Published in final edited form as:

Sci Total Environ. 2016 April 1; 0: 6–12. doi:10.1016/j.scitotenv.2016.01.038.

Household concentrations and personal exposure of PM_{2.5} among urban residents using different cooking fuels

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Abstract

Exposure to PM_{2.5} is a leading environmental risk factor for many diseases and premature deaths, arousing growing public concerns. In this study, indoor and outdoor PM_{2.5} concentrations were investigated during the heating and non-heating seasons in an urban area in northwest China. Personal inhalation exposure levels among different age groups were evaluated, and the difference attributable to different cooking fuels including coal, gas and electricity, were discussed. The average concentrations of PM_{2.5} in the kitchen and the bedroom were 125±51 and 119±64 µg/m³ during the heating season, and 80±67 and 80±50 µg/m³ during the non-heating season, respectively. Indoor PM_{2.5}, from indoor combustion sources but also outdoor penetration, contributed to about 75% of the total PM_{2.5} exposure. Much higher indoor concentrations and inhalation exposure levels were found in households using coal for cooking compared to those using gas and electricity. Changing from coal to gas or electricity for cooking could result in a reduction of PM_{2.5} in the kitchen by 40–70% and consequently lower inhalation exposure levels, especially for children and women.

Graphical abstract

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The authors declare no competing financial interests.

Keywords

household air pollution; inhalation exposure; different cooking fuel; PM_{2.5}

1. Introduction

Particulate matter with an aerodynamic less than 2.5 µm (PM_{2.5}) is a major air pollutant that has been raising public concerns. A correlation between PM_{2.5} pollution and human morbidity and mortality due to cardiovascular and respiratory diseases has been widely documented in literature (Franklin et al., 2006; Kumar et al., 2008; Liao et al., 1999; Morris, 2001; Pope III et al., 2002). The latest Global Burden of Disease reported that exposure to ambient air pollution and household air pollution (HAP) from solid fuel use are leading environmental risk factors in many developing countries including China (Lim et al., 2012). Severe ambient air pollution in China during the last few years has been reported by some previous studies, most of which were done in relatively developed regions and megacities (Cheng et al., 2013; Ma et al., 2014; Tao et al., 2014; Kong et al., 2013; Wang et al., 2014). The ambient PM_{2.5} levels are frequently found to be several times that of the World Health Organization standard (WHO, 2006) in most of these areas, and both primary emission sources and secondary formation are responsible for high pollution episodes (Huang et al., 2015).

Aside from outdoor pollution, indoor PM_{2.5} pollution is also a problem that cannot be ignored. In many countries, most people spend 80~90% of their time indoors (Delgado-Saborit et al., 2011; Koistinen et al., 2001; Scapellato et al., 2009). Because of the low burning efficiency of residential solid fuel combustion (Shen et al., 2010, 2012a), many studies found higher indoor PM_{2.5} concentrations compared to that in outdoor air, especially in rural areas. In fact, HAP from solid fuel combustion is considered to be responsible for more than one million premature deaths in China. Different from the heavy focus on outdoor PM_{2.5} pollution, few studies so far have investigated HAP in China, in either urban or rural regions (Chau et al., 2002; Mestl et al., 2006; Shen et al., 2014a; Wang et al., 2008) and considered the pollution characteristics by season and/or fuel type. The latest Chinese Environmental Exposure-Related Human Activity Patterns Survey (CEERHAPS) showed that many different sources of energies like gas, electricity, and traditional solid fuels

including biomass and coals, have been used for household cooking and heating nowadays, and the pattern varies notably between urban and rural areas (Duan et al., 2014). The use of clean fuels in the resident sector is expected to lower air pollution (Shen et al., 2012b, 2014b) and hence, to benefit human health. However, few studies so far quantified indoor air pollution attributable to different fuel use in households in China (Fischer and Koshland, 2007; Zhong et al., 2012).

The main objective of this study is to characterize household concentrations and personal inhalation exposure levels of PM_{2.5} during the heating and non-heating seasons among urban residents located in northwest China. Differences in household concentrations and inhalation exposure attributable to different cooking fuels were discussed. The results can be used as a reference to establish a model of PM_{2.5} exposure based on household cooking fuel type that would be informative for future epidemiologic studies. The study could also provide important information for future clean fuel intervention programs by quantifying probable changes in indoor PM_{2.5} concentration and inhalation exposure when switching from traditional solid fuels to cleaner household fuels.

2. Materials and methods

2.1 Study area and indoor/outdoor sampling

The study is conducted in Lanzhou (36°N; 103°40'E), northwest China (Figure S1). Usually, the heating season in Lanzhou lasts for 5 months, from November to March. A total of 53 and 54 households were investigated during the heating (February 27th ~ March 9th, 2013) and non-heating seasons (September 14th ~ September 24th, 2013), respectively.

Indoor PM_{2.5} samples were taken from two locations, the kitchen and the bedroom, in each household using air sampling pumps (LP-5, BUCK, USA) with a PM_{2.5} cutter connected at a flow rate of 2 L/min with a sampling duration of 24 hours. The flow rate of the sampling device was calibrated using a soap bubble flow corrector. The PM_{2.5} samples were collected on Teflon membrane filters (PALL, USA), with a diameter of 37 mm and an aperture of 2.0 µm. The Teflon filters were preheated at 35 ± 5°C for 4 hours, equilibrated in a dark desiccator for 24 hours, weighed using a hundred thousandth electronic balance (0.01 mg, Mettler-Toledo, Switzerland), and then stored in polytetrafluoroethylene Ziploc bags. Sample sites were closed off at the air-vent and the wall. In principle, the height of the sample point was consistent with the breathing zone and the range of relative heights were 1.0 ~ 1.5 m. When the instruments were in place, each household member was advised to maintain their daily habits and to make timely contact with the person responsible for the sampling if any problems occurred with the instruments. The necessary data including volumes and sampling durations were recorded at the end of each sampling period. The particle-loaded filters were removed carefully from the PM_{2.5} cutter, equilibrated in a desiccator for 24 hours, and then gravimetrically weighed (0.01 mg, Mettler-Toledo, Switzerland). Based on the sampling volume of about 2.88 m³ (2.0 L/min lasting for 24 hours), the PM_{2.5} concentration is present at a precision of 1 microgram per cubic meter.

Outdoor air samples were collected by using intelligent constant flow sampling pumps (KC-120, Qingdao, China) with a flow rate of 100 L/min during the heating and non-heating

seasons, same as that in the indoor air sampling campaign. The quartz membrane filters (diameter = 90 mm, PALL) were wrapped in silver foil, baked at 400°C for 4 hours in a muffle furnace and then equilibrated in a desiccator for 24 hours. The treated filters were weighed and stored in the same way as the Teflon filters. During the sampling period, all of the sites were well ventilated. The weather was mainly cloudy or sunny, and there was no severe weather such as gales, rainstorms, or sand storms. Since ambient air pollution of fine PM_{2.5} in an urban scale is often homogeneous, we only collected 18 outdoor samples (7 during the heating season and 11 during the non-heating season).

2.2 Data analysis

The PM_{2.5} exposure for different gender/age groups was estimated using equation (1):

$$E_i = \frac{1}{24} \sum t_j q_j, \quad (1)$$

where E_i is the exposure level of PM_{2.5} pollution ($\mu\text{g}/\text{m}^3$); t_j is the time spent by population groups in microenvironment j ; and q_j is the 24-h PM_{2.5} average concentration in microenvironment j . The microenvironments investigated here included the kitchen, bedroom, and outdoor. The average outdoor PM_{2.5} concentration, calculated from all outdoor sampling sites, was used for different age groups using different fuels. Measured indoor PM_{2.5} concentration was used with respect to the indoor microenvironments and fuel types. Due to small differences in climate, social economy, and living habits, the time activity patterns of Shanxi province (Mestl et al., 2006) (also in northwest China) were used in this study (Table S1). The results were expressed as means and standard deviations ($\bar{x} \pm s$).

A structured questionnaire was used to collect household information, including the type of cooking fuel (coal, gas or electricity), space heating approach (central heating system or individual household heating stoves), food preparation methods (boiled, light-frying, deep frying etc), cooking frequency, smokers present in family, and so on. The information was used in a mixed effect regression model to identify key factors affecting indoor PM_{2.5} level. SPSS 20.0 was used for the data analysis. A significance level of 0.05 was adopted. The graphs presented here were drawn using Origin8.5 or Excel.

3. Results and Discussion

3.1 Indoor and outdoor PM_{2.5} concentrations

The PM_{2.5} concentration in the kitchen and the bedroom are summarized in Table 1. There were no significant differences in the PM_{2.5} concentrations found between the kitchen and the bedroom during either season ($p > 0.05$), but as expected, the PM_{2.5} levels were significantly higher during the heating than those during the non-heating season ($p < 0.05$). A significantly positive correlation was found between the kitchen PM_{2.5} concentration and the bedroom PM_{2.5} concentration (Figure 1), suggesting that they may be affected by the same sources, or a well air exchange between the kitchen and the bedroom.

The average outdoor daily PM_{2.5} concentration was 80±49 µg/m³ (40–166 µg/m³ as range) during the non-heating season and much higher during the heating period with a mean and standard derivation of 328±104 µg/m³ (225–530 µg/m³ as range). The Coefficients of Variation (COVs, defined as standard derivation divided by the mean) were 32% and 61% during the heating and non-heating sampling periods, respectively. Since outdoor samples were collected from different sites in the studied urban area, the variance in 30–60% may suggest that the outdoor PM_{2.5} pollution at the urban scale is often homogeneous and support our current sampling approach—that is paired bedroom-kitchen samples in each household but selected outdoor PM_{2.5} samples in these two seasons (see method section).

Indoor PM_{2.5} concentrations, in both the kitchen and the bedroom, were not significantly different from the outdoor PM_{2.5} level during the non-heating season ($p>0.05$). However, during the heating period, outdoor PM_{2.5} was significantly higher than the kitchen and bedroom PM_{2.5} concentrations (Figure 2). One main reason is a distinct indoor-outdoor air exchange between the heating and non-heating periods. During the cold heating seasons, most residents close windows while in the non-heating periods, people may like to keep windows open for a relatively longer time. Results from questionnaires confirmed that the average durations of “how long windows were open per day” were 7.7 hours during the heating season, significantly lower than that of 15.8 during the non-heating season.

3.2 Inhalation exposure and indoor and outdoor contributions

Based on the measured concentrations and fractions of the day spent in each microenvironment (method section), personal inhalation exposure levels were estimated for different groups of children under 14 years (same activity pattern for boys and girls), males and the females aged 15–64 years, and males and the females older than 65 years during the heating and non-heating seasons. During the heating season, the average PM_{2.5} exposures for children aged 0–14 years were 58±22 µg/m³. The concentrations were 54±20 and 64±22 µg/m³ for males and females aged 15–64 years, respectively, and 54±20 and 59 ±21 µg/m³ for males and females older than 64 years, respectively. During the non-heating season, the corresponding values were 38±18 µg/m³ for children under 14 years, 34±16 and 41±19 µg/m³ for males and females aged 15–64 years, and 34±16 and 38±17 µg/m³ for elder males and females above 64 years, respectively. The average PM_{2.5} exposure for each category of people evaluated during the heating season was significantly higher than for those evaluated during the non-heating season.

Relative contributions of PM_{2.5} in different microenvironments differed among the population groups. Overall, indoor PM_{2.5} contributed largely to the overall PM_{2.5} exposure. During the heating season, the contributions of indoor PM_{2.5} exposure for children under 14 years, males aged older than 15, females aged 15–64 and females older than 64 were 76.6%, 74.5%, 78.6%, and 76.7% of the total, respectively. The corresponding contributions of outdoor PM_{2.5} exposure were only about 21.4%–25.5% for the studied population groups. During the non-heating season, 79.8%, 77.8%, 81.4%, and 79.8% of the total PM_{2.5} exposure were attributable to indoor PM_{2.5} for the four groups. The contribution of PM_{2.5} in outdoor air to total inhalation exposure appeared to increase slightly during the heating seasons compared to that in the non-heating seasons, though the outdoor PM_{2.5}

concentration was much higher in the heating season. As people spent a smaller fraction of the day outdoors, the increase was smaller in total inhalation exposure compared to the increase in outdoor air concentration.

It is necessary to note that the indoor $PM_{2.5}$ here was from indoor combustion sources but also partly from outdoor penetration, especially in the heavy pollution period during the heating seasons. And, vice versa, indoor combustion can contribute to outdoor $PM_{2.5}$ at different degrees varying on sampling periods and sites. The estimated relative contributions of indoor and outdoor exposure did not indicate contributions from indoor and outdoor $PM_{2.5}$ sources. The generalization of this result should be taken with caution.

The contribution of $PM_{2.5}$ in the bedroom was the highest compared to that in the kitchen and in outdoor air. This is because of relatively longer duration in the bedroom than that in the kitchen and outdoor. The $PM_{2.5}$ in the bedroom may come from indoor combustion sources like fuel combustion in the kitchen, and also outdoor penetration. As mentioned above, a significantly positive correlation was found between kitchen $PM_{2.5}$ and bedroom $PM_{2.5}$, suggesting common sources of these particles; however it is impossible to separate or identify the common sources of indoor fuel combustions and/or outdoor penetration based on only PM mass concentration data here. Again, the contributions here are calculated for $PM_{2.5}$ in different microenvironments to the total overall $PM_{2.5}$ exposure, rather than for sources in indoor and/or outdoor areas. However, it would be highly interesting and meaningful to do this. The contribution of $PM_{2.5}$ in the kitchen was lower for children under 14 years, but higher for females aged 15–64 years. That is again mainly due to different times spent in the kitchen among different population groups.

3.3 Difference attributable to household cooking fuels

Household fuel use is one important source of indoor $PM_{2.5}$ pollution. Among the investigated households, near 75% of households used gas fuels like liquefied petroleum gas (LPG) and natural gas for daily cooking, while about 13% used electricity for cooking with the remaining using coal as the main cooking fuel. The fuel use profile was very similar to that found in the last and also the first CEERHAPS (Duan et al., 2014). Variances in indoor levels of air pollutants in the use of different fuels are often expected. As shown in Figure 3, during the heating season, the average $PM_{2.5}$ concentrations in kitchens when coals were used ($204 \pm 50 \mu\text{g}/\text{m}^3$) were significantly higher than in those using gas ($114 \pm 39 \mu\text{g}/\text{m}^3$) and in those using electricity ($107 \pm 43 \mu\text{g}/\text{m}^3$) ($p < 0.01$). The average $PM_{2.5}$ concentrations in the bedrooms of homes using coal, electricity, and gas were $159 \pm 60 \mu\text{g}/\text{m}^3$, $139 \pm 99 \mu\text{g}/\text{m}^3$, and $109 \pm 57 \mu\text{g}/\text{m}^3$, respectively, with a statistically significant high daily $PM_{2.5}$ concentration in the bedroom of homes using coals ($p < 0.01$).

During the non-heating season, the average $PM_{2.5}$ concentrations in the kitchen using coal, gas, and electricity were $213 \pm 89 \mu\text{g}/\text{m}^3$, $65 \pm 42 \mu\text{g}/\text{m}^3$, and $55 \pm 35 \mu\text{g}/\text{m}^3$, respectively (Table 2), and the differences were again statistically significant ($p < 0.05$). For the $PM_{2.5}$ in the bedroom, the daily average in homes using coal, gas, and electricity were $102 \pm 65 \mu\text{g}/\text{m}^3$, $79 \pm 49 \mu\text{g}/\text{m}^3$, and $68 \pm 41 \mu\text{g}/\text{m}^3$, respectively. High indoor contamination levels of $PM_{2.5}$ when coals were used for cooking were also revealed, however, the differences were not

statistically significant ($p>0.05$), which could be probably due to good ventilation conditions and relatively longer ventilation times during the non-heating season.

Such a difference in indoor air would result in consequent variations in daily $PM_{2.5}$ exposure levels of the population using different fuels. Higher inhalation exposure concentration were observed among residents using coals as the main cooking fuel, followed by those using electricity and gas (Figure 4). The tendency was same in the heating and non-heating sampling periods. Consequently, calculated contributions of $PM_{2.5}$ in the kitchen to the overall inhalation exposure vary among groups using different household cooking fuels. The percentages increased among groups who used coals for cooking compared to among those using gas and electricity for daily cooking. The contributions of indoor $PM_{2.5}$ to the overall total exposure were approximately 4~7-fold more than that of outdoor $PM_{2.5}$ (4.5-, 4.0-, 5.3-, and 4.6-fold more during the heating season and 5.6-, 5.1-, 7.4-, and 6.2-fold more during the non-heating season for the four groups, respectively) when coals were used.

3.4 Difference attributable to other influencing factors

Cooking frequency—Aside from the fuel types used for cooking, cooking methods and frequency may affect indoor air quality as well. Due to similar habits among residents in the region, light-frying and/or boiling are typical food preparation ways in most families in their daily lives. The average kitchen $PM_{2.5}$ concentrations were $92\pm33\text{ }\mu\text{g}/\text{m}^3$, $115\pm35\text{ }\mu\text{g}/\text{m}^3$, $131\pm57\text{ }\mu\text{g}/\text{m}^3$, and $135\pm54\text{ }\mu\text{g}/\text{m}^3$ when the daily cooking frequency was 0, 1, 2 and 3, respectively. There was an increased tendency, but statistically not significant.

Household heating approach—In cold seasons, space heating is required in Lanzhou, same as in most Chinese households located in north region. Two distinct heating ways are most commonly in the urban area of Lanzhou: heating supplied by the central heating system or individual household heating by installing coal stoves. The average daily $PM_{2.5}$ concentrations in the kitchen and bedroom of households using individual coal stove for heating were $167\pm40\text{ }\mu\text{g}/\text{m}^3$ and $177\pm85\text{ }\mu\text{g}/\text{m}^3$, respectively. The concentrations were much higher than those in households covered by the central heating system ($109\pm45\text{ }\mu\text{g}/\text{m}^3$ and $98\pm38\text{ }\mu\text{g}/\text{m}^3$, respectively) (Table 2). The burning efficiency of residential coal burning in individual household heating stoves is usually low, and hence produces high emissions of air pollutants from the incomplete combustion process. Therefore, the use of low efficiency individual household heating stove may directly result in severe indoor air pollution.

Smokers in household—Smoking is one important behavior affecting indoor air quality. The daily kitchen and bedroom $PM_{2.5}$ concentrations were $137\pm49\text{ }\mu\text{g}/\text{m}^3$ and $118\pm51\text{ }\mu\text{g}/\text{m}^3$, respectively when there are smokers present. The levels were apparently higher than $125\pm70\text{ }\mu\text{g}/\text{m}^3$ and $115\pm62\text{ }\mu\text{g}/\text{m}^3$ when no smokers were reported at the sampling time, but statistically not significant ($p>0.05$). This could be due to large variances in measured $PM_{2.5}$ concentrations and interacted impacts with other influencing factors.

Information for many other factors like household layout, household area, and separate kitchens, are also collected from questionnaires and analyzed by using the multivariable linear regression models. The results showed that the sampling period (heating vs non-heating seasons) and cooking fuels (gas, electricity or coal) are the two most significant

factors, while the influences of others are statistically insignificant. It is necessary to note that some quantitative information like hours of open windows per day, duration in the kitchen area and cooking times, are all self-reported. Self-reported errors cannot be avoided, causing potential uncertainties in the analysis results of these factors.

3.5 Discussion and limitations

Exposure to PM_{2.5} has been identified as a leading environmental risk factor for many diseases and premature deaths globally, especially in developing countries like China. So far, PM_{2.5} is not regulated in the Chinese Indoor Air Quality Standard (GB/T 18883-2002). WHO air quality guidelines of daily PM_{2.5} concentration is 25 µg/m³ (WHO, 2006) and this is also the guideline applicable to indoor environments since there is no convincing evidence of a difference in the hazardous nature of particles from indoor sources as compared to in those from outdoor sources (WHO, 2006, 2010). Therefore, results from the present study indicated that daily indoor PM_{2.5} levels exceeded the standard limit nearly all days during the heating season, and over 85% of days during the non-heating season. Overall, the indoor PM_{2.5} concentrations during the heating and non-heating seasons were 122±58 µg/m³ and 80±59 µg/m³, respectively, which were 4.9- and 3.2-fold of the limit of 25 µg/m³, respectively. In the new Chinese ambient air quality standard, the limit of daily PM_{2.5} level is 75 µg/m³. In comparison, outdoor PM_{2.5} pollution in the studied area clearly exceeded the national air quality standard in both heating and non-heating seasons. Nearly 4.7-fold of the standard could be found in the heavily polluted heating season. Such a high pollution level would indicate more serious detrimental impacts on human health.

Female aged 15–64 years had the highest PM_{2.5} inhalation exposure concentration. Shimada and Matsuoka (2011) analyzed the PM_{2.5} exposure level in four Asian countries and found that the PM_{2.5} exposure level was highest for unemployed women aged 35–64 years. Balakrishnan *et.al* (2004) investigated the indoor PM concentrations over a 24-hour period in 412 households using bio-fuels in the Andhra Pradesh, and also found that PM exposure levels for the female between 5–40 years were significantly higher than those for the male and younger children. Women in this age group were most likely to be involved in cooking activities (Balakrishnan *et al.*, 2004). The PM_{2.5} exposure concentrations were generally higher among children aged 0–14 years and women when compared with the exposure levels among males older than 14 years, indicating that children and women could be more vulnerable to air pollution than men. Therefore, reducing PM_{2.5} levels is of high priority for protecting females and children.

As most residents spend longer time indoors rather than outdoors, severe indoor air pollution often results in high inhalation exposure and consequent high risks for many respiratory and cardiovascular diseases. Though varying among different age groups, the indoor PM_{2.5} contributed to nearly 75% of the total PM_{2.5} inhalation exposure. Severe outdoor PM_{2.5} pollution in heating seasons may increase the relative contribution of outdoor PM_{2.5} exposure to the total. However, due to relatively short fractions of the day spent outdoors, the increase might be small. In addition, increased outdoor PM_{2.5} would also result in elevated indoor PM_{2.5} levels due to outdoor penetration, and hence show higher indoor contributions since we now calculated the contributions of indoor and outdoor PM_{2.5}.

exposure, instead of individual contributions of indoor and outdoor sources. Chau *et al.* (2012) investigated the exposure concentrations of PM₁₀ for different groups in Hong Kong and reported that indoor microenvironments contributed to 54.7%, 38.7%, and 32.1% of the PM₁₀ exposure for the juvenile, the adult, and the elderly, respectively. Likewise, Wang *et al.* (2008) estimated that PM₁₀ in indoor microenvironments contributed to 41%, 54%, and 80% of the PM₁₀ exposure of the juvenile, the adult, and the elderly, respectively. Therefore, the indoor environment makes an important contribution to the overall particulate matter exposure for urban residents, even though the relative contribution percents display a temporal and regional variation. In the high pollution episode, the public is often guided to protect themselves by staying at home and/or closing windows. However, due to a much larger fraction of the day spent indoors, it may be more necessary to conduct effective actions to reduce indoor pollution of PM_{2.5}, as well as other pollutants, to lower exposure level and protect human health.

Household solid fuel use is one important source of PM_{2.5}, as well as some other air pollutants. The use of traditional solid fuels like coals for cooking leads to significantly high HAP and personal inhalation exposure as compared to the use of relatively cleaner gas and electricity. The kitchen PM_{2.5} level may decrease by about 40–70% if a change is made from the use of coals to gas and/or electricity. The reduction in the bedroom PM_{2.5} was around 30%. Consequent decrease in daily PM_{2.5} exposure could be also expected. Differences in indoor air pollution attributable to different fuel use have also been evident in some previous studies. For example, Siddiqui *et al.* (2009) monitored 51 kitchens using wood and 44 kitchens using LPG, and found that the daily average PM_{2.5} concentration in the kitchen using wood (2740 µg/m³) was significantly higher than in those using LPG (380 µg/m³) ($p < 0.001$). Brauer *et al.* (1995) investigated 22 kitchens in rural areas in Mexico and reported that the average PM_{2.5} concentration in the kitchen using biomass was 555 µg/m³, which was significantly ($p < 0.05$) higher than that in the kitchen using LPG (69 µg/m³). These studies confirm that the use of traditional solid fuels like biomass and coal may lead to high indoor pollution and subsequent higher exposure concentration, while the use of clean fuels like gas and electricity could lower indoor air pollution significantly. But, it is very important to note that even in households when gas and electricity were used for cooking, the indoor PM_{2.5} might be still very high like in this study, in which they were still above the WHO guideline of 25 µg/m³, indicating more effective efforts and pollution control actions are needed in the future to improve indoor air quality.

We acknowledged that one important limitation of this study is that personal inhalation exposure was estimated based on the concentrations measured from stationary samplers and literature reported personal activity patterns. The use of personal carried samplers is more appropriate for the evaluation of inhalation exposure, and the technology has been adopted in some field studies. However, because of relatively high costs and high cooperation of local residents, there are often more difficulties in the field use of personal carried samplers. Another limitation of this study is that only three microenvironments including the kitchen, bedroom and the outdoors are analyzed here. People may stay at other microenvironments. The contributions of PM_{2.5} in different microenvironments to the overall total PM_{2.5} exposure in the present study did not indicate contributions from indoor and outdoor

sources. Indoor combustion sources may contribute to outdoor PM_{2.5} and vice versa. Therefore, future studies to identify potential sources of indoor and outdoor PM_{2.5} and attribute contributions to different source types would be helpful for policy makers to develop effective pollution control countermeasures. It is also noted that in the present study, only external inhalation exposure was characterized, while the risks and health outcomes due to PM_{2.5} inhalation exposure are not studied here. Further works would be interesting, particularly those taking dose-effect relationship and variances in individual susceptibility into account.

4. Conclusions

There are significant seasonal variations in indoor PM_{2.5} levels among different microenvironments. The average PM_{2.5} concentrations in the kitchen and the bedroom were $125 \pm 51 \mu\text{g}/\text{m}^3$ and $119 \pm 64 \mu\text{g}/\text{m}^3$ during the heating season and $80 \pm 67 \mu\text{g}/\text{m}^3$ and $80 \pm 50 \mu\text{g}/\text{m}^3$ during the non-heating season, respectively, without significant differences between the kitchen and the bedroom in both seasons. The PM_{2.5} concentration in the bedroom positively correlated with that in the kitchen, indicating that they are from or affected by similar indoor and/or outdoor sources. Overall, the PM_{2.5} exposure in indoor air contributed up to about 75% of total inhalation exposure. However, it is necessary to note that PM_{2.5} in indoor air may come from outdoor air, especially in heavily polluted heating seasons, and vice versa. Therefore, the result should not be simply generalized and must be used with caution in future studies. During the heating season, the daily average inhalation exposure of PM_{2.5} were $58 \mu\text{g}/\text{m}^3$, $54 \mu\text{g}/\text{m}^3$, $64 \mu\text{g}/\text{m}^3$, and $59 \mu\text{g}/\text{m}^3$ for children at 0–14 years, males older than 15, females aged 15–64, and females older than 64, respectively. The corresponding results were $38 \mu\text{g}/\text{m}^3$, $34 \mu\text{g}/\text{m}^3$, $41 \mu\text{g}/\text{m}^3$, and $38 \mu\text{g}/\text{m}^3$, respectively, during the non-heating sampling period. Generally, the PM_{2.5} exposure in grown females was the highest and in grown/elderly males the lowest.

The indoor PM_{2.5} concentrations in households using coal were significantly higher than in those using gas or electricity. And consequently, the exposure concentration in the group using coal for cooking was significantly higher than those in groups using gas and/or electricity. The contribution of the indoor microenvironments using coal for daily cooking to the overall PM_{2.5} exposure was 4 ~ 7-fold higher than that of the outdoor environment. Changing from coal to gas or electricity would have a reduction of PM_{2.5} in the kitchen by about 40–70% and result subsequent reductions in personal inhalation exposure levels.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

This research was supported by the Ministry of Environmental Protection of China (201109064), the State Key Laboratory of Environmental Criteria and Risk Assessment (SKLECRA2015OFP02 and SKLECRA2013OFP005) and the U.S. National Institutes of Health (K02HD70324). We also sincerely thank Mr. Zhihan Zou (McGill University) for his proof reading for English language.

Appendix

Information about the location of the sampling site and activity patterns for different age/gender groups is provided in the appendix and available online.

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Highlights

- Comparison and seasonal differences in indoor and outdoor PM_{2.5}
- Estimate personal inhalation exposure and indoor/outdoor contributions
- Distinct indoor PM_{2.5} levels attributable to different cooking fuels
- Use of coal for cooking lead to higher indoor pollution and exposure level
- Indoor PM_{2.5} exposure contributed to near 75% of total inhalation exposure

Figure 1. Relationship between PM_{2.5} concentration in the bedroom and that in the kitchen measured using stationary samples during the heating and non-heating seasons. The scales are in the logarithmic scale. A 1:1 line is shown.

Figure 2. Comparison of indoor (kitchen and bedroom) and outdoor PM_{2.5} concentrations during the non-heating and the heating sampling periods. Data shown are means and standard derivations.

Figure 3.

Comparison of daily PM_{2.5} concentrations in the kitchen and bedroom of households using different cooking fuels during the heating and non-heating seasons. Data shown are means and standard deviations. The sample size in each sub-group is listed.

Figure 4.

Estimated daily $PM_{2.5}$ inhalation exposure for different age groups (0–14, 14–64 and >65 for the male and the female) using different household cooking energies (gas, electricity and coal).

The PM_{2.5} concentrations (µg/m³) in the kitchen and the bedroom of the investigated households during the heating and non-heating sampling periods.

Table 1

Season	Sites	N	x±s	P25	M	P75	Range
Heating	Kitchen	53	125 ± 51	85	119	149	48~ 279
	Bedroom	53	119 ± 64	79	104	139	38~ 368
Non-heating	Kitchen	54	80± 67	36	61	106	9 ~ 388
	Bedroom	54	80 ± 50	47	72	97	14~ 212

Data shown are sample size (N), means and standard derivations (x±s), median (M), the 1st and 3rd interquartile (P25 and P75), and range.

Table 2

Daily PM_{2.5} concentrations (µg/m³) in the kitchen and the bedroom when different energies used for cooking during the heating and non-heating sampling periods. During the heating period, there are two different heating ways: central heating and individual household heating stoves.

		N	Kitchen				Bedroom			
			median	geomean	mean	stdev	median	geomean	mean	stdev
Non-heating season	Coal	6	189	200	213	89	84	82	102	65
	Gas	7	59	53	65	42	73	65	79	49
	Electricity	41	49	43	55	35	67	56	68	41
	Coal	1	279				71			
Heating season	Gas	34	110	102	107	37	92	92	99	39
	Electricity	4	89	81	84	26	95	88	92	30
		39	109	102	110	45	91	91	98	38
	Coal	6	194	187	191	40	171	167	173	50
	Gas	6	145	145	148	35	124	145	164	104
	Electricity	2	153	151	153	32	232	209	232	144
		14	170	163	167	40	143	162	178	85

Data shown are sample size (N), means and standard derivations (stdev), median (M), and geometric mean (geomean).