Indoor PM2.5 Mortality in China when Outdoor Air Meets 2021 WHO AQG

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Title Page

Indoor $PM_{2.5}$ Mortality in China when Outdoor Air Meets 2021 WHO AQG

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Abstract

The World Health Organization (WHO) Air Quality Guidelines (AQG) 2021 for $PM_{2.5}$ is tightened to be 5 μg/m^3. We firstly estimated deaths attributable to human exposure to $PM_{2.5}$ (DAHP) to be 455 thousand (372-527) in urban China in 2019, of which indoor sources contributed 253 thousand (207-294) deaths. The economic losses related to $PM_{2.5}$ from indoor sources were 0.98 trillion (0.80-1.14) RMB, accounting for 56% of the total economic losses. We then further projected the DAHP at 328 thousand (260-392) when the outdoor $PM_{2.5}$ concentration is 5 μg/m^3, while $PM_{2.5}$ from indoor sources still causes 297 thousand (235-355) deaths and 1.27 trillion (1.00, 1.51) in economic losses each year. There are significant health hazards and economic losses caused by indoor $PM_{2.5}$, even the outdoor air is clean enough. The formulation and implementation of more air pollution policies are therefore in urgent need to control indoor sources of $PM_{2.5}$.

Keywords: indoor air, fine particulate matter, health effect, cooking, smoking, China.

Introduction

$PM_{2.5}$ pollution is a global concern. The World Health Organization (WHO) issued a new set of guidelines on air pollution on Sept 22, 2021, tightening the $PM_{2.5}$ Air Quality Guidelines (AQG) from 10 μg/m^3 to 5 μg/m^3[1]. Particularly, the guidelines stated that the same AQG should be applied to indoor environments. There are important sources of $PM_{2.5}$ indoors. WHO has been calling for attention to household air pollution due to solid fuels and kerosene in open fires for cooking. However, even in households using clean fuels and technologies, typically in urban areas, cooking and smoking produce a large amount of $PM_{2.5}$[2, 3]. Our latest study separated the contribution of indoor and outdoor sources for human exposure to $PM_{2.5}$ in urban China, and we figured out that indoor sources contribute over 50% of total $PM_{2.5}$ exposure for Chinese urban residents in 2019 [4]. However, the health effect and corresponding economic losses related to $PM_{2.5}$ from indoor sources are not clear. In particular, current policies on air pollution control of various countries still aim at reducing outdoor $PM_{2.5}$ concentrations, including strengthening industrial emission, electrification of road vehicles, adjustment of energy structure[5]. However, in view of the significant contribution of $PM_{2.5}$ from indoor sources to human exposure, indoor $PM_{2.5}$ concentrations are likely to remain very high when outdoor $PM_{2.5}$ meets the AQG, resulting in considerable health effects and economic losses. In this study, we estimated the deaths and economic losses attributable to $PM_{2.5}$ from indoor and outdoor sources based on our previous modelled human exposure to $PM_{2.5}$ from indoor and outdoor originated sources in Chinese urban areas in 2019 [4], and we further analyzed the scenario when the outdoor air meets the WHO AQG 2021.

Results

The deaths and economic losses attributable to $PM_{2.5}$ in Chinese urban areas in 2019. The deaths attributable to human exposure to $PM_{2.5}$ (DAHP) was 455 thousand (372-527) [mean(95%CI)] in Chinese urban areas in 2019, which equates to 84 deaths (69-97) per 100,000 people. The corresponding economic losses were projected to be 1.76 trillion (1.44-2.04) RMB, approximately equivalent to 2% of GDP in China in 2019 (**Table 1**). Ischemic heart disease (IHD) and stroke were the two leading causes of DAHP, causing 142 thousand (117-161) and 136 thousand (116-154) deaths, accounting for 31% and 30% of the DAHP, respectively (**Fig. 1a**). The DAHP related to chronic obstructive pulmonary disease (COPD), lung cancer (LC), lower respiratory infections (LRI) and type 2 diabetes (DM2) were 176 thousand (139-212) deaths in total. DAHP in Chinese urban areas is splited according to sources of $PM_{2.5}$ (**Fig. 1b**). The DAHP from indoor sources were estimated to be 253 thousand (207-294) in Chinese urban areas in 2019, of which indoor cooking and smoking contributed 193 thousand (158-224) and 60 thousand (49-70) deaths, accounting for 43% and 13% of the DAHP, respectively. The economic losses related to $PM_{2.5}$ from indoor sources were 0.98 trillion (0.80-1.14) RMB, accounting for 56% of the total economic losses, including 0.75 trillion (0.61-0.87) RMB from cooking and 0.23 trillion (0.19-0.27) RMB from smoking (**Table 1**).

The human exposure of $PM_{2.5}$ and its health effect when the outdoor air meets the WHO AQG 2021. The concentration of human exposure to $PM_{2.5}$ was projected to decrease from 62.6 μg/m^3 (58.5-67.5) in 2019 [the annual average concentration of ambient $PM_{2.5}$ is 36±15 μg/m^3 (mean±standard deviation)] to 39.3 μg/m^3 (35.3-44.0) when the outdoor air meets the WHO AQG 2021 (i.e., the annual concentration of ambient $PM_{2.5}$ is 5 μg/m^3) in Chinese urban areas, and the contribution of $PM_{2.5}$ from indoor sources to human exposure increased from 56% (55%-61%) to 91% (90%-92%). The DAHP were going to be 328 thousand (260-392) when the outdoor air meets the WHO AQG 2021, equivalent to 72% (70%-74%) of the DAHP in 2019. $PM_{2.5}$ from indoor sources still causes 297 thousand (235-355) deaths (**Fig. 1b**) and 1.27 trillion (1.00, 1.51) RMB in economic losses each year (**Table 1**). The DAHP related to different diseases were shown in **Fig. 1a**. IHD and stroke were still the most contributed causes of the DAHP when the outdoor air meets the WHO AQG 2021, with the deaths of 103 thousand (82-120) and 98 thousand (82-114).

Discussions

Our results demonstrate significant health hazards and economic losses caused by $PM_{2.5}$ originated from indoor sources in Chinese urban areas, where solid fuels and kerosene are almost of no use. There are still hundreds of thousands of people who die from illnesses attributable to $PM_{2.5}$ from indoor sources, even if the outdoor air meets the WHO AQG 2021. It is essential to control the $PM_{2.5}$ from indoor sources to reduce the DAHP.

The WHO AQG 2021 for $PM_{2.5}$ is 5 μg/m^3 applied to both outdoor and indoor environments. The concentration of human exposure to $PM_{2.5}$ was projected to be about 39.3 μg/m^3 when the outdoor air meets the WHO AQG 2021 in Chinese urban areas. To meet the WHO AQG 2021, an additional 34.3 μg/m^3 reduction in human exposure to $PM_{2.5}$ is required by controlling indoor sources. Cooking and smoking are sources of $PM_{2.5}$ in residences in Chinese urban areas, with the emission rate of $PM_{2.5}$ reaching up to 10 mg/min[2] and 4 mg/min[3], respectively. More than 90% of households in Chinese urban areas cook at home at least once a day according to our survey[4]. People usually run range hoods to reduce indoor $PM_{2.5}$ concentration during cooking. But the exhaust efficiencies of range hoods are very low in Chinese homes, less than 60%[2]. High exhaust efficiency but low-energy-consumption range hoods and scientific kitchen layouts, structures, and ventilation designs are urgently needed for households in Chinese urban areas to protect people from exposure to $PM_{2.5}$ emitted during cooking[6]. Maintaining good habits of using range hoods, such as washing them regularly and running for some time after cooking, are also ways to reduce human exposure to $PM_{2.5}$ from cooking. The smoking ban has been implemented in China for many years. However, there are still 44.9% of adults and 63.2% of adolescents exposed to second-hand smoke[7, 8]. Strict enforcement of banning smoking is also in urgent need to reduce exposure to secondhand smoke in China. In addition, the use of air purifiers can effectively remove $PM_{2.5}$ indoors, and there has been evidence supporting the health benefits of using air purifiers[9]. However, they are still not cost-benefit effective[10]. Reducing the cost of air purifiers may be beneficial for their promotion, particularly for middle- and low-income groups.

More than 70% of the people in the world use clean fuels or technologies[11]. This study showed that approximately 250 thousand people using clean fuels or technologies could have premature mortality or morbidity attributable to $PM_{2.5}$ from indoor sources in China in 2019, indicating the significant health effect of $PM_{2.5}$ from indoor sources in areas using clean fuels or technologies. A study based on *the WHO Global HAP Database* showed the concentration of human exposure to $PM_{2.5}$ were ranged 20-102 μg/m^3 in families using gas or electric energy sources in Latin America, Asia and Africa[12]. Several other studies in the US[13] and Europe[14] have also shown the significant contribution of indoor sources of $PM_{2.5}$. The strong contribution of indoor sources to human exposure to $PM_{2.5}$ implies the potential significant health impact around the world in areas using clean fuels or technologies, but unfortunately being overlooked, likely because indoor sources are more technically challenging to be monitored at scale. We are calling for the formulation and implementation of more air pollution policies to control indoor sources of $PM_{2.5}$.

Materials and Methods

Human exposure to fine particulate matter ($PM_{2.5}$) from different sources in Chinese urban areas. The concentration of human exposure to $PM_{2.5}$ (represented by the parameter *C*) is defined as the arithmetic means of the $PM_{2.5}$ concentrations over the exposure period, reporting in μg/m^3. The annual average *C* originated from three kinds of sources, i.e., cooking, smoking, and ambient, in Chinese urban areas in 2019, have been reported in our previous study [4]. There, we established a source-specific $PM_{2.5}$ exposure model to separate the contribution of indoor and outdoor sources to *C*. After validating the model with measured human exposure concentration in different cities, we simulated *C* from indoor and outdoor sources of different populations by combining the model with the concentration of ambient $PM_{2.5}$ from outdoor monitoring stations in China, the measured emission rates of $PM_{2.5}$ from smoking and cooking, and the habits of cooking and smoking in Chinese urban areas [4]. The simulated results provided intra-population variability distribution of annual *C* from indoor and outdoor sources for urban residents in 333 Chinese cities in 2019, where the population was grouped according to their age (10 age groups, i.e., 0–0.5, 0.5–1, 1-2, 3–6, 7–11, 12-17, 18–44, 45–59, 60–79, and beyond 80 years old), gender (male and female) and second-hand smoke (from smoking and non-smoking households) [4].

Here, $C_{ambient}$ and $C_{cooking}$, referring to the *C* from outdoor and indoor sources of non-smoking households (i.e., only cooking present as indoor source) in the population respectively, were applied for later estimation of disease burden. These two parameters were denoted as OEC (outdoor source exposure concentration) and

IEC (indoor source exposure concentration) for non-smoking households in Hu and Zhao (2021) [4]; and the values of them were provided in Table S13 in Hu and Zhao (2021) [4]. Then, *C* from smoking ($C_{smoking}$) were calculated with the following equation:

$$C_{smoking} = \left(C_{SHS,indoor} - C_{cooking}\right)P_{SHS} \tag{S1}$$

where $C_{SHS,indoor}$ is the *C* from indoor source of smoking households in the population. The value of $C_{SHS,indoor}$ (denoted as IEC for smoking households) was also provided in Table S13 in Hu and Zhao (2021) [4]. P_{SHS} is the proportion of the population exposed to second-hand smoke, calculated by

$$P_{SHS,group} = 1 - \left(1 - P_{smoking,group}\right)\left(\sum_{f} P_{number,f}\left(1 - P_{smoking}\right)^{f-1}\right) \tag{S2}$$

where $P_{smoking}$ is smoking rate, the subscript *group* represents the population with specific age and gender, and $P_{number,f}$ is the proportion of the population that the family household size is *f*. The age-, sex-, and provincial-specific smoking rates in 2019 were calculated using the age-, sex-, and provincial-specific smoking rates in 2013 [15] and the ratio of smoking rates between 2013 [15] and 2019 [16]. The proportion of family household size 1 to 10 in 31 Chinese provinces were obtained from the National Bureau of Statistics of China [17].

We also estimated C_{ambien}, $C_{cooking}$ and $C_{smoking}$ for urban residents of ages and genders in 333 Chinese cities when outdoor concentration of $PM_{2.5}$ was 5 μg/m^3 [the World Health Organization (WHO) Air Quality Guidelines (AQG) issued in 2021] [1]. We set the concentration of ambient $PM_{2.5}$ at 5 μg/m^3 and applied the same validated source-specific model in Hu and Zhao (2021) [4] to simulate *C* from indoor and outdoor sources in Chinese urban areas. Then we calculated C_{ambien}, $C_{cooking}$ and $C_{smoking}$ with Equations S1 and S2.

Deaths attributable to human exposure to $PM_{2.5}$ (DAHP). We estimated DAHP in Chinese urban areas in 2019 and when outdoor air meet the WHO AQG 2021 following the approach employed in Global Burden of Disease Study (GBD) 2019 [18]. Its great advantage is that it can split DAHP into deaths from multiple sources of $PM_{2.5}$ and estimate DAHP caused by six diseases, including ischemic heart disease (IHD), obstructive pulmonary disease (COPD), lung cancer (LC), lower respiratory infections (LRI), type 2 diabetes (DM2) and stroke.

The DAHP from specific sources of $PM_{2.5}$ (M_s) is determined by the source-specific annual average concentration of human exposure to $PM_{2.5}$ ($\bar{C}$), population (*N*), age- and disease- specific death rates (*MR*), and population attributable fraction (*PAF*). *PAF* refers to the proportion of deaths in a population that can be attributed to a certain risk factor [18], i.e., human exposure to $PM_{2.5}$ in this study. The DAHP from specific sources for specific diseases in Chinese urban areas ($M_{s,d}$) were calculated with the following equation as that applied in GBD 2019 study [18]:

$$M_{s,d} = \sum_{g}\left(\frac{\overline{C_{s,g}}}{\overline{C_{ambient,g}} + \overline{C_{cooking,g}} + \overline{C_{smoking,g}}} \times PAF_{d,g} \times MR_{d,g} \times N_g\right) \tag{S3}$$

where the subscript *s* represented the source of $PM_{2.5}$ and it is *ambient*, *cooking* and *smoking* in this study; the subscript *d* represented the type of disease and subscript *g* represented a population of specific age groups (19 age groups, i.e., 0-1, 1-5, 5-10, 10-15…0–85, and beyond 85 years old) and gender groups (male and female) in specific cities (333 Chinese cities). The group-specific population size in Chinese urban areas in 2019 was calculated based on the urban population of each city in 2019 [19] and the age and gender composition of the population of each province[17]. The age-, sex-, province- and disease- specific baseline mortality rate for residences in Chinese urban areas in 2019 was calculated using the age-, sex-, region- (east, west and central China) and disease-specific baseline mortality rate in 2019 [20] and the ratio of provincial and regional mortality rates [21].

PAF caused by disease *d* of the population *g* was calculated by

$$PAF_{d,g} = \frac{RR_{d,g} - 1}{RR_{d,g}} \tag{S4}$$

where *RR* is the relative risk, defined as the ratio of the probability of developing a disease in an exposed group to the probability of developing a disease in a comparison group. In this study, *RR* represented the ratio of risk at *C* to risk at theoretical minimum-risk exposure level (2.4-5.9 μg/m^3) [18]. A set of cause-specific risk curves [meta-regression—Bayesian, regularised, trimmed (MR-BRT) curves] were provided in GBD 2019 for calculating the risk of developing a disease at specific concentrations of human exposure to $PM_{2.5}$ [18]. The risk curves are age-specific for IHD and stroke and were uniform across different age groups for COPD, LC and LRI.

e then calculated the population level *RR* for specific diseases considering the rate of second-hand smoke by

$$RR_{d,g} = RR_{SHS,d,g} \times P_{SHS,g} + RR_{non-SHS,d,g} \times \left(1 - P_{SHS,g}\right) \quad (S5)$$

where RR_{SHS} and $RR_{non\text{-}SHS}$ were *RR* for people from smoking and non-smoking households, calculated based on exposure concentration in the population in smoking households and non-smoking households (IEC+OEC, both provided in Table S13 in Hu and Zhao (2021) [4]) and risk curves.

Finally, the DAHP from source *s* (M_s) was estimated by

$$M_s = \sum_d M_{s,d} \quad (S6)$$

Economic losses due to premature deaths. We estimated the economic losses due to DAHP in Chinese urban areas in 2019 and when outdoor meet the WHO AQG 2021. The value of statistical life (*VSL*) for mortality is widely used to convert the health effect of air pollution from premature deaths into monetary value [22-25]. The *VSL*s vary with cities and social–economic factors. We used the following equations to estimate the economic losses due to DAHP in a specific city in Chinese urban (E_{target}).

$$E_{target} = VSL_{target} M_{target} \quad (S7)$$

$$VSL_{target} = VSL_{baseline} + \left(INC_{target} - INC_{baseline}\right) MVSL \quad (S8)$$

where the subscript *baseline* and *target* represented the baseline and target city, respectively. The baseline city was Chongqing in this study [26]. *INC* is per capita disposable income in Chinese urban areas in 2019, from the China city statistical year book-2020 [19]. *MVSL* is the coefficient of marginal increase for saving a statistical life, which was the marginal increase for saving a statistical life (119,800 RMB) divided by annual income increases (1,200 RMB) in China [26]. The $VSL_{baseline}$ in this study was 437,138 RMB which was determined for people in Chongqing [26].

Uncertainty analysis. We applied a two-stage Monte Carlo simulation [10, 27] to obtain the mean and 95% confidence interval of DAHP and economic loss. The two stages reflected the intra-population variability distribution of human exposure to $PM_{2.5}$ and the uncertainty of the risk curve, respectively. We performed 2,000 and 1,000 iterations (2,000,000 runs in total) at variability and uncertainty stages, respectively. We then averaged the variability stage to obtain 1000 population-level *RR*s, and further calculated *PAF*, DAHP, and economic loss and reported their mean and uncertainty intervals, i.e., the 2.5th–97.5th percentile of their values in the 1,000 uncertainty runs. Finally, we tested the robustness of the model by performing 250 times of Monte Carlo simulations and calculating the error of those 250 simulations. The result showed that the error was within 5% [27], indicating 2000×1000 runs were sufficient to quantify the uncertainty of the projected results.

Data availability

The deaths attributable to human exposure to $PM_{2.5}$ in urban areas in 333 Chinese cities in 2019 (**Table S1**) and when outdoor air meets the WHO Air Quality Guideline 2021 (**Table S2**) were provided online. The source data underlying **Fig. 1** is provided as a Source Data file.

Code availability

The codes used for analyzing data are available from the corresponding author on reasonable request.

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Author Contributions
Ying Hu designed the study and planned the analysis, performed the model analysis, analyzed the simulation results, interpreted the results, validated and completed all figures, and drafted the manuscript. **John S. Ji** drafted and commented on the manuscript. **Bin Zhao** coordinated and supervised the project, designed the study and planned the analysis, analyzed the simulation results, interpreted the results, and drafted the manuscript.

Competing Interest Statement
The authors declare no competing interests.

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Figures

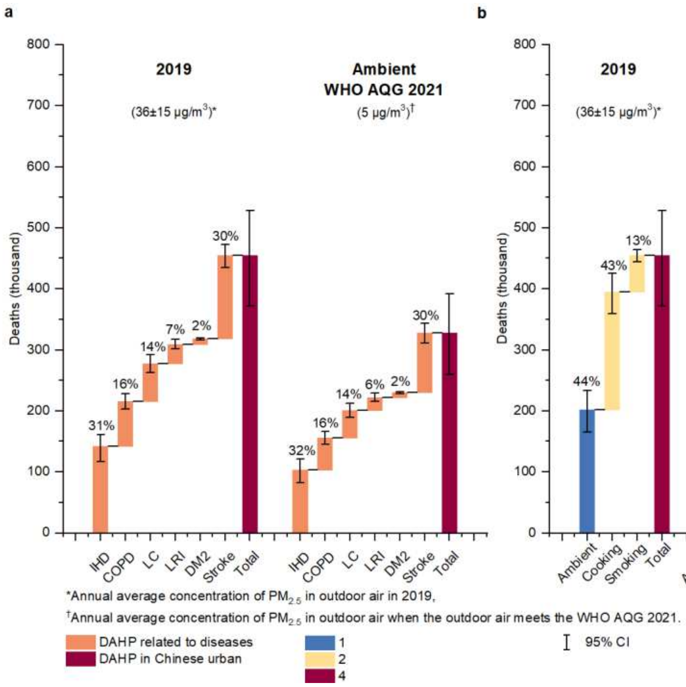

Fig. 1. The attributable deaths of $PM_{2.5}$ in Chinese urban in 2019 and when the outdoor air meets the WHO AQG 2021. a Attributable deaths related to different diseases, **b** attributable deaths of $PM_{2.5}$ from different sources. DAHP, the deaths attributable to human exposure to $PM_{2.5}$; IHD, ischemic heart disease; COPD, Chronic obstructive pulmonary disease; LC, lung cancer; LRI, lower respiratory infections; DM2, type 2 diabetes.

Tables

Table 1. The economic losses related to attributable deaths of $PM_{2.5}$ in Chinese urban areas in 2019 and when the outdoor air meets the WHO AQG 2021. [in unit trillion RMB, mean (95%CI)]

	2019 (36±15 μg/m³) # Sources				Ambient WHO AQG 2021 (5 μg/m³) ‖ Sources			
Diseases	Ambient	Cooking	Smoking	Total	Ambient	Cooking	Smoking	Total
IHD*	0.24 (0.19, 0.19)	0.24 (0.18, 0.19)	0.07 (0.05, 0.06)	0.55 (0.43, 0.44)	0.04 (0.03, 0.03)	0.28 (0.21, 0.22)	0.08 (0.06, 0.06)	0.40 (0.30, 0.31)
COPD†	0.13 (0.10, 0.10)	0.12 (0.10, 0.10)	0.04 (0.03, 0.03)	0.28 (0.23, 0.23)	0.02 (0.02, 0.02)	0.14 (0.11, 0.11)	0.04 (0.03, 0.03)	0.20 (0.16, 0.16)
LC‡	0.11 (0.08, 0.08)	0.10 (0.07, 0.08)	0.03 (0.03, 0.03)	0.25 (0.18, 0.18)	0.02 (0.01, 0.01)	0.12 (0.09, 0.09)	0.04 (0.03, 0.03)	0.18 (0.13, 0.13)
LIR§	0.05 (0.04, 0.04)	0.05 (0.04, 0.04)	0.02 (0.01, 0.01)	0.12 (0.09, 0.09)	0.01 (0.01, 0.01)	0.06 (0.04, 0.04)	0.02 (0.01, 0.01)	0.08 (0.06, 0.06)
DM2¶	0.02 (0.01, 0.01)	0.02 (0.01, 0.01)	0.00 (0.00, 0.00)	0.04 (0.03, 0.03)	0.00 (0.00, 0.00)	0.02 (0.02, 0.02)	0.01 (0.00, 0.00)	0.03 (0.02, 0.02)
Stroke	0.23 (0.20, 0.20)	0.22 (0.19, 0.19)	0.07 (0.06, 0.06)	0.52 (0.45, 0.45)	0.04 (0.03, 0.03)	0.27 (0.22, 0.22)	0.08 (0.06, 0.06)	0.38 (0.31, 0.31)
Total	0.78 (0.63, 0.63)	0.75 (0.60, 0.60)	0.23 (0.19, 0.19)	1.76 (1.42, 1.43)	0.12 (0.09, 0.09)	0.89 (0.69, 0.70)	0.26 (0.20, 0.20)	1.27 (0.99, 1.00)

*ischemic heart disease,
†chronic obstructive pulmonary disease,
‡lung cancer,
§lower respiratory infections,
¶type 2 diabetes,
#Annual average concentration of $PM_{2.5}$ in outdoor air in 2019,
‖Annual average concentration of $PM_{2.5}$ in outdoor air when the outdoor air meets the WHO AQG 2021.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- SourceData.xlsx
- TableS1.xlsx
- TableS2.xlsx