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Modeling of residential indoor $PM_{2.5}$ exposure in 37 counties in China☆

Yanjun Du, Yanwen Wang, Zonghao Du, Yi Zhang, Dandan Xu, Tiantian Li*

National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, 100021, China

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ABSTRACT

It is critical to estimate the exposure to indoor air pollution of residents spending most of their time in such microenvironments. However, the understanding regarding $PM_{2.5}$ exposure in residential indoor environments is very limited. In this study, we collected participants' basic information and time–activity patterns, as well as details of other factors related to indoor air pollution exposure, through questionnaires presented to a large population in 37 counties of China. Continuous monitoring of ambient $PM_{2.5}$ concentrations was performed using an environmental fixed-site monitoring network. Residential indoor $PM_{2.5}$ concentrations were predicted using a mass balance model based on the data obtained. Evaluation of continuous daily average residential indoor $PM_{2.5}$ exposure doses for large populations during winter revealed concentrations ranged from 67 to 195 μg/m^3. Finally, differences in residential indoor $PM_{2.5}$ exposure between northern and southern China were investigated. The results suggested that residential indoor $PM_{2.5}$ concentrations in northern China, associated with heating, were higher than in the south. The established model could be important for improved understanding of human exposure to indoor $PM_{2.5}$ air pollution.

1. Introduction

In China, air pollution of fine particulate matter ($PM_{2.5}$) is severe (Huang et al., 2017a), especially during winter (CNEMC, 2017). This has adverse impacts on human health (Xu et al., 2013; Du and Li, 2016; Huang et al., 2016, 2017b) because many toxic pollutants can be adsorbed by airborne $PM_{2.5}$ (Zhang et al., 2016; Yang et al., 2017). Previous studies have reported that large numbers of people spend over 80% of their time in indoor microenvironments (Ministry of Environmental Protection of the People's Republic of China, 2013; Spalt et al., 2016). Thus, it is critical to estimate the degree of exposure to air pollution in such microenvironments, especially in countries with high levels of air pollution. However, the understanding of $PM_{2.5}$ exposure in residential indoor environments in China is limited.

One method of monitoring residential indoor $PM_{2.5}$ concentrations is to sample indoor air. Earlier studies that have reported on residential indoor $PM_{2.5}$ concentrations in Shanghai, Taiyuan, and Beijing (Xu et al., 2015; Meng et al., 2007; Du et al., 2016) used between 23 and 154 samples, and they found residential indoor concentrations in China were 13.0–283.9 μg/m^3. However, the sampling methods adopted were labor intensive and they required effective compliance of the survey subjects; thus, results were achieved for only small populations. Furthermore, continuous monitoring is difficult to undertake for large populations. Another method of monitoring residential indoor $PM_{2.5}$ concentration is through model simulation (Huang et al., 2014; Gaffin et al., 2016; Otto et al., 2003; Avril et al., 2015; Burke et al., 2001). Such studies have established simulation models by correlating indoor and outdoor $PM_{2.5}$ concentrations. Indoor $PM_{2.5}$ concentrations can be obtained by incorporating outdoor $PM_{2.5}$ concentration data into simulation models. Simulating indoor concentrations often requires large data sets and consequently, few such modeling studies have been conducted for large populations in China. Shi et al. (2017) and Xie et al. (2017) have both simulated indoor $PM_{2.5}$ exposure in Beijing, China. However, because China is such a vast country with diverse population-activity patterns, studies of indoor $PM_{2.5}$ exposure in many more areas should be conducted to improve the understanding of the human health risk on the national scale.

This study conducted a comprehensive residential indoor $PM_{2.5}$ exposure survey in 37 counties throughout northern and southern China, to reflect the typical indoor exposure scenario on a national

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* Corresponding author.
E-mail address: litiantian@nieh.chinacdc.cn (T. Li).

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scale. The results obtained in this study could provide practical information regarding human health protection during air pollution episodes. The primary aims of the present study were: 1) to simulate daily residential indoor $PM_{2.5}$ concentrations and exposure doses consecutively during winter in China; and 2) to study the differences in residential indoor $PM_{2.5}$ exposure between southern and northern China counties during winter.

2. Materials and methods

2.1. Area and period of study

In China, ambient $PM_{2.5}$ pollution is more severe in winter than in other seasons. Therefore, we conducted our research in China during winter 2013–2014 (December 1, 2013 through February 28, 2014). Thirty-seven counties were investigated (Fig. 1), where fixed-site stations for monitoring ambient $PM_{2.5}$ have been established. Overall, 22 counties were located to the north of the Huai River and the Qinling Mountains and 15 counties were to the south of those areas. Further information regarding the 37 counties surveyed is provided in the Supporting Information (Table S1).

2.2. Data

2.2.1. Overview of participant questionnaire

In each county surveyed, one community with a population >10,000 was selected according to community compliance. Then, more than 1000 people were chosen based on cluster random sampling. People of all ages were included as study participants.

Each participant was asked to complete an exposure factor questionnaire to ascertain details regarding their domestic characteristics and typical activity patterns during winter. The questions were asked during face-to-face interviews during December 2013 and February 2014. Participants were asked specific questions about family household population, time spent at home, time spent with open windows, time spent with closed windows, and the other behaviors related to individual exposure in winter. Times were recorded in minutes in a diary. To minimize deviations attributable to different investigators, the investigators were subjected to a uniform training program prior to conducting the surveys. The survey data were input separately using Epidata software by two investigators. Then, agreement between the two databases was checked. Finally, data with missing rate ≥5% and error rate ≥5% were removed to ensure the quality of the data used in this study.

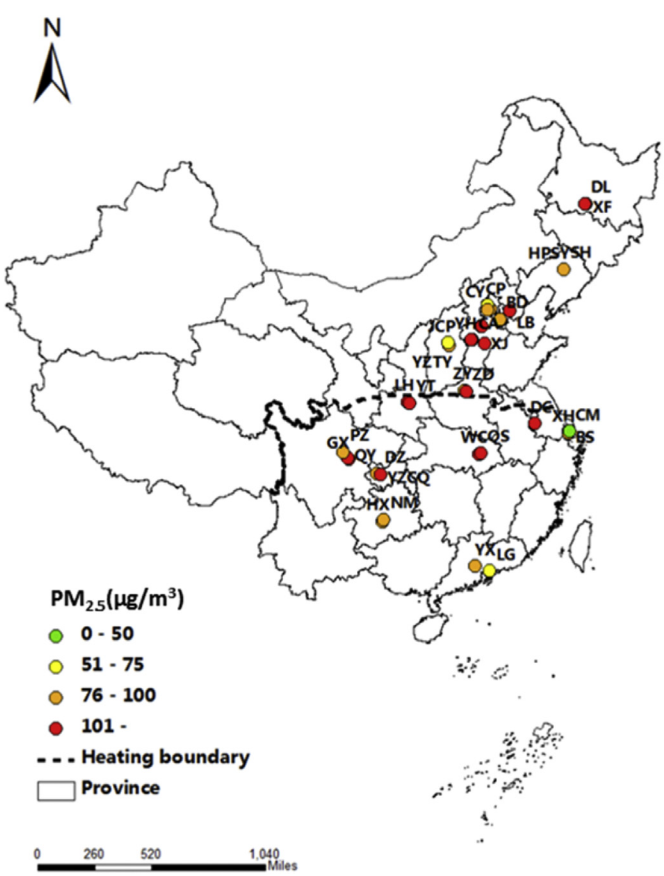

Fig. 1. Location of 37 Chinese counties investigated in this study.

2.2.2. Ambient $PM_{2.5}$ data

We obtained ambient $PM_{2.5}$ data from the fixed monitoring sites during winter 2013–2014 from the China National Environmental Monitoring Center (2017). The raw data were provided as hourly average $PM_{2.5}$ concentrations. Details of the data are given in Fig. S1. Data from the nearest ambient monitoring site were matched with the locations at which the questionnaire survey data were obtained.

2.2.3. Other parameters

Other parameters used for the calculations were derived from references. Natural ventilation associated with open windows was assumed 4.8 h^{-1} (Zhou et al., 2013) and that with closed windows was 0.31 h^{-1} (Shi et al., 2015). The penetration factor of an open window was taken as 1.0 (Chen et al., 2012) and that of a closed window was 0.8 (Chen et al., 2012; Shi et al., 2013). Per capita floor space of housing was derived from the National Bureau of Statistics of China (2014), average height of the room was 2.8 m (Shi et al., 2013), and the surface removal rate constant was set as 0.09 h^{-1} (Chen et al., 2012). Details of the raw materials are given in Table S2.

2.3. Models and calculations

2.3.1. Simulation of residential indoor $PM_{2.5}$ concentrations

Residential houses in China do not normally use air filtration systems. This means that the principal factors governing indoor $PM_{2.5}$ levels are the contributions from outdoor sources and the rate of deposition of particles on indoor surfaces. Therefore, a mass balance model was used to simulate residential indoor $PM_{2.5}$ concentrations. The equation used for the calculation of indoor particle concentrations was as described below (Ji and Zhao, 2015):

$$V\frac{dC_{in}}{dT_{home}} = Q_n P_p C_{out} - Q_n C_{in} + M_{cooking} - kVC_{in}, \tag{1}$$

where V is the residential volume of the house (i.e., equal to the family household population multiplied by the per capita floor space and height of the room), C_{in} is the residential indoor $PM_{2.5}$ concentration, C_{out} is the ambient $PM_{2.5}$ concentration outdoors at the fixed-site monitoring station, T_{home} is the time participants spent at home indoors, Q_n is the natural ventilation of the residential house that is equal to the air exchange rate multiplied by the residential volume (natural ventilation associated with window opening and closing was calculated separately), P_p is the penetration factor, and k is the surface removal rate constant. Details of the parameters are listed in Table S2.

2.3.2. Exposure assessment of residential indoor $PM_{2.5}$

The daily residential indoor $PM_{2.5}$ exposure was calculated using the residential indoor $PM_{2.5}$ concentration and the time spent at