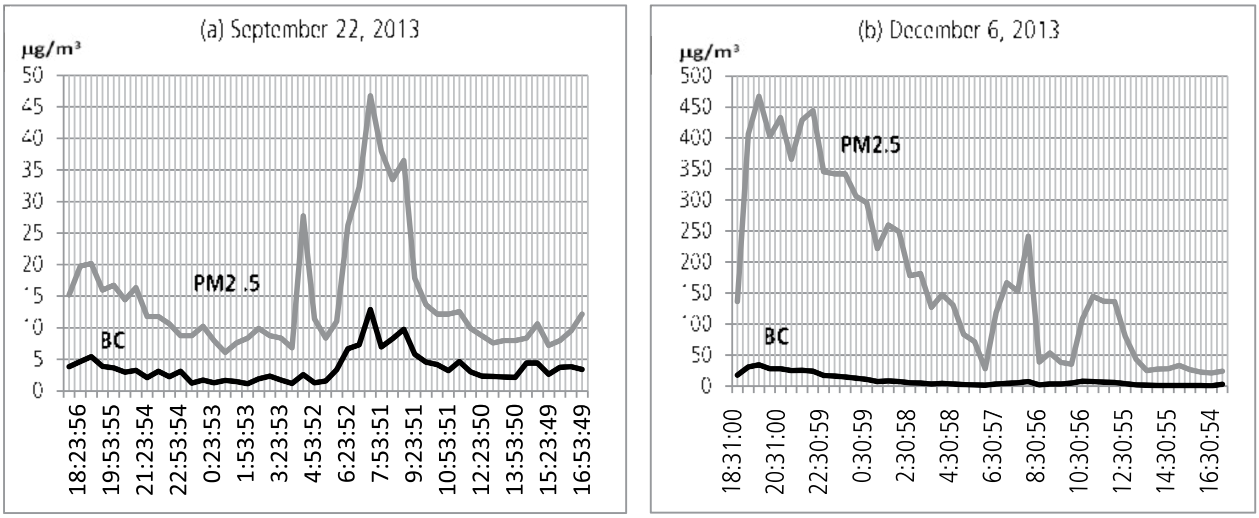

Figure 2. Daily time series of PM2.5 (grey) and BC (black) measured in µg/m³ at the same site (NUM) in central UB in (a) September and (b) December, 2013.

The activity diary along with the personal exposure tracing for a 10-year-old girl, living in a Ger in the highly polluted Ger district in winter, February 2, 2014 (Figure 3a). Peaks of exposure before 18:00 are related to commuting on the bus; peaks between 19:50 and 23:18 are related to opening the Ger door, going outside the Ger to visit friends and relatives; peaks at 11:00 are related to going to school and playing outside at school. Note the maximal peak outdoor PM2.5 exposure >580 µg/m³ which occurred at 21:15 when walking home form a neighbor's Ger.

The activity diary revealed the following for the personal exposure (ng/m³) tracing of a 12-year-old boy living in an apartment away from the Ger district in winter on 23 December, 2013 (Figure 3b). Peaks between 15:00 and 17:30 are related to commuting in the car; peak at 07:00 is related to Dad smoking in the apartment; peaks at 13:00-15:14 are related to travel to school by car and outside play at school.

The children living in the Ger district, whether in a Ger or a wooden house were thus found to have been subjected to the highest peak levels of outdoor BC PM2.5 AP, >500 µg/m³, which was essentially the same as peak ambient levels of exposure at that time of winter in the Ger district. Moreover, the duration of peak PM2.5 exposure >200 µg/m³ was 8-fold longer in children living in Gers (>4 hours) than for the children in wooden houses (<0.5 hours). Examination of each of the children's personal activity diaries revealed that the peak exposures for children living in a Ger were related mostly to opening the door and going outside, although fire lighting and cooking activities also played an important role, whereas in the wooden houses in the Ger district peak exposures were more related to going outside or opening the door.

Table 2. Summary of key maxima and minima of personal exposure to PM2.5 µg/m³ in child residents aged 5-15 years of Ger districts (n = 6) versus apartments (n = 6) in UB.

Domicile	Peak outdoor ambient PM2.5	Peak personal exposure	Peak morning commute personal exposure	Peak indoor (18:00-24:00) personal exposure	Trough indoor (04:00-06:00) personal exposure
Ger district	>650	>700	<350	<200	<2
Apartment district	>16	<16	<16	<5	<3
Ger: Apartment exposure ratio	40X	44X	22X	40X	1X

According to Table 2, it can be readily seen that Ger dwelling children in UB are presently exposed to quite staggering levels of PM pollution, many (>40) times greater than are residents of apartments. Detailed statistical analysis of individual and classes of personal exposure patterns revealed the following important significant patterns of comparison between children

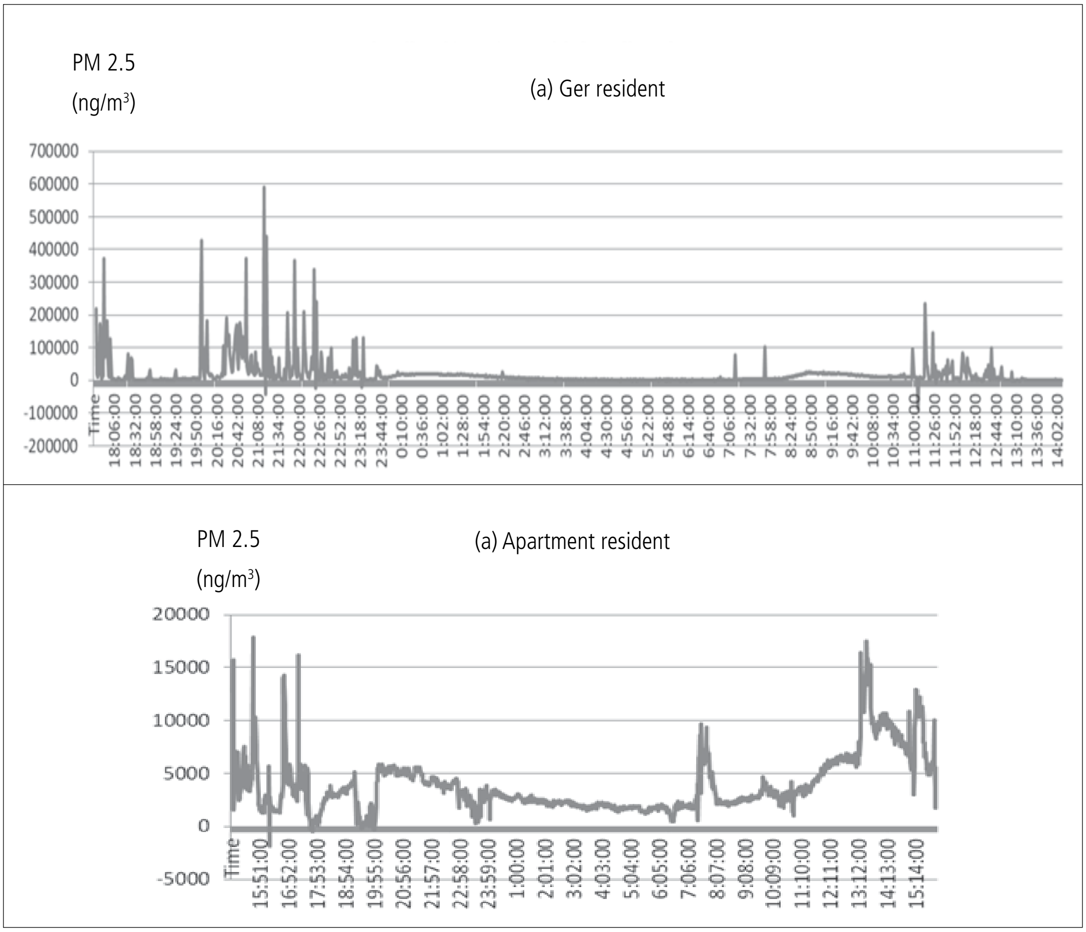

Figure 3. Personal exposure to BC PM2.5: aethalometer tracings for (a) a typical child living in a Ger in the Ger district in winter versus (b) a child living in an apartment in UB in winter. Note that the vertical axis is scaled respectively in each panel to accommodate peak PM2.5 reading for each child.

living under different housing conditions in UB (Table 2). First, in winter, for children living in Gers, walking home from school, riding on the bus and playing outside in the evening yielded peak exposure levels exactly the same as atmospheric outside ambient levels (>650 μg/m^3), versus the 3-fold lower levels that were experienced after arriving home and staying in the Ger, even with the stove being lit, dinner being cooked and father smoking (178 μg/m3, $p<0.02$). Second, overnight, following the cessation of indoor solid fuel burning, the level of PM2.5 in the Ger fell a further 118-fold to a mean level of 1.5 μg/m^3, $p<0.009$. Third, walking to school in the morning raised personal PM2.5 exposure of Ger dwellers once again to ambient outdoor atmospheric levels (47 μg/m^3, $p<0.0002$). But, while inside their school, Ger dwelling children were exposed to PM2.5 concentrations 16-fold below ambient outside levels of exposure (<3 μg/m^3, $p<0.0002$).

The children living in apartments away from the Ger district had much lower peak exposure levels when outside than the children living in the Ger district. Further, indoor exposure peak levels were notably lower in the apartment-dwelling children. However in one case where the mother left the window open for "fresh air" cooling, this child got approximately double the early morning (04:00-06:00) trough exposure of the other apartment dwelling or even Ger dwelling children whose families kept the windows and doors shut.

Thus, we conclude that the major driver of BC PM2.5 exposure for children living in UB is outdoor AP and there is by far the greatest personal exposure in children living in the Ger district. Time spent exposed to outdoor AP is thus a critical determinant of exposure dose for all children no matter what their domicile may be. However, inside Gers, stove fire lighting and burning as well as cooking are major drivers of indoor PM2.5 exposure.

Children who live in other forms of accommodation than Gers in Ger districts, such as wooden houses and apartments appear to be relatively protected from PM2.5 pollution exposure at home compared to Ger dwelling children when the doors an windows are kept shut. Nevertheless, trough levels of indoor AP at school, inside apartments and even overnight in Gers are surprisingly acceptable by WHO and Mongolian National standards. But, indoor tobacco smoking contributes additionally and quite substantially to BC PM2.5 exposure for all classes of children in UB.

Discussion

Herein we report on personal BC PM2.5 winter time exposure measurements versus ambient exposure levels in a small but fairly representative sample of two key subpopulations of children living in UB, Mongolia. In summary, we found that personal exposure to AP of the children in this study was affected principally by ambient outdoor levels of AP, season of the year, time of day, relative location of residence with regard to Ger districts, time spent outdoors as well as Ger stove lighting, cooking and tobacco smoking indoors, and importantly, time with the doors or windows open.

From the point of view of personal exposure to AP, we found that the safest place for children to be in general during the winter months in UB is indoors in an apartment or school with the doors and windows shut. Then, in order of increasing levels of personal exposure an apartment with a window open and then a wooden house and lastly in a Ger in a Ger district. But importantly, we also noted significant levels of personal exposure that approach or reach ambient AP levels during the commute to school, outside playtime and family shopping trips and car rides. Opening the door of the Ger for access or the windows of the centrally steam-heated apartment for "fresh air cooling" and indoor smoking also produce important levels of personal exposure, sometimes even approaching outdoor ambient levels.

We readily acknowledge that the study has some limitations, principally because of the relatively small number of children (12) studied. However, the statistical power of personal exposure monitoring rests on the myriad data points captured within each subject. For example, our aethalometer readings captured personal exposure readings every minute (1,440 data points per day), which, taken together over a 24-hour period together with a contemporaneous activity diary, allowed us to obtain detailed minute to minute significance estimates not only of individual personal exposure, but from these records we could also infer which temporal, environmental and behavioral factors might be driving personal exposure. Multiple days of sampling for each child also allowed us to build a representative picture of personal exposures, which cannot be matched by fixed point ambient monitoring, and reduced the impact of outlying data points skewing results for individual children. Nevertheless it should be born in mind that personal aethalometry does not measure actual minute ventilation with polluted air, which may affect personal uptake of AP particulates. Minute ventilation and thus personal uptake of particulates may be increased, for example, during active play, sports, bicycle riding or other forms of exercise. Although we have previously shown that, at lower ambient levels of BC, personal exposures may actually be lower when walking or bicycling in London than when riding in a car, which was attributed to freedom of ambient air movement [6]. Moreover this was clearly not the case in UB.

Many of the personal PM2.5 exposure aethalometer readings we took on children in winter 2013-14 in UB vastly exceeded both WHO and Mongolian National clean air standards, (<10 μg/m^3 and <25 μg/m^3, respectively for annual PM2.5), most particularly for children living in the Ger districts. The peak levels of PM2.5 AP we recorded in the Ger district are in fact comparable to levels of side stream particulate exposure reported to be caused by smoking a cigarette in a phone booth [7]. Much of this personal exposure was driven by time spent outside breathing ambient levels of AP. However, while levels of AP inside the Ger in the evening were approximately half to a third the external levels of AP, they were still very markedly elevated above WHO safety standards. But surprisingly AP levels in the Ger did drop substantially overnight after the stove was allowed to go out. In contrast, children living in apartments in winter were exposed to much lower levels of AP in general, which may reflect the lower levels of ambient outdoor AP that we and others have measured away from the Ger district.

Gers have been used in Mongolia for thousands of years, are cheap and portable and because of their felt insulation are well adapted to the cold climate. Nevertheless, Ger heating in the severe Mongolian winter at present still requires either biomass or coal burning. This becomes a challenge in concentrated Ger districts, where >182,000 Gers are pitched in close proximity to each other and all have a stove alight in the evening and morning. This leads to atmospheric BC overload, particularly as the valley in which UB is situated is subject to atmospheric inversion, leading to massive BC accumulation in the city atmosphere. The Government of Mongolia and UB City Government have made major efforts, in collaboration with the Millennium Challenge Fund and the World Bank, to install more efficient Ger stoves on a quite massive scale. Yet, our results suggest that even more needs to be done to ameliorate or eliminate coal burning in Ger districts in UB.

It has been suggested based on projected DALY calculations that >80% reduction in coal burning related AP may be needed to make a significant positive impact on health outcomes related to AP in adults in UB [1]. However, the dose-response of children to AP at the extremely high levels found in UB has not been well studied. Certainly, our Mongolian colleagues have noted anecdotally that there is a marked increase in respiratory and cardiac health events among the general adult population during the AP winter season. Moreover, we have recently reported a significant correlation between increased fetal death and seasonal winter elevation of AP [5]. Meanwhile, the WHO has declared diesel PM2.5 AP to be a carcinogen.

Lung development in young children is a crucial determinant of the apogee of lung function, which occurs in young adulthood. The amplitude of this apogee determines the lung reserve, which inexorably declines with the inevitable deterioration of lung function during aging. The dose-response of the extremely high levels of AP on lung function in Mongolian children has not been well studied. Nevertheless, it has been estimated that an average AP level of 70 $\mu g/m^3$ in UB will cause 130 premature deaths of children due to pneumonia, as well as 1440 adult premature deaths due to cardiovascular events [1]. It should be noted that peak exposures to AP in UB, particularly in the Ger districts, is much higher than this, as shown herein.

In Southern California it is well established that proximity to freeways and major roads, which are the major sources of pollution in California, is associated strongly with reduced growth in lung function in school aged children [8, 9]. But, the lung function of children in Los Angeles has recently improved quite dramatically with the successful implementation of abatement measures of traffic related AP [10]. Meanwhile, we have reported that lung function is much worse in children who live in the central parts of UB than in those who live in the less-polluted countryside [11], raising the question of how urban dwelling children in UB will fare regarding the developmental apogee and rate of decline of their lung function over their lifespan [12].

Since 80% of AP in UB in winter is caused by coal burning in Ger stoves, while traffic only contributes <15% of AP in winter, and since children are being exposed personally to massive doses of PM2.5 pollution, particularly in the Ger districts, we hope that our study results will justify further industrial scale efforts to solve the AP challenge by significantly ameliorating, reducing or even eliminating coal burning in Ger stoves in UB. However, once coal burning is gone, then attention must turn to ameliorating traffic exhaust and indoor smoking as the next most important residual air pollutants.

Conflict of Interest

The authors state no conflict of interest.

Acknowledgements

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