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Household air pollution and personal inhalation exposure to particles (TSP/$PM_{2.5}$/$PM_{1.0}$/$PM_{0.25}$) in rural Shanxi, North China☆

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ABSTRACT

Personal exposure to size-segregated particles among rural residents in Shanxi, China in summer, 2011 were investigated using portable carried samplers (N = 84). Household air pollution was simultaneously studied using stationary samplers in nine homes. Information on household fuel types, cooking activity, smoking behavior, kitchen ventilation conditions etc., were also collected and discussed. The study found that even in the summer period, the daily average concentrations of $PM_{2.5}$ and $PM_{1.0}$ in the kitchen were as high as 376 ± 573 and 288 ± 397 μg/m^3 (N = 6), that were nearly 3 times of 114 ± 81 and 97 ± 77 μg/m^3 in the bedroom (N = 8), and significantly higher than those of 64 ± 28 and 47 ± 21 μg/m^3 in the outdoor air (N = 6). The personal daily exposure to $PM_{2.5}$ and $PM_{1.0}$ were 98 ± 52 and 77 ± 47 μg/m^3, respectively, that were lower than the concentrations in the kitchen but higher than the outdoor levels. The mass fractions of $PM_{2.5}$ in TSP were 90%, 72%, 65% and 68% on average in the kitchen, bedroom, outdoor air and personal inhalation exposure, respectively, and moreover, a majority of particles in $PM_{2.5}$ had diameters less than 1.0 μm. Calculated time-weighted average exposure based on indoor and outdoor air concentrations and time spent indoor and outdoor were positively correlated but, was ~33% lower than the directly measured exposure. The daily exposure among those burning traditional solid fuels could be lower by ~41% if the kitchen was equipped with an outdoor chimney, but was still 8–14% higher than those household using cleaning energies, like electricity and gas. With a ventilator in the kitchen, the exposure among the population using clean energies could be further reduced by 10–24%.

1. Introduction

Exposure to ambient particulate matter (PM) has been documented to be associated with morbidities and mortalities of respiratory and cardiovascular diseases in many epidemiological studies (Englert, 1999; Kan et al., 2005; Pope et al., 2002, 2009; Schwartz et al., 2001). In 2012, nearly 7.0 million premature deaths globally were caused due to inhalation exposure to indoor and outdoor air pollution (WHO, 2014). Of various PM sources, residential solid fuel combustion is a major emitter because of large fuel consumption and low combustion efficiency. It was estimated that globally about 27% of the primary $PM_{2.5}$ (PM with diameter less than 2.5 μm) emissions were from residential combustions of coal and biomass (Huang et al., 2014).

Though outdoor air pollution was identified as one important risk factor globally, especially in developing countries, the influence of indoor air pollution is considerably significant because people usually spend more time indoors (Shimada and Matsuoka, 2011; Wang et al., 2008a). Moreover, indoor pollution in many rural households could be much more severe than that outdoors due to factors like direct impacts of inefficient solid fuel burning and poor ventilation conditions (Pan et al., 2001; Wang and Xu, 2007). The

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contribution of indoor microenvironments to personal exposure to submicron particle could be up to 90% (Buonanno et al., 2012). Exposure to household air pollution has been recognized as one of the top environmental risk factors (Zhang and Smith, 2007), causing about 4 million premature deaths globally (WHO, 2014).

In the evaluation of personal inhalation exposure, pollution levels in each microenvironment and time spent indifferent microenvironments are two important aspect (Wilson and Brauer, 2006). For instance, Wilson and Brauer (2006) estimated that ambient $PM_{2.5}$ exposure (including exposure to outdoor $PM_{2.5}$ while outdoors and exposure while indoor to $PM_{2.5}$ that infiltrated indoors) only ascribed to 44% of total personal exposure. Lim et al. (2012) found that average contributions from residential indoor, non-residential indoor, transportation, and outdoor to total personal exposure for a person lived in Seoul, Korea were 36.2%, 53.4%, 6.7% and 3.7%, respectively. Thus, it is becoming more common to adopt personal carried samplers in inhalation exposure measurements (Hu et al., 2014; Johannesson et al., 2007; Williams et al., 2008). However, relatively high costs and inconvenience are main barriers in a large-scale use of personal samplers in field. Most exposure measurements using personal samplers so far are mainly in developed countries and many only reported $PM_{2.5}$ (Braniš and Kolomazníková, 2010; Janssen et al., 2000; Johannesson et al., 2007; Lachenmyer, 2000; Lim et al., 2012; Mohammadyan and Ashmore, 2005; Ohura et al., 2005; Sørensen et al., 2005), while exposure to submicron and ultrafine particles was rarely studied (Buonanno et al., 2012, 2014). Usually, smaller particles can penetrate deeper into the lung area (Brown et al., 1950) causing much more severe adverse effects on human health, but it also reported that coarse particles may induce more cytotoxicity potentials in vitro study than $PM_{2.5}$ because of higher percentage of endotoxins (Osornio-Vargas et al., 2003). To better understand potential health risks of ambient particles, size distribution of particles, instead of a single fine or coarse fraction, is essential.

Severe indoor and outdoor air pollution in rural China has been documented in some past studies (Chen et al., 2016; Hu et al., 2014; Wang et al., 2008b; Zhang and Smith, 2007). However, personal samplers were rarely adopted in inhalation exposure study in China, and a few available studies (Hu et al., 2014; Zhong et al., 2012) mainly focused on $PM_{2.5}$, without detailed size distribution information. In this study, a field investigation was conducted to measure inhalation exposure of PM in a rural community in China by using personal samplers. Four p.m. size fractions with diameters $\leq$0.25, 0.25–1.0, 1.0–2.5 and > 2.5 μm (denoted as $PM_{0.25}$, $PM_{0.25\text{-}1}$, $PM_{1\text{-}2.5}$ and coarse $PM_{>2.5}$, respectively) were measured. The results were compared to that calculated personal daily exposure based on stationary indoor and outdoor samplers. The influences of factors like household energy use and personal cooking and smoking behaviors that are often recognized as important factors affecting household air pollution and personal inhalation exposure were investigated.

2. Material and method

2.1. Study site and personal exposure measurement

The measurement was in four mountain villages (Songyan, Yixing, Liyang and Pingsong) in rural Shanxi, China, during a summer period (May 7th to 14th) in 2011. Relative high morbidities of some diseases especially lung cancer and neural tube defects have been found in this area, which are thought to be highly related to a wide use of traditional solid fuels because of easy access and low costs (Li et al., 2011; Ren et al., 2011; Zhang et al., 2009). For example, coal was the main fuel used in Songyang. Clean energies like Liquid Petroleum Gas (LPG) and electricity were available in some high-income households. For example, LPG and electricity were widely used in Yixing and Liyang.

Depending on the willingness, eighty-four adult residents from these four villages were measured for their daily inhalation exposure measurement to particulate matter. The participants were asked to carry the personal samplers (SKC, USA) for a duration of 24 h. The pump was placed in a waist bag and carried by the resident. A tube was connected to the pump with its inlet placed close to participant's nose so as to sample inhaled air. The samplers were required to be placed nearly within 1 m when the residents were sleeping or using the restroom. The time when the pump was on and off (the next day) was recorded on the sampling record form, and also the sampling volume saved automatically in the instrument was recorded. These acts as a check for the sampling duration and only samples with a valid duration of 22–26 h were saved and used in data analysis. Owing to a limitation of only 20 instruments available, 12–15 volunteers were enrolled in the measurement in each day. All measurements were completed in one week.

The pump flow (~8.2 L/min) was calibrated before and after every day measurement (Bios. Defender 510, USA). Four particle size fractions (>2.5 μm, 1.0–2.5 μm, 0.25–1.0 μm and <0.25 μm) were collected using Sioutas cascade impact (SKC) on glass fiber filters (GFFs, 0.45 μm, BUCK, Orlando FI, USA). Written informed consents were assigned individually. Information including name, sex, cooking and smoking behaviors, ventilation condition in kitchen, whether the bedroom is separated from kitchen or not, household energy types and daily activities when wearing personal sampler were reported by themselves and recorded (Table 1, and details in Tables S1–S5).

2.2. Household air pollution measurement

Besides direct personal exposure measurement, stationary samplers were also applied to collect indoor (kitchen and bedroom) and outdoor air. Of the 84 volunteers in personal exposure measurement, nine had stationary samplers placed in their homes, depending on their own willingness and also due to limited samplers available in this field campaign. There was one home where cook and sleep were in the same room, while for the others the bedroom was separated from the kitchen. Of these 9 homes, 6 had paired indoor-outdoor samples while the other 3 only had indoor samples. In the 6 homes had paired indoor-outdoor samples, 5 have both samples in the kitchen and the bedroom while the other one only had a sample in the bedroom. Therefore, a total of 21 stationary samples was obtained, of which 7 were from the kitchen, 8 were from bedroom and 6 for outdoor (Table S6). The pump, cascade and filter were exactly the same as those used by personal samplers. Stationary samplers were placed approximately 1–2 m above ground and $\geq$0.5 m from a wall, and the samplers in the kitchen were placed about 2.0 m away from the stove. Outdoor air samplers were placed in the center of front yard.

2.3. Data analysis

Particle mass concentrations were calculated from the mass of particles on the filters (gravimetrical measurement using a digital balance with a readability of 0.01 mg) divided by the recorded sampling volume. Field blanks were taken and reported concentrations are blank corrected. TSP was calculated as the sum of the four particle size fractions. $PM_{2.5}$ was calculated as the sum of latter 3 particle size fractions (1.0–2.5 μm, 0.25–1.0 μm and <0.25 μm). $PM_{1.0}$ was calculated as the sum of latter 2 particle size fractions (0.25–1.0 μm and <0.25 μm), and $PM_{0.25}$ was particle fraction with size <0.25 μm.

To indicate relatively importance of indoor and outdoor