Evaluation of Potential Average Daily Doses (ADDs) of PM$_{2.5}$ for Homemakers Conducting Pan-Frying Inside Ordinary Homes under Four Ventilation Conditions

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**Abstract:** Several studies reported that commercial barbecue restaurants likely contribute to the indoor emission of particulate matters with a diameter of 2.5 micrometers or less (PM$_{2.5}$) while pan-frying meat. However, there is inadequate knowledge of exposure level to indoor PM$_{2.5}$ in homes and the contribution of a typical indoor pan-frying event. We measured the indoor PM$_{2.5}$ concentration and, using Monte-Carlo simulation, estimated potential average daily dose (ADD) of PM$_{2.5}$ for homemakers pan-frying a piece of pork inside ordinary homes. Convenience-based sampling at 13 homes was conducted over four consecutive days in June 2013 ($n=52$). Although we pan-fried 100 g pork for only 9 min, the median (interquartile range, IQR) value was 4.5 (2.2–5.6) mg/m$^3$ for no ventilation and 0.5 (0.1–1.3) mg/m$^3$ with an active stove hood ventilation system over a 2 h sampling interval. The probabilities that the ADDs from inhalation of indoor PM$_{2.5}$ would be higher than the ADD from inhalation of PM$_{2.5}$ on an outdoor roadside (4.6 µg/kg·day) were 99.44%, 97.51%, 93.64%, and 67.23%, depending on the ventilation conditions: (1) no window open; (2) one window open in the kitchen; (3) two windows open, one each in the kitchen and living room; and (4) operating a forced-air stove hood, respectively.

**Keywords:** PM$_{2.5}$; average daily doses; indoor; ventilation; pan-frying

1. Introduction

According to statistics reported in 2013, the number of deaths in South Korea due to cancer was 149 per 100,000: 34 from lung cancer, 22.6 from liver cancer, 18.2 from stomach cancer, and 74.2 from other cancers [1]. Yu et al. reported in 2006 that exposure to indoor toxic compounds emitted during cooking activity at home was likely a risk factor increasing the incidence of lung cancer among nonsmoking women [2]. Particulate matters with a diameter of 2.5 micrometers or less PM$_{2.5}$ particles emitted during pan-frying can be harmful to human health due to their relatively small size and corresponding ability to penetrate deep into the lungs and enter the blood stream unfiltered. The results of many studies have indicated that PM$_{2.5}$, particulate matter with an aerodynamic diameter equal to or smaller than 2.5 µm, could be produced during cooking activities [3–6], and it has been reported that acute reduction of lung function was associated with exposure to PM$_{2.5}$ during cooking activities [7,8]. In 2010, the International Agency for Research on Cancer (IARC), a specialized cancer agency of the World Health Organization (WHO), reported that emissions from high-temperature frying are probably carcinogenic to humans (Group 2A) although there is limited evidence in humans for the carcinogenicity of emissions from high-temperature frying. However, there is sufficient evidence in experimental animals for the carcinogenicity of emissions from high-temperature unrefined rapeseed
oil [9]. Therefore, cooking related indoor PM$_{2.5}$ levels should be carefully monitored due to their potential harmful characteristics, as we described above.

According to a report from the Ministry of Environment of South Korea [10], the amount of PM$_{2.5}$ produced by pan-frying meats was 3022 tons/year, assuming a meat consumption rate of 31.3 kg/year per person. Because pan-fried pork belly is a popular dish among Koreans at home [11], it is probable that homemakers are exposed to high levels of PM$_{2.5}$ emitted during the pork pan-frying process. They are also potentially exposed to secondary particles formed by combination of chemicals derived from the oxidation of primary gases produced during pan-frying.

Many researchers have reported that commercial barbecue restaurants likely contribute to the emission of toxic chemicals and PM$_{2.5}$ into indoor and outdoor air during the commercial food pan-frying or pan-frying process [12]. According to a recent report in South Korea, PM$_{2.5}$ emitted from commercial restaurants serving barbecue accounted for 8.7% of all the PM$_{2.5}$ produced in Gyeonggi Province [13]. However, information on the indoor PM$_{2.5}$ concentration in homes contributed to by residential pan-frying, and the degree of PM$_{2.5}$ reduction related to the ventilation conditions prevalent in homes, is insufficient.

We conducted this study to evaluate the potential indoor exposure and average daily dose of homemakers to PM$_{2.5}$ generated during pan-frying meat in ordinary South Korean homes. To this end, four different arrangements of ventilation were simulated.

2. Materials and Methods

2.1. Sampling Sites

Convenience-based sampling in 13 homes (six single houses, six apartments, and one multiunit) was conducted over four consecutive days to measure the indoor PM$_{2.5}$ concentration levels. Our experiments ($n = 52$) were conducted from June to December 2013 in Cheonan and Seoul, South Korea.

The total floor area of these homes ranged from 52.8 to 112.2 m$^2$ and the approximate height from floor to ceiling was 2.5 m or less in each home. We conducted four measurements per house per day. During our experiments, operating a fan or air conditioning system was not allowed. For one day before the experiment in each home, pan-frying other meats or fishes was not allowed by our monitoring agents. Characteristics of our sampling sites are summarized in Table 1.

| Site No. | House Type | Area (m$^2$) | Height (m) | Indoor Smoking | Air Conditioner |
|----------|------------|-------------|------------|----------------|-----------------|
| 1        | Single house | 66.0        | 2.4        | No             | No              |
| 2        | Apartment   | 52.8        | 2.0        | No             | No              |
| 3        | Apartment   | 52.8        | 2.0        | No             | No              |
| 4        | Single house | 66.0        | 2.0        | No             | No              |
| 5        | Single house | 66.0        | 2.5        | No             | No              |
| 6        | Apartment   | 112.2       | 2.2        | No             | No              |
| 7        | Multi units | 92.4        | 2.2        | No             | No              |
| 8        | Single house | 108.9       | 2.0        | No             | No              |
| 9        | Single house | 66.0        | 2.5        | No             | No              |
| 10       | Single house | 52.8        | 2.5        | No             | No              |
| 11       | Apartment   | 112.2       | 2.3        | No             | No              |
| 12       | Apartment   | 108.9       | 2.3        | No             | No              |
| 13       | Apartment   | 92.4        | 2.3        | No             | No              |

2.2. Pan-Frying Process and Ventilation Conditions Applied

Our experiments were done by simulating the barbequing of pork belly (100 g) for 9 min over a 2-h measurement period per trial under four different ventilation conditions. With our pre-established
standard operating protocol, a portion of pork belly (100 g) was pan-fried for 9 min: 3 min on Side A, 3 min on Side B; then 1.5 min for Side A again, and a final 1.5 min for Side B again. We used the same nonstick pans for every experiment without cooking oil. Pan-frying in all houses was done with their gas-ranges using natural gas (41.0–44.4 MJ/Nm$^3$) supplied by our national distributor, Korea Gas Corporation [14].

The ventilation conditions were as follows: (1) No windows open; (2) one window, of size 0.5 ± 0.28 m$^2$, open in the kitchen was selected as the simplest natural ventilation method, where no forced-air stove-hood operation system is available; (3) two windows open, both in the kitchen and the living room (window size on the opposite side of the kitchen, 2.3 ± 0.20 m$^2$), likely increasing natural ventilation by allowing air circulation and expelling it from both ends (kitchen and living room); and (4) forced-air stove-hood operating during the entire pan-frying process. All households had a gas-range hood and windows, and no other windows were opened during the experiment. Floor area (5.3–11.2 m$^2$) of the kitchen was approximately 10% of entire floor area (52.8–112 m$^2$) and no separation door existed between the kitchen and living room of any of the houses (Figure 1).

To avoid the carry-over effect of PM$_{2.5}$ concentrations between simulations and to minimize the effect of non-target sources contributing to our PM$_{2.5}$ measurement results [15], we took measurements of the background PM$_{2.5}$ concentrations inside the kitchen and outside the kitchen window for five minutes before and after conducting our experiments. Later, we subtracted the indoor background concentration from our indoor values.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Floor layout of a typical sampling site (unit of length: mm) and schematic of sampling frequency and duration.

### 2.3. PM$_{2.5}$ Measurement

We used real-time PM$_{2.5}$ monitors (Sidepak, TSI, Shoreview, MN, USA) to measure the indoor PM$_{2.5}$ levels (flow rate 1.7 L/min) as a stationary sampler. Every day prior to PM$_{2.5}$ monitoring, we performed zero calibration and checked the flow rate [16]. Our monitor was 50 cm from the stove...
hood fan and 1 m above the kitchen floor. We used two SidepakS for each experiment. We applied 0.65
as a Sidepak correction factor of PM$_{2.5}$ concentrations over the pork pan-frying process according
to the previous study results, reporting real-time particle monitor calibration factors for multiple indoor
emission sources by comparing the outcome of real-time laser photometers, including Sidepak, and a
filter-based PM$_{2.5}$ gravimetric sampler to quantify the monitor calibration factors (CFs) [17]. We kept a
minimum distance of 50 cm between the two SidepakS. The final distributions of PM$_{2.5}$ concentrations,
according to four ventilation conditions, were obtained from the 13 PM$_{2.5}$ median concentration values
for 13 sampling sites. At each pan-frying trail, we took a PM$_{2.5}$ concentration value every 1 min over a
2 h sampling period.

2.4. Average Daily Dose

The PM$_{2.5}$ doses inhaled by housewives on monitoring days, under four different ventilation
conditions, was determined using Equation (1), adopted from the average daily dose calculation
handbook [18] of U.S. Environmental Protection Agency (EPA), as well as from the Korean exposure
handbook [19].

$$ADD \ (mg/kg \cdot day) = \frac{C \times IR \times ET}{BW \times AT \times 1000} \ (1)$$

C: Arithmetic mean concentration of the PM$_{2.5}$ (mg/m$^3$); IR: inhalation rate (L/min); BW: body
weight (kg); ET: exposure time (min); AT: average time (days).

ADD is the average daily dose (milligrams per kilogram per day, mg/kg · day) by inhalation. Here, C is the average value of the 13 median PM$_{2.5}$ concentrations from pan-frying pork (mg/m$^3$)
measured over a 2 h period in houses. IR is the estimated air inhalation rate (L/min) and BW, ET, and
AT are the estimated body weight (kg), exposure time (min), and average time (days) for housewives,
respectively [20]. The PM$_{2.5}$ ADD by inhalation obtained for housewives on monitoring days, with
different ventilation conditions, was compared with their estimated PM$_{2.5}$ ADD by inhalation of
roadside PM$_{2.5}$ levels.

According to the Korean exposure handbook [19], we applied the inhalation rate 10.9 ± 3.8 L/min
for adult women (average body weight 56.4 ± 7.81 kg) assuming pan-frying pork at home once a week
for 35 years (until their retirement at the age of 60 years). We also assumed that the pork pan-frying
related cooking time was 65 min [21]. For the comparison purposes, we used the 24-h outdoor PM$_{2.5}$
standard (0.05 mg/m$^3$) from the Korea National Ambient Air Quality scale [22]. For this comparison,
we assumed that the women worked outside and they were exposed to roadside PM$_{2.5}$ for 8 h/day
(daytime) and 40 h/week for 35 years (until their retirement at the age of 60 years). For calculation
of ADD by inhalation of roadside PM$_{2.5}$, we applied the same inhalation rate (10.9 ± 3.8 L/min) for
women working outside, near roadsides [19]. Under assumptions of 8 h working time outside for
7 days over 35 years, we obtained 4.6 mg/kg · day.

2.5. Probabilistic Modeling: ADD Distribution by Monte-Carlo Simulation

Using a Monte-Carlo simulation with Crystal Ball (version 11, Oracle, Redwood Shores, CA, USA),
we compared probabilistic distributions of ADDs for inhalation of indoor as well as outdoor PM$_{2.5}$
particles for homemakers. For this simulation, we assumed that indoor or outdoor PM$_{2.5}$ concentrations
were log-normally distributed while the distributions of body weight and inhalation rate were normal
and that of exposure duration was a constant value. To obtain the probabilistic distribution, we
repeated the simulation procedure 10,000 times.

2.6. Statistical Analysis

The distributions of indoor PM$_{2.5}$ concentrations under each different ventilation condition was
compared with the results obtained with no ventilation using the Wilcoxon rank-sum test.
3. Results

3.1. Indoor PM$_{2.5}$ Levels According to Ventilation Conditions

We obtained different median (interquartile range, IQR) PM$_{2.5}$ concentrations ($n = 13$ per each ventilation scenario), over a 2 h sampling period, in relation to the different ventilation conditions: 4.5 (2.2–5.6) mg/m$^3$ for no ventilation, 1.8 (1.4–3.3) mg/m$^3$ or 1.9 (0.4–2.5) mg/m$^3$ for one or two windows open, and 0.5 (0.1–1.3) mg/m$^3$ with the forced-air stove hood ventilator operating (Table 2). In detail, the median (IQR) concentrations of indoor PM$_{2.5}$ during the first 9 min fan-frying period were 5.1 (3.0–9.2), 5.0 (1.7–7.0), 3.8 (1.3–6.2), and 1.16 (0.2–2.3) mg/m$^3$, respectively. The corresponding dissipation kinetics after cooking was completed were 38.2 (26.6–79.4), 47.4 (17.0–84.6), 54.7 (20.1–99.9) and 55.2 (6.5–78.7) µg/m$^3$ (Table 3).

The median (interquartile range) of the ratio of PM$_{2.5}$ concentrations with one or two windows open, or with cooker stove hood operating, to the concentrations without ventilation, for each paired observation for each home were 0.63 (0.40–0.69), 0.41 (0.23–0.56), or 0.17 (0.08–0.25), respectively (Figure 2).

![Figure 2. Distributions of median indoor particulate matters with a diameter of 2.5 micrometers or less (PM$_{2.5}$) concentrations obtained at each sampling site according to ventilation condition and distribution of ratios of PM$_{2.5}$ concentrations obtained with ventilation, to those without ventilation; Concentrations were lower than the reference ($p < 0.05$).](image)

3.2. Average Daily Dose (ADD) of Homemakers

On the basis of the arithmetic mean values of the PM$_{2.5}$ concentrations observed during pork pan-frying, under the ventilation conditions and exposure scenario mentioned above, we obtained average daily PM$_{2.5}$ doses of 48.1, 27.4, 21.2 and 10.0 µg/kg·day, respectively, while the dose from roadside PM$_{2.5}$ was 4.6 µg/kg·day. Also, the median (IQR) value of ADD by inhalation of indoor PM$_{2.5}$ due to exposure to the pan-frying process, from our Monte-Carlo simulation, was 41.7 (26.9–62.8), 47.4 (17.0–84.6), 54.7 (20.1–99.9) and 55.2 (6.5–78.7) µg/m$^3$ (Table 3).

The probabilities that the ADDs from inhalation of indoor PM$_{2.5}$ would be higher than the ADD by inhalation of outdoor roadside PM$_{2.5}$ (4.6 µg/kg·day) were 99.4%, 97.5%, 93.6% and 67.2%, depending on the ventilation conditions (no ventilation, one window open, two windows open, stove hood operating, respectively) (Figure 3).
Table 2. Distributions of average daily doses (ADDs) from Monte-Carlo simulation using the distribution of indoor PM$_{2.5}$ levels observed under different ventilation conditions, as well as outdoor PM$_{2.5}$ levels obtained from urban roadsides.

| Caption                        | ADD (mg/kg·Day) from Equation (1) | PM$_{2.5}$ Concentration (mg/m$^3$) * from Simulation ($n = 10,000$) | Exposure Time (min/Day) | Exposure Frequency (Weekly) | Life Time Exposure Duration ** (Year) |
|-------------------------------|-----------------------------------|-----------------------------------------------------------------------|--------------------------|-----------------------------|--------------------------------------|
|                               | Median (IQR) Mean (95% CI)        | Median (IQR) Mean ± SD                                                |                          |                             |                                      |
| No ventilation                | 0.0481 (0.0269–0.0628)            | 0.0496 (0.0490, 0.0502)                                              | 4.51 (2.24–5.64)         | 3.83 ± 1.98                 | 65 1 35                              |
| One window open               | 0.0274 (0.0138–0.0353)            | 0.0280 (0.0276, 0.0284)                                              | 1.82 (1.35–3.28)         | 2.18 ± 1.38                 | 65 1 35                              |
| Two windows open              | 0.0212 (0.0096–0.0276)            | 0.0217 (0.0213, 0.0221)                                              | 1.93 (0.42–2.51)         | 1.69 ± 1.29                 | 65 1 35                              |
| Forced-air stove hood         | 0.0100 (0.0038–0.0127)            | 0.0070 (0.0068, 0.0072)                                              | 0.51 (0.13–1.33)         | 0.79 ± 0.74                 | 65 1 35                              |
| Urban roadside ***            | 0.0046 NA                         | NA                                                                   | 0.05                     | 480 7 35                    |                                      |

IQR: interquartile range, CI: confidence interval, SD: standard deviation, NA: not available. * The distributions of PM$_{2.5}$ concentrations were obtained from the 13 PM$_{2.5}$ median concentration values for 13 sampling sites (real-time based 2 h measuring with pan-frying for the first 9 min), Median (IQR) background PM$_{2.5}$ concentration were 0.022 (0.012–0.042) mg/m$^3$. ** For housewife aged 25 years; *** Data from Air Korea (2016) [22].

Table 3. Distributions of indoor PM$_{2.5}$ concentrations during the first 9 min of cooking period and the dissipation kinetics after cooking was completed.

| Type of Ventilation | PM$_{2.5}$ Concentration (µg/m$^3$) during the First 9 min Fan-Prying Period | Dissipation Kinetics (µg/m$^3$/min) after Cooking Was Completed |
|---------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------|
|                     | Median 25%ile 75%ile                                                        | Median 25%ile 75%ile                                             |
| No ventilation      | 5142.2 2958.2 9228.7                                                        | 38.2 26.6 79.4                                                  |
| One window open     | 4970.6 1668.6 6990.8                                                        | 47.4 17.0 84.6                                                  |
| Two windows open    | 3777.2 1348.8 6192.6                                                        | 54.7 20.1 99.9                                                  |
| Forced-air stove hood | 1159.6 183.3 2269.2                                                        | 55.2 6.5 78.7                                                   |
Figure 3. Distribution of average daily dose obtained from Monte Carlo simulation with the distribution of indoor PM$_{2.5}$ levels observed under different ventilation conditions, and the probability of ADD by indoor PM$_{2.5}$ which was higher (Blue) than the ADD (0.0046 mg/kg day) estimate for roadside PM$_{2.5}$.
4. Discussion

Our study indicated that the levels of indoor PM$_{2.5}$ due to pan-frying in home kitchens were significantly high. Even though we pan-fried 100 g pork for only 9 min, the median values of PM$_{2.5}$ levels were 4.5 mg/m$^3$ for no ventilation and 0.5 mg/m$^3$ with operation of the forced-air stove hood ventilation system with a 2 h interval were approximately 10 to 90 times higher than the 24-h outdoor PM$_{2.5}$ standard (0.05 mg/m$^3$) from the Korea National Ambient Air Quality recommendations [22]. We used the Korean NAAQS as a reference for comparison because we do not have specific standards for indoor PM$_{2.5}$ levels. Our findings indicate that the pork pan-frying process contributes substantially to indoor PM$_{2.5}$ concentration levels at the ordinary Korean house and that this exposure is particularly elevated when ventilation is not available.

Our study results are supported by those of previous studies characterizing indoor PM exposure levels at Korean style barbeque restaurant. According to Lee et al. (2001) [23], the average levels of PM$_{2.5}$ at the Korean barbecue style restaurant in Hong Kong were as high as 1.17 mg/m$^3$, respectively. The level obtained in Hong Kong was similar to our study results (1.8 mg/m$^3$: one window open, 1.9 mg/m$^3$: two windows open, 0.5 mg/m$^3$: forced air stove hood applied). Another Chinese study reported that personal exposure level to PM$_{2.5}$ from burning biomass ranged from 0.136 to 0.162 mg/m$^3$ [24].

Our median value (0.5 mg/m$^3$) of PM$_{2.5}$ concentrations, even with the best ventilation (i.e., operating a stove hood), was approximately 2–3 times higher than the value obtained from the Chinese study above [24], or the value (0.15 mg/m$^3$) obtained from a casino [8], similar to the level obtained from the smoking areas (0.1 to 0.98 mg/m$^3$) in computer game rooms or night clubs [25]. Because our PM$_{2.5}$ results were obtained from sampling of stationary bases, rather than from personal monitoring, further exploration of the basis for the differences in distributions of PM$_{2.5}$ levels between our study and their studies is limited. Nevertheless, our study revealed the potential for high levels of exposure to PM$_{2.5}$ concentrations during pan-frying meat in ordinary households, especially in unventilated kitchens.

This study has some limitations. First, the sample size of our study was not large and we recruited the study homes at two cities, Seoul and Cheonan. Since Seoul and Cheonan are both highly urbanized areas, we assumed that the life patterns of people in the two cities were not different and there was no systemic difference in terms of cooking methods. The outcomes of the Monte Carlo simulation, which can provide the estimation of the probabilistic distribution of the ADDs of PM$_{2.5}$ for the young, female Korean population, should be interpreted with care since we estimated the ADDs according to the Korean exposure handbook [19] and we applied the inhalation rate 10.9 ± 3.8 L/min for female, adult Korean women (average body weight 56.4 ± 7.81 kg) assuming that they pan-fry pork at home once a week for 35 years (until their retirement at the age of 60 years). Because we randomly selected 13 homes (four measurements per home) of typical house types (i.e., one multi-unit house, six single houses and six apartments) for young adult couples found in South Korea, the distributions of the concentrations should not be systematically biased. According to statistics from Korea [26], it has been reported that 47% of Koreans live in apartments while the rest of the population live in single or multi-unit houses. In our study, 46% of results were conducted in apartments (24 results from apartments, 24 results from single-units, and 4 results from a multi-unit house). Nevertheless, generalization of our study outcomes to other study populations may be limited. Second, because we conducted stationary monitoring in kitchens over a 2-h interval to determine a daily peak level, rather than 24-h personal sampling, we could not provide personal exposure levels. Third, we could not measure air exchange or ventilation rate because of limitations in our time and funding. The concentrations observed in the first 4 sites and those observed in the last 9 sites seem to differ. This may be due to the increased air exchange rates in the first 4 sites. In future research, measurement of the ventilation and/or air exchange rates would improve the interpretation of the effects of open windows on indoor PM$_{2.5}$ levels. Nevertheless, to our knowledge, this study is the first study to provide the average daily dose by inhalation of indoor PM$_{2.5}$ during pork pan frying and to evaluate quantitatively the effectiveness of ventilation in Korean residential kitchens while pan-frying meat.
5. Conclusions

Our study provided quantitative evidence that, in South Korea, the probability of having high ADD due to exposure to indoor PM$_{2.5}$ during the pan-frying process is likely to be reduced by half with a forced-air stove hood at home. Ventilation through a window has a relatively minor impact on daily exposure. Operating a forced-air stove hood system is highly recommended for protecting homemakers from high PM$_{2.5}$ exposure levels during the pan-frying process in South Korean homes.

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Author Contributions: Sungroul Kim designed this study and conducted interpretation of the quantitative aspects of data analysis. Seonyeob Lee performed modeling simulation and Sol Yu provided editorial efforts. Sungroul Kim supervised the whole study.

Conflicts of Interest: The authors declare no conflict of interest.

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