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Determinants of Indoor $PM_{2.5}$ Concentrations in Ger, a Traditional Residence, in Mongolia

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Abstract

Objectives: Use of coal by residents of ger, the traditional Mongolian residence, is a major cause of increasing indoor $PM_{2.5}$ concentrations. While high-level of indoor $PM_{2.5}$ concentrations of ger have been reported in the previous studies, the contributions of daily activities, such as indoor coal burning, cooking and smoking to the indoor $PM_{2.5}$ concentrations have not been clearly determined. The aims of this study were to determine the factors of indoor $PM_{2.5}$ concentration in ger and to quantify the effect of them on both average and real-time indoor $PM_{2.5}$ concentrations.

Methods: $PM_{2.5}$ concentrations of gers and dwellings were measured in winter over three years. During the measurement, information of residents' indoor activities were observed. Multiple regression was carried out with daytime average indoor $PM_{2.5}$ concentration as a dependent variable. In order to determine the effect of indoor activities on real-time indoor $PM_{2.5}$ concentration, the peak analysis was performed.

Results: Indoor $PM_{2.5}$ concentration and I/O ratio were significantly higher in gers than dwellings. Outdoor $PM_{2.5}$ concentration and indoor smoking were significant factors affecting daytime average of indoor $PM_{2.5}$ concentration in gers. Daily activity factors were associated with real-time $PM_{2.5}$ concentration - average peak magnitude of 224.3 $\mu g/m^3$ occurred with fuel addition, 260.1 $\mu g/m^3$ with cooking, and 407.7 $\mu g/m^3$ with indoor smoking.

Conclusion: Indoor $PM_{2.5}$ concentration of ger was extremely high, even more than dwellings in adjacent area. The indoor smoking and outdoor air pollution affected average indoor $PM_{2.5}$ concentration in ger. Daily activities of residents of ger such as fuel usage, cooking and smoking increased indoor $PM_{2.5}$ concentration in a short time.

keywords: *Mongolian residence, indoor $PM_{2.5}$ concentration, residents, activities*

Introduction

More than 2.8 billion people in developing countries around the world use solid fuels [1]. Previous studies showed that indoor burning of the solid fuel increased the risk of adult pneumonia and lung cancer [2, 3]. One of the main pollutants of solid fuel, particulate matter less than 2.5 μm ($PM_{2.5}$), was known to be related to several adverse health effect [4]. Long-term exposure to $PM_{2.5}$ was associated with cardiovascular and respiratory diseases [5]. High $PM_{2.5}$ level increased hospital admissions for asthma and respiratory diseases of children [6]. Due to the related health problems listed above, WHO recommended not using a solid fuel for indoor heating or cooking [7, 8].

A ger is a traditional Mongolian house, made of wooden frame and felt. The residents of ger used coal, which was a major source for $PM_{2.5}$ in residential site of Mongolia [9]. The capital city,

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Ulaanbaatar, was the most polluted area in country, where 47 % of total population live in [10]. A recent study indicated that exposure of $PM_{2.5}$ in Ulaanbaatar was responsible for 24% of lung cancer death and 42% of stroke death [11].

Previous studies mainly focused on outdoor air pollution of Ulaanbaatar, and relatively small number of studies were conducted on indoor environment of ger. However, a recent study suggested that most $PM_{2.5}$ exposures occurred indoors [11]. Considering indoor factors affecting $PM_{2.5}$ are less known, it is therefore important to conduct a study on the indoor environment of ger. In a previous study, it was observed that $PM_{2.5}$ concentrations increased due to indoor activities such as coal injection, cooking, and cleaning in ger [12]. However, contribution of these factors to indoor $PM_{2.5}$ concentration were not determined. According to a subsequent study, frequency of opening stove was associated with average indoor $PM_{2.5}$ concentration in ger [13]. However, contribution of these factors to indoor $PM_{2.5}$ concentration were not clearly known due to limited sample size.

Impact of daily activity factors on the real-time $PM_{2.5}$ concentration were not well known. It was reported that short-term exposure of high level of $PM_{2.5}$ could have caused detrimental impact on both physical and mental health. For instance, short-term exposure of high $PM_{2.5}$ level had an immediate effect on cardiovascular outpatient visits [14]. Furthermore, short exposure to high $PM_{2.5}$ level was associated with increased risk of delirium [15]. It is therefore important to know how indoor activities affect the real-time $PM_{2.5}$ concentration.

The aim of this study was to determine factors of both average and real-time indoor $PM_{2.5}$ concentration in ger. We categorized factors as 1) indoor activities – fuel usage, cooking and indoor smoking, 2) characteristics of ger; separation of cooking room and stove type and 3) outdoor air pollution. In order to assess the indoor environment of ger compared to other type of residence, indoor $PM_{2.5}$ data of adjacent dwellings were collected.

Methods

2.1 Data Collection

This study was conducted on 76 gers and 40 dwellings in ger district, Ulaanbaatar, with 36 gers measured in Jan., 2016, 40 gers measured in Jan, 2018 and 40 dwellings measured in Jan, 2017. In each year, researchers measured temperature, relative humidity, and $PM_{2.5}$ number concentration of residence for 4 days during daytime (11:00 - 18:00). Temperature and relative humidity were measured by Onset HOBO Datalogger UX100-003 (Onset Computer Corporation, USA), and the number concentration of $PM_{2.5}$ was measured by utilizing a Dylos DC1799 (Dylos Corporation, USA). The instruments were located at a minimum distance of 0.5 m from the floor. The measurement interval of all instruments was one minute. The obtained number concentrations of $PM_{2.5}$ were converted to mass concentrations through the following equation (1).

$$PM_{2.5}\text{ mass concentration } (\mu g/m^3) = 1.354 \times \text{Dylos PNC } (\#/ft^3)/10{,}000 \quad (1)$$

During the measurement, the researchers observed the activities of the inhabitants and made notations in an observation log. The start and end times of activities such as cooking, fuel addition and fuel amount, indoor smoking, candle usage, food and beverage consumption, residents' exiting their residences, cleaning and ventilation were investigated through observation log. The amount of added fuel was examined quantitatively using a scale.

2.2 Outdoor $PM_{2.5}$ concentration data

We used public outdoor $PM_{2.5}$ concentration data of ger district (Figure1). Measuring station was located in Nisekh, sub-district of Khaan-Uul district in Ulaanbaatar (Figure 1). These data were accessed from the OpenAQ Platform (openaq.org) and originated from Mongolia National Agency of Meteorology and Environmental Monitoring (Accessed 3 March, 2018).

2.3 Data analysis

The average indoor $PM_{2.5}$ concentrations were calculated as the arithmetic mean of the measurement time after excluding adjustment time of the device. The average outdoor $PM_{2.5}$ concentrations were calculated using the arithmetic mean of $PM_{2.5}$ from 09:00 to 18:00.

The I/O ratio, representing the strength of indoor $PM_{2.5}$ concentration in that household, was calculated by dividing average indoor $PM_{2.5}$ concentration by average outdoor $PM_{2.5}$ concentration of the day. Based on I/O ratio, we excluded data that were more than three standard deviations from the mean. One dwelling was excluded by the criterion. Data with instrument malfunction during observation was removed. The final number of samples were 76 for the gers and 38 for the dwellings.

Simple linear regression was applied to obtain correlation of indoor-outdoor $PM_{2.5}$ concentrations for the two residential types. The regression equation was as follows: $C_{out} = aC_{in} + b$, where C_{in} and C_{out} represent average indoor and outdoor $PM_{2.5}$ concentrations, respectively.

Multiple linear regression was used to identify determinants of daytime average indoor $PM_{2.5}$ concentrations in ger. Gers with missing observation were removed from original data. The final number of samples used in multiple linear regression was 70. The predictors consist of the following three categories outdoor $PM_{2.5}$ concentrations, occupants' indoor activities and characteristics of gers. The activity factors include cooking frequency, fuel usage, and smoking (indoor smoking more than once during observation time). And separation of cooking room and stove type (traditional, improved) were classified into the characteristics of gers. To make the $PM_{2.5}$ data normally distributed, we performed a square root transformation for indoor $PM_{2.5}$ concentration and outdoor $PM_{2.5}$ concentration. After transformation, $PM_{2.5}$ data met normality assumption for the reliability of statistical analysis.

The peak analysis was conducted for residents' activity factor (fuel usage, cooking and smoking) to determine effect to the real-time indoor $PM_{2.5}$ concentration in ger. Total number of gers used in peak analysis was 68 (8 gers were excluded for missing observation log and measuring time error).

Table 1. (a) Descriptive statistics of indoor air quality in ger

Date	Temperature (°C)	Relative Humidity (%)	Indoor $PM_{2.5}$ (μg/m^3)
Jan. 15, 2016	22.1 ± 2.7	19.2 ± 6.0	275.7 ± 95.1
Jan. 16, 2016	23.6 ± 2.3	22.1 ± 6.5	106.4 ± 51.8
Jan. 18, 2016	20.1 ± 5.5	20.7 ± 8.1	213.8 ± 88.2
Jan. 19, 2016	22.6 ± 5.3	23.8 ± 8.2	226.9 ± 94.7
Jan. 16, 2018	23.8 ± 2.4	22.0 ± 7.4	179.0 ± 117.2
Jan. 17, 2018	24.3 ± 2.5	21.3 ± 8.3	269.0 ± 142.8
Jan. 19, 2018	25.1 ± 3.6	20.6 ± 6.0	64.6 ± 31.0
Jan. 20, 2018	23.5 ± 2.8	23.1 ± 8.3	165.2 ± 65.2
Average	23.2 ± 3.6	21.6 ± 7.1	192.1 ± 114.0

(b) Descriptive statistics of indoor air quality in dwelling

Date	Temperature (°C)	Relative Humidity (%)	Indoor $PM_{2.5}$ (μg/m^3)
Jan. 13, 2017	20.8 ± 2.8	26.7 ± 6.1	108.2 ± 65.0
Jan. 14, 2017	18.6 ± 2.5	26.7 ± 6.2	73.5 ± 32.1
Jan. 16, 2017	18.1 ± 3.7	21.5 ± 4.9	148.1 ± 64.6
Jan. 17, 2017	18.8 ± 3.7	25.5 ± 8.2	251.4 ± 81.7
Average	19.2 ± 3.2	25.4 ± 6.5	147.1 ± 91.7

Table 2. I/O ratios of two residential types

Type of residence	Outdoor Temperature(°C) [a]	I/O ratio (range)	p-value [b]
Traditional ger	-26 ± 2	1.33 ± 0.61 (0.42 - 3.0)	< 0.001
Dwelling	-25 ± 4	0.89 ± 0.42 (0.34 - 1.99)	

[a] Daily average of outdoor temperature was used. (https://www.wunderground.com/)
[b] based on Student's t-test

We defined the peak as the case where the difference between the lowest value and the highest value within 30 minutes of active time was 35 or more. All statistical analysis was performed using R software, version 3.4.1 (R Core Development Team, 2017).

Results

3.1 Description of indoor air quality

Table 1 shows descriptive statistics of temperature, humidity and indoor $PM_{2.5}$ concentrations by observation dates in gers and dwellings. On average, temperature and indoor $PM_{2.5}$ concentration were higher in ger, but relative humidity was higher in the dwelling.

We used the coefficient of variation (c_v) as an indicator of between-home variability. In case of temperature, between-home variability was relatively small (c_v=0.18). It indicated that there was not much difference in temperature between gers. The relative humidity were moderately variable between gers (c_v=0.33). However, the variability of indoor $PM_{2.5}$ was considerable (c_v=0.59). The between-home variability of temperature and indoor $PM_{2.5}$ concentration in dwelling showed similar to ger (c_v=0.16, 0.62, respectively). The variability of relative humidity was slightly smaller than that of ger (c_v=0.26), but it was not statistically significant.

3.2 Comparison of Indoor $PM_{2.5}$ concentration between ger and dwelling

The average indoor $PM_{2.5}$ concentration in the ger was higher than dwelling ($p<0.05$). The proportion of households where average indoor $PM_{2.5}$ concentration is high (> 300 μg/m^3) differed between the two residential types. In the case of ger, 15.8 % (n=12) of households had a $PM_{2.5}$ level above 300 μg/m^3, compared to 7.9 % (n=3) for dwellings. 6.6 % (n=5) of gers exhibited extremely high indoor $PM_{2.5}$ levels over 400 μg/m^3, whereas no applicable data were observed in dwellings.

Table 2 shows the I/O ratios of gers and dwellings. The I/O ratio of ger was significantly higher than that of dwellings ($p<0.001$). It suggested that indoor $PM_{2.5}$ was still larger than dwellings after accounting for influence of outdoor air. In the case of the I/O ratio over 1 households, ger was 64 % (n=49) and dwelling was 42 % (n=16). For households with I/O ratio over 2, ger was 17 % (n=13) and there was no dwelling.

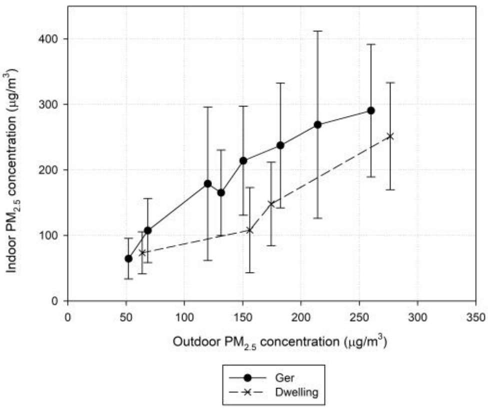

Figure 1. Indoor-outdoor $PM_{2.5}$ distribution of two residential types

Error bars indicate one standard deviation from sample average. Regression equation was $C_{in} = 1.07C_{out} + 32.78$ (r = 0.63; 95% C.I 0.47-0.75, $p<0.001$) for ger and $C_{in} = 0.86C_{out} + 0.52$ (r = 0.72; 95% C.I 0.52-0.84, $p<0.001$) for dwellings.

3.3 Determinants of average indoor $PM_{2.5}$ concentration

As shown in Figure 1, correlation of indoor-outdoor $PM_{2.5}$ concentration was considerable (r = 0.63, 0.72 for ger and dwelling).

Table 3. Multiple linear regression result on indoor $PM_{2.5}$ concentrations in ger

Variable	n (%) / mean ± sd	adj. coeff. (95 % CI)	p-value
[a]Outdoor $PM_{2.5}$ (μg/m³)	11.76 ± 2.88	0.85 (0.56, 1.13)	< 0.001
Smoking	9 (12.9 %)	2.69 (0.12, 5.26)	0.04
Separated cooking room	17 (24.3 %)	-1.1 (-2.97, 0.76)	0.334
Cooking frequency	1.36 ± 1.01	0.4 (-0.41, 0.76)	0.328
Stove: traditional vs. improved	36 (51.4 %)	0.87 (-0.79, 2.53)	0.554
Fuel usage frequency	1.64 ± 0.92	-0.58 (-1.52, 0.37)	0.266
Fuel amount (g)	7,133.9 ± 5,446.4	0 (0, 0)	0.78

[a] Square root transformed outdoor PM2.5 arithmetic mean of daytime (09:00-18:00) in ger district.
[b] Indoor smoking more than once during observation period.

Despite the short observation period, daily variation of average outdoor $PM_{2.5}$ concentration was large so that data was relevant to infer indoor-outdoor $PM_{2.5}$ correlation ($p<0.001$ for both). Regression coefficients were not significantly different between two residential types (i.e. effect modification of outdoor $PM_{2.5}$ concentration was not confirmed).

In regression models, mean absolute error calculated as average absolute distance from expected value was larger in gers ($p<0.05$). It resulted in a smaller correlation coefficient of ger than that of dwelling.

Table 3 shows the multiple linear regression result on average indoor $PM_{2.5}$ concentration in ger. Under this model, outdoor $PM_{2.5}$ concentration was the most influential factor for average indoor $PM_{2.5}$ concentration ($p<0.001$).

The average indoor $PM_{2.5}$ concentration was higher in the house where smoking was observed more than once during the observation period ($p<0.05$). The separated cooking room, cooking frequency, stove type, fuel amount and fuel usage frequency were not significantly associated with average indoor $PM_{2.5}$ concentration.

3.4 Determinants of real-time indoor $PM_{2.5}$ concentration

Three activity factors - fuel usage, cooking and indoor smoking affected real-time $PM_{2.5}$ concentration causing peaks of indoor $PM_{2.5}$ concentration (Table 4). More than half of the fuel usage raised the peaks of more than 35 μg/m³ within 30 minutes before and after fuel usage. In case of the cooking, the average increase was larger than fuel usage, but the peak occurrence rate was smaller than that of fuel usage. As for indoor smoking, it showed that most smoking caused a strong peak within a short time. The average increase of indoor smoking was 407.7 μg/m³, which was significantly the largest factor among the three activity factors.

Figure 2 shows examples of real-time changes of indoor $PM_{2.5}$ concentration in gers according to three activity factors. Each activity frequently caused large increases of $PM_{2.5}$ concentration in a short time. After peak occurred, $PM_{2.5}$ concentration gradually decreased and returned to

Table 4. Activity factors influencing indoor $PM_{2.5}$ concentrations peaks in a ger

Activity factors	Total occurrences	[a]Peak frequency	Average peak magnitude (μg/m³)
Fuel usage	108	57 (53 %)	224.3 ± 190.5
Cooking	87	34 (39 %)	260.1 ± 207.4
Smoking	21	19 (90 %)	407.7 ± 252.9

[a] Only those over 35 μg/m³ increase within 30 minute of activity were considered peak.

the original level.

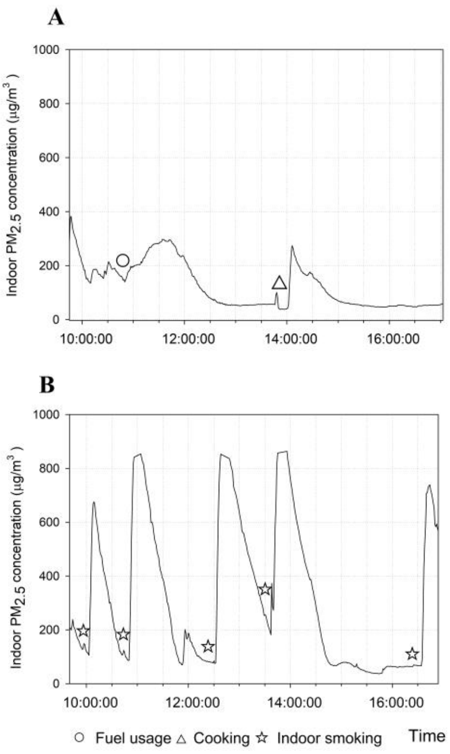

Figure 2. Influences of indoor activities to real-time indoor $PM_{2.5}$ concentrations

Discussion

4.1. Overall indoor air quality in ger

The overall indoor environment of ger was not suitable for occupant's well-being. The relative humidity was considerably deviated from the indoor air quality standard. Previous studies suggested that atmospheric humidity of at least 30 - 40 % had to be maintained to prevent drying of the nasal mucosa membrane [16]. However, small proportion of households met this standard (22 %). The low indoor humidity was known to affect eyes and skin irritation [17, 18]. According to our survey, substantial proportion of residents had been suffering eye irritation and skin problems (42 %, 17 %, respectively). It is necessary to maintain relative humidity at an adequate level for reducing related adverse health risk of residents.

The indoor $PM_{2.5}$ concentrations of ger need instant improvement. Indoor $PM_{2.5}$ concentrations of gers was extremely high on average. It was much worse than the WHO Air Quality Guideline of indoor $PM_{2.5}$ concentration (25 μg/m^3). In some gers, average $PM_{2.5}$ concentration exceeded the industrial air quality standard. The threshold of eight hour time weighted average exposures to $PM_{2.5}$ was 300 μg/m^3 [19]. This threshold was exceeded in some gers (15.8 %).

In the most gers, the temperature was acceptable. The average temperature in gers met the winter temperature standard of 19.2 - 27.8 ºC of the American Society of Heating, Refrigerating and Air-conditioning Engineers [20].

4.2 Comparison of indoor $PM_{2.5}$ concentration between ger and dwelling

There was a remarkable difference in $PM_{2.5}$ level for each residential type: almost as factor of one and half for I/O ratio (Table 2). The I/O ratio was commonly used to indicate the strength of indoor generated pollutants [21]. High indoor $PM_{2.5}$ level in ger is presumably caused by influence of indoor generated pollutants and infiltration of outdoor pollution.

It could be inferred that the characteristics of house may be related to high indoor $PM_{2.5}$ level in ger. Because indoor activities of dwelling was not particularly different with ger [12]. The effect of indoor generated pollutants on $PM_{2.5}$ level according to the characteristics of house remain to be determined.

Controlling indoor particulate matter concentration will be necessary to improve overall health outcomes of Ulaanbaatar. More than half families in Ulaanbaatar live in ger or dwelling other than apartment [11]. Our results suggest a large number of population of Ulaanbaatar live in an indoor environment that is similar to, or even worse than outdoor environment.

4.3. Determinants of average indoor $PM_{2.5}$ concentration

Determining factors of $PM_{2.5}$ was a crucial issue for Mongolian government to establish policy for improving indoor $PM_{2.5}$ level. Our results provided an understanding of factors for indoor $PM_{2.5}$ concentrations. As expected, the outdoor $PM_{2.5}$

concentration was a significant factor of indoor $PM_{2.5}$ concentration of ger. We showed significant association of indoor-outdoor $PM_{2.5}$ correlation in ger district, Ulaanbaatar (Table 2). It implied that serious air pollution in Ulaanbaatar could directly affect an indoor air of residence in Ulaanbaatar, possibly causing an adverse health effects on residents.

Among indoor activities, smoking was the most influential factor of indoor $PM_{2.5}$ concentration. Indoor smoking was only significantly associated with average indoor $PM_{2.5}$ concentrations. Influence of second hand smoke exposure on human health is well documented [22]. It indicated that indoor smoking might have large impact on occupant's health compared to the other indoor activities.

The impacts of cooking and fuel usage on average $PM_{2.5}$ concentrations were not determined. However, they frequently increased indoor $PM_{2.5}$ concentrations after actions (Table 3). It suggested that real-time analysis was more suitable to determine impact of these activities on indoor $PM_{2.5}$ concentrations.

4.4 Determinants of real-time indoor $PM_{2.5}$ concentration

All of three indoor activities considerably affected real-time indoor $PM_{2.5}$ concentrations raising peak after actions. Smoking had the largest peak occurrence rate and magnitude. Peaks of $PM_{2.5}$ were observed immediately after smoking for most of cases (Table 3).

Cooking also had a large impact on indoor $PM_{2.5}$ concentration. For cooking, peak occurrence rate was the smallest, but the peak magnitude was larger than fuel usage. It was known that certain type of cooking had a significant effect on indoor $PM_{2.5}$ concentrations. Frying food affected indoor $PM_{2.5}$ in the cooking space [23]. According to the observations in this study, only 24.3 % of ger had separate cooking space. Therefore, indoor $PM_{2.5}$ exposure from cooking might be considerable in ger.

4.5. Limitation of study

Because 24 hours could not be observed, it was difficult to understand how the behavior factors of various residents affected indoor air quality. There were overlapping of various activities at the time when peak concentration occurred. In particular, it was difficult to grasp the influence of certain variables in situations where various activities overlapped in the time of peak occurrence. There might be observational biases from different observers. Outdoor $PM_{2.5}$ was approximated using publicly available data. Given that the $PM_{2.5}$ distribution in Ulaanbaatar could be spatially different, it would have been better to collect outdoor $PM_{2.5}$ concentration data near target households as much as possible to ascertain outdoor influence on indoor $PM_{2.5}$ concentration. However, we used publicly available data, because device could not directly measure outdoor $PM_{2.5}$ due to very low temperature of Ulaanbaatar.

Conclusion

This study presented the results of three years of indoor $PM_{2.5}$ concentration data of ger and dwellings in Ulaanbaatar, Mongolia. Both indoor $PM_{2.5}$ concentration and I/O ratio of ger were higher than that of dwelling presumably due to high-level of indoor generated pollutants. Three activities of residents such as fuel usage, cooking, and smoking affected real-time $PM_{2.5}$ concentration in ger by increasing $PM_{2.5}$ in a short period of time. Among activity factors, only smoking was associated with the average $PM_{2.5}$ concentration. As expected, outdoor $PM_{2.5}$ concentration of Ulaanbaatar was considerably correlated with average indoor $PM_{2.5}$ level in gers.

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