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**Working Paper**

## The Impact of Air Pollution on Attributable Risks and Economic Costs of Hospitalization for Mental Disorders

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## ABSTRACT

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# The Impact of Air Pollution on Attributable Risks and Economic Costs of Hospitalization for Mental Disorders

This study aims to fill the gap in our understanding about exposure to particulate matters with diameter less than 2.5  $\mu\text{m}$  (PM<sub>2.5</sub>) and attributable risks and economic costs of mental disorders (MDs). We identify the relationship between PM<sub>2.5</sub> and risk of hospital admissions (HAs) for MDs in Beijing and measure the attributable risk and economic cost. We apply a generalized additive model (GAM) with controls for time trend, meteorological conditions, holidays and day of the week. Stratified analyses are performed by age, gender and season. We further estimate health and economic burden of HAs for MDs attributable to PM<sub>2.5</sub>. A total of 17,252 HAs for MDs are collected. We show that PM<sub>2.5</sub> accounts for substantial morbidity and economic burden of MDs. Specifically, a 10  $\mu\text{g}/\text{m}^3$  daily increase in PM<sub>2.5</sub> is associated with a 3.55% increase in the risk of HAs for MDs, and the effect is more pronounced for older males in colder weather. According to the WHO's air quality guidelines, 15.12 percent of HAs and 16.19 percent of related medical expenses for MDs are respectively attributable to PM<sub>2.5</sub>.

**JEL Classification:** Q51, Q53, I24, I31, G11, G41, J24

**Keywords:** attributable risk, economic cost, hospital admissions, mental disorders, PM<sub>2.5</sub>

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## 1. Introduction

Mental disorder is one of the three leading causes of Disabled Adjusted Life Years (DALYs) among non-communicable diseases, and it has been estimated that there are 162 million DALYs due to MDs in the world in 2015(Kassebaum et al., 2016). And MDs is a particularly challenging group of conditions with heavy disease burden in all geographies(Kassebaum et al., 2016). The global cost of mental health conditions in 2010 was estimated at \$2.5 trillion, and it will reach \$6.0 trillion by 2030(World Economic Forum, 2011). In China, the total annual costs of MDs increased from \$21.0 billion in 2005 to \$88.8 billion in 2013, the later accounted for 15% of the total health expenditure and 1.1% of China's gross domestic product in 2013(Xu et al., 2016a).

A variety of factors, such as genetic profiles, brain damage, substance abuse, socioeconomic status, and life conditions, may influence mental status. Recent studies have indicated a role of environmental factors, especially particulate matters, in the morbidity of MDs(Lin et al., 2017). Historically, extensive environmental and epidemiological studies around the world showed that PM<sub>2.5</sub> is a ubiquitous environmental hazard and has exerted severe health outcomes on human beings(Benaissa et al., 2019; Chen et al., 2018b; Collaborators, 2017; David Mulenga, 2019; Motesaddi Zarandi et al., 2017). And toxicological studies found PM<sub>2.5</sub> hazards on brain and neurodevelopment(Block et al., 2012; Grandjean and Landrigan, 2014), which will trigger biological reactions displaying a psychological, emotional or behavioral character(Yackerson et al., 2011).

Thus, it is not surprising that emerging studies showed significant association between PM<sub>2.5</sub> and MDs. A study focusing on the individuals living across the United States showed PM<sub>2.5</sub> was significantly associated with anxiety symptoms and depressive symptoms, with the largest increase for 180-days moving average (OR=1.61) and 30-day moving average (OR=1.16), respectively(Pun et al., 2017). Likewise, Studies conducted in Barcelona(Vert et al., 2017), south Korea(Kim et al., 2016), and China(Gao et al., 2017; Qiu et al., 2019; Song et al., 2018; Wang et al., 2018; Xue et al., 2019) also found the increase of PM<sub>2.5</sub> concentrations is associated with the risk of mental disorder morbidity. However, the evidence is still mixed as some other studies conducted in many parts of the world showed no association between particulate matter and MDs(Chen et al., 2018a; Tong et al., 2016; Wang et al., 2014; Zhang et al.,

2019). For instance, a study based on four European general population cohorts found no association between PM<sub>2.5</sub> and depression(Zijlema et al., 2016).

Some referenced studies above may generate contradicting results even if they are conducted in the same city or same country. Moreover, to our knowledge, no studies have estimated the attributable risk and economic cost of MDs because of PM<sub>2.5</sub> exposure in Beijing, where people especially suffered from heavy air pollution(Chen et al., 2018b). Relative to only measuring increase in relative risk, attributable risk and economic cost are more intuitive to evaluate the burden caused by air pollutants to the society and households.

In the present study, firstly, a time-series analysis was conducted to identify the possible correlation between PM<sub>2.5</sub> and risk of HAs for MDs in Beijing, China during 2013-2015. Secondly, we further estimated the attributable risk and economic cost of HAs for MDs due to PM<sub>2.5</sub>.

## **2. Materials and Methods**

### **2.1 Data collection**

#### **2.1.1 Health data**

The health data used in this study were from the Beijing Urban Employees and Residents Basic Medical Insurance System (UERBMIS), which was officially launched in 1998. Daily counts of HAs between 1 January 2013 and 31 December 2015 were obtained from billing claims of medical insurance enrollees. The record for each inpatient contained demographic information, including birthday, sex, and hospital admission information, including date of service, disease diagnosed according to International Classification of Diseases, 10th Revision (ICD-10), and medical expenses consists of total medical expenses and out-of-pocket cost. Daily counts of MDs (ICD 10: F00-F99) HAs were extracted from the records.

#### **2.1.2 Air pollution and meteorological data**

The hourly concentrations of six air pollutants have been monitored by China National Environmental Monitoring Center (CNEMC, <http://www.cnemc.cn/>) since October 2012, which included PM<sub>2.5</sub>, particulate matter  $\leq 10$   $\mu$ m in aerodynamic diameter (PM<sub>10</sub>), sulfur dioxide (SO<sub>2</sub>), nitrogen dioxide (NO<sub>2</sub>), carbon monoxide

(CO) and ozone (O<sub>3</sub>). There were 35 monitoring stations dispersed in different districts of Beijing. In this study, data of PM<sub>2.5</sub>, PM<sub>10</sub> and other gaseous pollutants in each of monitoring stations from January 2013 to December 2015 in Beijing were obtained from the website platform of CNEMC. Then, 24-h average concentrations of PM<sub>2.5</sub>, PM<sub>10</sub>, SO<sub>2</sub>, NO<sub>2</sub>, CO and maximum 8-h moving average concentrations for O<sub>3</sub> were calculated by averaging the concentrations of all stations to represent the citywide pollution exposure.

Daily data of weather conditions, including average relative humidity (%), temperature (°C), wind speed (m/s) and sunshine hours (hr.) were obtained from the National Meteorological Science Data Sharing Center (<https://data.cma.cn/>) on the corresponding period.

## 2.2 Statistical analyses

A time-series analysis was applied to examine the associations between PM<sub>2.5</sub> and HAs for MDs. We utilized an over-dispersed generalized additive model (GAM) which allowed the quasi-Poisson distribution to analyze the data. Natural cubic spline function (*ns*) was adopted to filter out long-term trends and seasonality in daily HAs, and potential non-linear effects of daily mean temperature and relative humidity. The degree of freedom (*df*) for the time trends and other meteorological variables were selected based on previous studies (Gao et al., 2017; Qiu et al., 2019). A *df* of 7/year was adopted for the time trends and seasonality, 3 *df* for the daily mean temperature and relative humidity. We also adjusted for the day of the week (DOW) and public holidays in the models. The main model is shown below (Equation. (1)):

$$\begin{aligned} \ln[E(Y_i)] = & \beta_0 + \beta AP_i + ns(time) + ns(temp_i) + ns(rh_i) + as.factor(DOW) \\ & + as.factor(holiday) + intercept \end{aligned} \quad (1)$$

where  $E(Y_i)$  represents the number of HAs due to MDs on day  $i$ ;  $\beta$  is the relative coefficient;  $AP_i$  indicates the concentration of PM<sub>2.5</sub> on day  $i$ ;  $temp_i$ ,  $rh_i$  are the average temperature, relative humidity on day  $i$ ;  $DOW$  is day of the week.

Relative risk increase (RRI) was defined as Relative Risk (RR) -1. The results were

expressed as the RRI (%) in HAs for MDs per 10  $\mu\text{g}/\text{m}^3$  increment of  $\text{PM}_{2.5}$  concentrations (Equation (2)):

$$\text{RRI}(\%) = (\text{RR} - 1) * 100\% = (\exp(\beta * 10) - 1) * 100\% \quad (2)$$

where  $\beta$  indicates the coefficient of the  $\text{PM}_{2.5}$ -HAs association obtained from Equation (1).

We incorporated both single-day lag (from current day to 20 days before: lag0-lag20) and multi-day moving average (from lag01 to lag020), fitting separate models with the same parameter settings as in the main model for each lag day to estimate the lag patterns of  $\text{PM}_{2.5}$ . Subgroup analyses were performed to examine whether the association differed by age ( $\leq 44$  years, 45-64 years, and  $\geq 65$  years), gender, and season (cool: October to March, warm: April to September). The statistical significance of subgroup differences were tested through Z-test (Di et al., 2017).

The robustness of the analysis results was assessed with respect to: 1) building two-pollutant models ( $\text{PM}_{2.5}$  with  $\text{SO}_2$ ,  $\text{NO}_2$ ,  $\text{O}_3$  and  $\text{CO}$ ) to examine the robustness of the effect estimates after adjusting for co-pollutants, 2) choosing the  $df$  used for the confounding adjustment for time (4-10  $df$  per year) (Gao et al., 2017; Qiu et al., 2019) and temperature (6 and 9  $df$ ) (Di et al., 2017), 3) adding wind speed and sunshine duration into our model (Qiu et al., 2019).

We further estimated the attributable number of HAs for MDs due to  $\text{PM}_{2.5}$  exposure (denoted as AN) based on the effect estimates obtained in the above analyses. Two standards including WHO's air quality guidelines (24 h mean:  $25 \mu\text{g}/\text{m}^3$  for  $\text{PM}_{2.5}$ ) and China grade II standards for air quality (24 h mean:  $50 \mu\text{g}/\text{m}^3$  for  $\text{PM}_{2.5}$ ) were applied as the reference concentrations. The equation was shown below (Equation (3)):

$$\text{AN}_i = (\exp(\beta * \Delta \text{AP}_i) - 1) / \exp(\beta * \Delta \text{AP}_i) * N_i \quad (3)$$

where  $\text{AN}_i$  represents the number of HAs that could be attributable to exceeding  $\text{PM}_{2.5}$  exposure on day  $i$ ;  $\beta$  indicates the coefficient of the  $\text{PM}_{2.5}$ -HAs association



obtained from Equation (1);  $\Delta AP_i$  is the concentration difference between the observed and the reference concentration of PM<sub>2.5</sub> on day  $i$ ;  $N_i$  is the count of HAs on day  $i$ ;  $AN$  is the sum of overall  $AN_i$  during the study period.

We then calculated the economic cost of HAs (including total hospital admission expenses and out-of-pocket cost, denoted as  $AC_{total}$  and  $AC_{pocket}$ , respectively) for MDs due to PM<sub>2.5</sub> exposure. The equations were shown below (Equations (4), (5)):

$$AC_{ytotal} = AN_y * Cost_{ytotal} * CPI_y \quad (4)$$

$$AC_{ypocket} = AN_y * Cost_{ypocket} * CPI_y \quad (5)$$

where  $AC_{ytotal}$  and  $AC_{ypocket}$  represent the total hospital admission cost and out-of-pocket cost that could be attributable to exceeding PM<sub>2.5</sub> exposure in year  $y$ ;  $AN_y$  is the sum of overall  $AN_i$  (obtained from Equation (3)) during year  $y$ ;  $Cost_{ytotal}$  and  $Cost_{ypocket}$  indicate the case-average total hospital admission expenses and out-of-pocket cost in year  $y$ , respectively;  $CPI_y$  is the product of customer price indexes from year  $y+1$  to 2018;  $AC_{total}$  is the sum of  $AC_{ytotal}$ , and  $AC_{pocket}$  is the sum of  $AC_{ypocket}$  during the study period.

The overall research methodology is shown as the following flow chart (Fig. 1). All analyses were conducted using R software (version 3.5.3, R Development Core Team, 2019). The statistical tests were two-sided, and  $p$ -value  $< 0.05$  was considered as statistically significant.

### 3. Results

#### 3.1 Data description

A total of 17,252 HAs for MDs were collected. The average age of the studied subjects was 52.3 years old. The young ( $\leq 44$ ) and the elderly ( $\geq 65$ ) patients accounted for 30.7% and 21.6%, respectively. The number and proportion of male patients and female patients were 9,725 (56.3%) and 7,527 (43.6%), respectively. HAs for MDs were slightly higher in the cool season (51.6%) than in the warm season (48.4%). The overall medical expenses were 320.3 million Chinese Yuan (CNY), 23.3% (74.6 million CNY) of which were self-paid. The case-average total

medical expenses and the out-of-pocket cost were 18.6 and 4.3 thousand CNY, respectively. Daily mean concentrations were 83.2  $\mu\text{g}/\text{m}^3$  for  $\text{PM}_{2.5}$ . Daily mean temperature, relative humidity, wind speed, and sunshine duration are 13.6 °C, 53.9%, 21.0m/s, 6.5 hours, respectively (Table 1).

Concentrations of  $\text{PM}_{2.5}$  were positively associated with concentrations of  $\text{PM}_{10}$  ( $r=0.89$ ,  $p < 0.001$ ), and other gaseous pollutants except for  $\text{O}_3$  (for  $\text{SO}_2$ ,  $\text{NO}_2$ , and  $\text{CO}$ ,  $r=0.58\sim0.81$ ,  $p < 0.001$ , for  $\text{O}_3$ ,  $r=-0.2$ ,  $p<0.001$ ). Moderate correlation was observed for  $\text{PM}_{2.5}$  with meteorological factors (Table 2).

### 3.2 Health effects of $\text{PM}_{2.5}$ in overall and subgroup population

Fig. 2 shows the associations of  $\text{PM}_{2.5}$  with HAs for MDs using single pollutant models. The effects of  $\text{PM}_{2.5}$  exposure on total MDs were significant on lag10, lag11, lag16, with the largest effects on lag11 day. Per 10  $\mu\text{g}/\text{m}^3$  increase in the lag11 day exposure for  $\text{PM}_{2.5}$  was associated with a RRI of 3.55% (95%CI: 0.67%–6.51%) increase in total mental disorder admissions.

Fig. 3 illustrates the effect estimates of stratified analyses by age, gender and season.  $\text{PM}_{2.5}$  was associated with larger increase in hospital admission rate in some subgroups. The effects of  $\text{PM}_{2.5}$  pollution on HAs for MDs were more pronounced in males (RRI: 3.93% [95%CI: 0.86%-7.09%],  $p<0.05$ ) than in females (RRI: 3.09% [95%CI: 0.38%-5.86%],  $p<0.05$ ). In age-specific analyses, the effects were significant among older patients (RRI: 6.92% [95% CI: 2.74%-11.27%],  $p<0.05$ ) and those of middle-aged (RRI: 3.76% [95%CI: 0.70%-6.91%],  $p<0.05$ ). Positive but insignificant associations were found among the young. In terms of the differences in season groups, we observed positive and significant association in cold seasons (RRI: 3.61% [95%CI: 0.46%-6.86%],  $P<0.05$ ), higher than the risk in warm seasons. The difference between old and young population was significant, while no significant difference was found in other subgroup comparisons.

### 3.3 Sensitivity analysis

The robustness check results are shown in Table 3. In the two-pollutant models, the risk estimates of  $\text{PM}_{2.5}$  on total mental disorder admissions remained statistically

significant on after adjusting for SO<sub>2</sub> and O<sub>3</sub>. After adjusting for NO<sub>2</sub> and CO, the RRI of models were slightly lower than the single-pollutant model, and showed no significance. The percentage change (95% CI) in HAs for MDs with each 10 µg/m<sup>3</sup> increase in of PM<sub>2.5</sub> under varying degrees of freedom for the smooth functions of calendar time and daily mean temperature changed little, suggesting that the findings on the associations of PM<sub>2.5</sub> exposure and HAs for all-cause MDs were robust in our study. After adding wind speed and sunshine duration into the single pollutant model, our result remained robust to these additional controls.

### 3.4 Attributable health risks and economic costs due to PM<sub>2.5</sub>

Table 4 summarized the estimations of the number of HAs and medical expenses attributable to exceeding PM<sub>2.5</sub> exposure using air quality guidelines. Taking WHO's air quality guideline as the reference concentrations, from 2013 to 2015, 15.12% of HAs (2,609 person-times out of 17,252 person-times) for MDs could be attributable to exceeding PM<sub>2.5</sub>. And 16.19% of the total medical expenses for HAs (51.86 million CNY out of 320.3 million CNY) could be attributable to exceeding PM<sub>2.5</sub>. As for out-of-pocket cost, 12.10 million CNY could be attributable to exceeding PM<sub>2.5</sub>, 23.33% of the extra total expenses. Under China grade II standard concentrations, AN,  $AC_{total}$  and  $AC_{pocket}$  are 1,819 person-time, 36.25 million CNY, and 8.44million CNY, respectively.

## 4. Discussion

This study is the first to investigate the risk and economic cost of HAs for MDs in Beijing. In this time series study of all HAs in UERBMIS in Beijing from 2013 to 2015, a 10 µg/m<sup>3</sup> daily increase in PM<sub>2.5</sub> was associated with a statistically significant risk increase of 3.55% for total HAs for MDs. The effects of PM<sub>2.5</sub> exposure on HAs for MDs were more pronounced in males, older persons individuals and in cold seasons and the difference between old and young population was statistically significant. Using WHO's air quality guidelines as the reference, approximately one sixth of HAs and the related medical expenses for MDs were estimated to be attributed to PM<sub>2.5</sub>, respectively. And about one forth of the extra total expenses were self-paid. Our results were robust, as they were generally not sensitive to model specifications.

In recent years, an increasing number of studies have suggested that PM<sub>2.5</sub> have harmful impacts on MDs (Kim et al., 2016; Pun et al., 2017; Song et al., 2018; Tong et al., 2016; Wang et al., 2018). In our study, significant associations between PM<sub>2.5</sub> exposure and MDs were found, which were supported by literature in the wider context of research. A cohort study conducted in six low- and middle-income countries showed that the odds ratio (OR) for depression was 1.10 (95% CI: 1.02–1.19) per 10 µg/m<sup>3</sup> increase in ambient PM<sub>2.5</sub> (Lin et al., 2017). Qiu H. et al found an increment of 2.89% (95% CI: 0.75–5.08%) in MDs HAs was associated with each 10 µg/m<sup>3</sup> increase in PM<sub>2.5</sub> at lag06 in Chengdu (Qiu et al., 2019). One study summarized the associations of particulate matter with daily hospitalizations for MDs in Beijing Anding hospital and estimated that a 0–6-day cumulative effect of PM<sub>2.5</sub> per 10 mg/m<sup>3</sup> increase was respectively associated with a 1.01% (95% CI: 0.02–2.00%) increase in schizophrenia admissions (Gao et al., 2017).

Zhang X. et al found that worsening air quality was a driving force of the stagnant happiness trend by influencing people's satisfaction of life, which may be a psychological channel through which PM<sub>2.5</sub> may affect mental health (Zhang et al., 2017). As for the biological mechanisms, firstly, former findings indicated that the brain is a critical target for PM<sub>2.5</sub> exposure. Smaller particles may penetrate the brain's blood barrier and thus affect the central nervous system. It has been indicated that air pollutants may lead to biological changes in the brain, such as change in brain activity (Xu et al., 2016b), diminishing white matter or neuronal degeneration (Gladka et al., 2018). A cohort study found that late-life exposure to ambient particulate air pollutants has a deleterious effect on brain aging and brain volumes (Chen et al., 2015). Secondly, studies have also suggested that the development of MDs is dependent on the interaction between genetic and environmental factors, which may be mediated by the activation of the immune system, oxidative stress and inflammation (Block and Calderon-Garciduenas, 2009). The results from a natural experiment showed that the over secretion of glucocorticoid activated immunity and inflammation in excess after PM<sub>2.5</sub> exposure and thus led to a series of mood-related behaviors disorder (Jia et al., 2018).

This study found the elder ( $\geq 65$  years old) individuals were more vulnerable than

the younger (0–44) and middle-aged (45–64) groups, which were generally consistent with previous studies(Gao et al., 2017; Lee et al., 2019a) though some studies did not obtain the same results(Chen et al., 2018a; Qiu et al., 2019). The possible reasons might be that the impairment of cognitive function is expected to grow as people ages(Ferri et al., 2005) and PM<sub>2.5</sub> could aggravate the process especially when it comes to the elder population(Lee et al., 2019a). Our results appeared that males were more susceptible to the effects of PM<sub>2.5</sub> exposure than females, which is in line with findings from human and animal studies(Costa et al., 2014; Qiu et al., 2019; Song et al., 2018). However, other authors reported the opposite result(Gao et al., 2017; Wang et al., 2018), this could be associated with the socioeconomic, behavioral(Wen et al., 2007) and psychological(Segev et al., 2011) heterogeneity among the study populations. Studies also showed that females and males are vulnerable in different subset of mental problems, respectively(Shin et al., 2019). Thus, further studies are encouraged to focus on the epidemiological researches and biological mechanisms of specific MDs. We found that the associations of PM<sub>2.5</sub> with MD HAs were more pronounced in cold seasons than in warm seasons, which is consistent with studies in Shijiazhuang and Chengdu(Qiu et al., 2019; Song et al., 2018). The stronger associations in cold seasons may be attributable to higher concentration of ambient air pollutants. However, other studies have demonstrated different seasonal patterns(Chen et al., 2018a; Lee et al., 2019b), which may due to the complex components of air pollution, climatic conditions and exposure patterns in different regions. So far there were no conclusive findings about the heterogeneity in effects of ambient pollution on HAs for MDs. More studies concerning specific subtype of mental or behavior disorders are needed in the future to determine the sensitive populations.

Our study estimated the health burden of HAs for MDs attributable to PM<sub>2.5</sub> exposure, which is of great value for air quality improvement and mental disease prevention. AN possesses important public health implications to policy-makers on the quantitative benefits of lowering ambient PM<sub>2.5</sub> levels(Lin et al., 2016). Such approaches were first applied by Qiu H. et al. to estimate the morbidity burden of MDs due to particulate matter exposure in Chengdu, finding that 9.53% (95%CI: 2.67%, 15.58%) of HAs for MDs could be attributable to PM<sub>2.5</sub>(Qiu et al., 2019). Furthermore, for the first time, our study calculated the related economic cost, the

total medical expenses and the out-of-pocket cost, brought by the extra  $PM_{2.5}$  exposure in Beijing. The results provide straightforward information for cost-benefit analysis in pollution cap project, healthcare resources allocation in health department(Sánchez-Barroso and Sanz-Calcedo, 2019), as well as the basic data for willingness-to-pay studies(Barwick et al., 2018).

From 2013 to 2015, there showed increased yearly trends for AN,  $AC_{total}$  and  $AC_{pocket}$ . A study summarizing the hospital admissions and the related direct medical costs for mental disorders in Shanghai also showed the same trend(Chen et al., 2017). Moreover, based on a back-of-envelope calculation using results from Table 4, the fraction of health burden and economic cost incurred by  $PM_{2.5}$  went up from 2013 to 2014, and declined in 2015, which indicated the efficiently controlled  $PM_{2.5}$  concentration(Chen et al., 2018b) after the Air Pollution Prevention and Control Action Plan(Chinese State Council, 2013) implemented by the Chinese government may account for the lower burden in 2015. However, further studies are appealed to focus on longer time period to figure out the long term fluctuation of the health and economic burden due to exceeding  $PM_{2.5}$  to track and forecast the pollution-related burden as well as the pollution control benefits.

This study has several strengths. First, our data were obtained from billing claims of medical enrollees based on UERBMIS in Beijing, converging more than 70% of the total urban population(Wang, 2018), so our results have good representativeness for urban population in Beijing. Second, to our knowledge, it is the first time that the attributable economic costs of HAs for MDs due to  $PM_{2.5}$  exposure has been estimated using the accurate direct medical expenses information from the UERBMIS, which is more intuitive for researchers and authorities to understand the adverse impact of  $PM_{2.5}$  than only estimating changes in relative risk. Finally, we evaluated both the total medical expenses and out-of-pocket cost attributable to  $PM_{2.5}$ , which provided useful information to show the economic burden to both the society and individuals.

Despite its strengths, our study's findings have limitations. First, the average concentration of  $PM_{2.5}$  in the whole city was taken as the proxy of personal  $PM_{2.5}$  exposure, which may result in measurement error. Second, the risk factors that we

analyzed in our models were air pollutants and meteorological factors. Other factors, such as socioeconomic conditions, and behavioral characteristics like smoking status(Lin et al., 2017) could also be considered in follow-up studies. Third, the economic burden calculated in this study tends to be a lower bound estimate of the real economic cost of HAs due to MDs, since this cost only accounts for those who came to hospital to seek care, while those who were not able to afford hospital bills or who didn't have time were left out. Fourth, the economic cost in our results only included the direct medical expenses, further studies should try to figure out the direct non-medical costs and indirect costs(Xu et al., 2016a).

## **5. Conclusions**

This study suggested that ambient PM<sub>2.5</sub> exposure significantly elevates the risks of HAs for MDs. Male and elderly individuals were more susceptible to PM<sub>2.5</sub> pollution. Additionally, a substantial morbidity and economic burden of MDs for both society and individuals could be attributable to exceeding PM<sub>2.5</sub> exposure. Therefore, policy considerations in environmental protection and public health interventions are essential to improve the mental health status of the population, and more attention should be paid to the sensitive subgroups. Our study serves as a trigger to figure out the health and economic burden due to PM<sub>2.5</sub> in Beijing. In addition to the causal relationship between PM<sub>2.5</sub> pollution and mental disorders, more studies in the field of public health and economics are needed to confirm the direct and indirect economic cost due to PM<sub>2.5</sub>.

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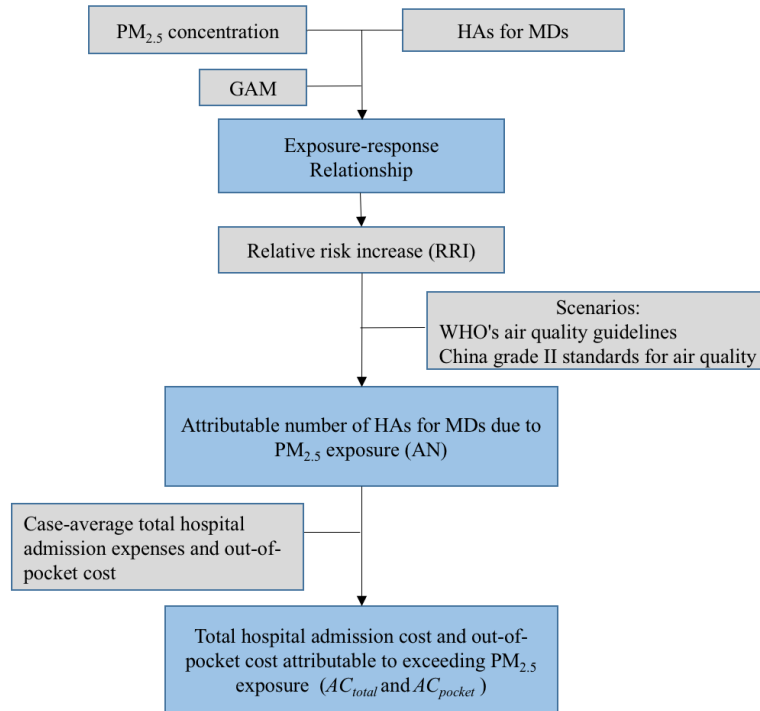
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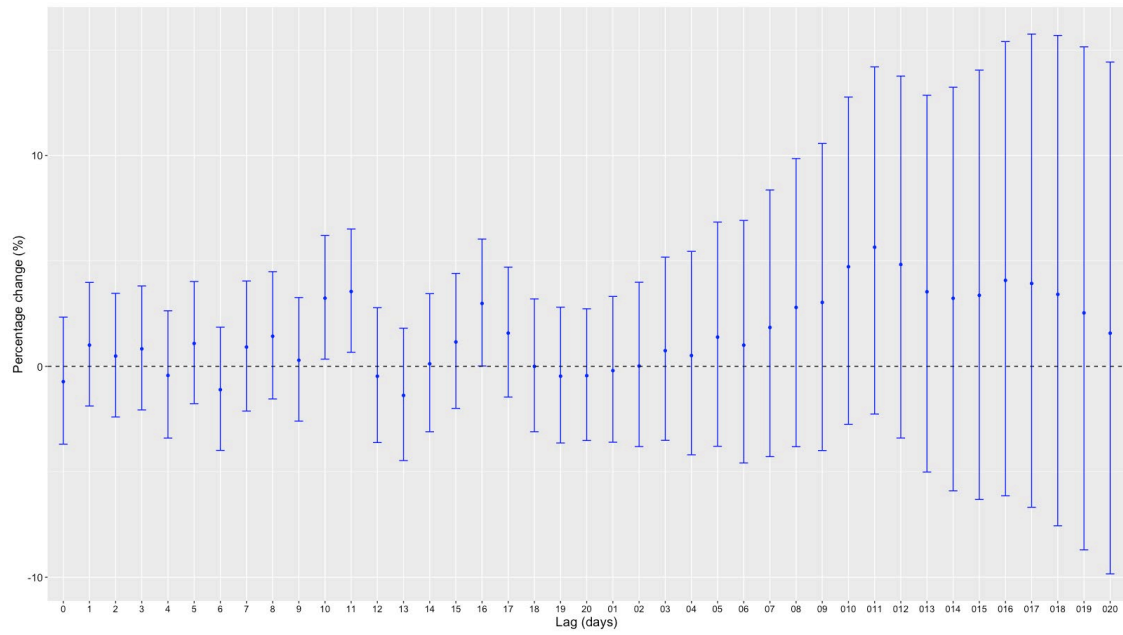
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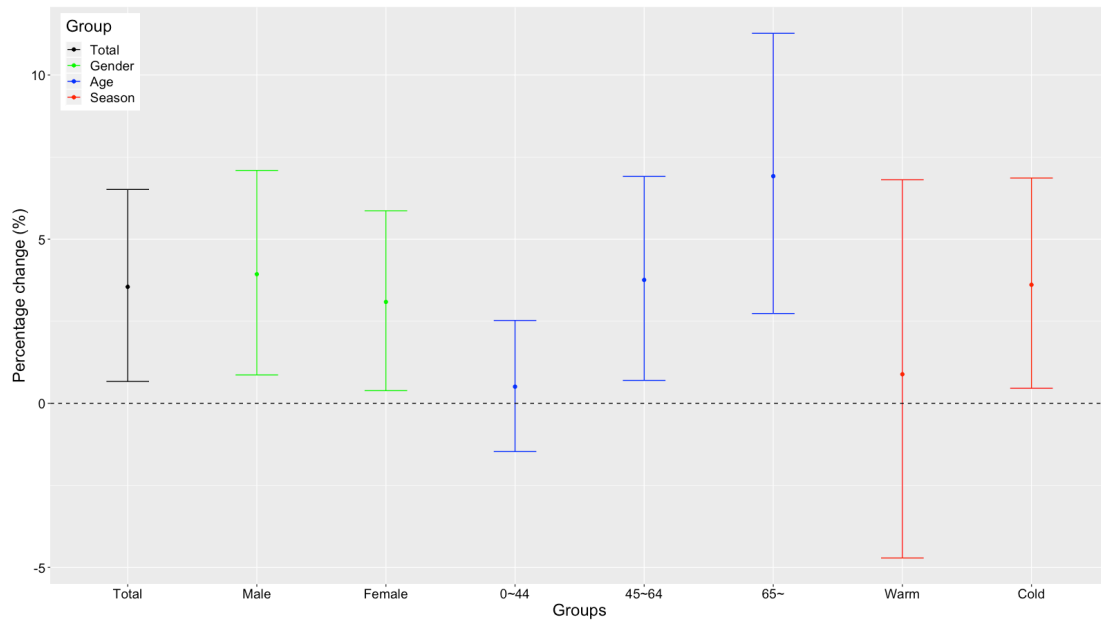
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**Fig. 1 Research methodology flow chart.** The flow chart shows the steps in ascertaining exposure-response relationship and calculating attributable risk and economic cost.



**Fig. 2 Percentage change (95% CI) in HAs for MDs associated with a 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> along different lag structures using single-pollutant models. Note: the effects of single-day lags (from current day to 20 days before: lag0-lag20) and multi-day moving average lags (from lag01 to lag020) were plotted.**



**Fig. 3 Percentage change (95% CI) in HAs for MDs associated with a  $10\mu\text{g}/\text{m}^3$  increase in  $\text{PM}_{2.5}$  at lag11 stratified by gender, age and season.**



**Table 1 Summary statistics for HAs for MDs, the related medical expenses, air pollutants concentrations and meteorological factors in Beijing, 2013-2015**

Variable	Total	Daily mean	SD	Min	P25	Median	P75	Max
Mental disorder	17,252	16	44	0	3	7	13	723
Age								
0-44	5,301	5	13	0	1	3	5	284
45-64	8,232	8	22	0	1	3	6	335
≥65	3,719	3	12	0	0	1	2	104
Gender								
Male	9,725	9	28	0	1	3	7	452
Female	7,527	7	17	0	1	3	6	271
Season								
Warm	8,350	8	24	0	0	0	7	222
Cool	8,902	8	39	0	0	0	7	723
Medical expenses <sup>a</sup>								
Total expenses	32,027.8	29.2	59.0	0	11.5	18.4	29.6	982.1
Out-of-pocket cost	7,456.8	6.8	21.7	0	2.0	3.6	5.5	388.7
Air pollutants								
PM <sub>2.5</sub>	—	83.2	69.1	5.6	34.1	62.9	113.5	467.4
PM <sub>10</sub>	—	119.5	77.7	5.6	67.1	102.7	151.2	612.2
SO <sub>2</sub>	—	19.9	21.9	1.2	5.2	10.8	26.9	146.2
NO <sub>2</sub>	—	51.7	24.5	7.5	34.4	45.7	63.3	154.7
CO	—	1.3	1.0	0.2	0.7	1.0	1.6	7.9
O <sub>3</sub>	—	56.9	36.6	2.2	27.4	51.9	80.4	197.3
Meteorological variables								
Temperature (C°)	—	13.6	11.0	-9.7	3.1	15.2	23.7	32.6
Relative humidity (%)	—	53.9	19.8	8.0	38.0	54.0	69.0	99.0
Wind speed (m/s)		21.0	8.5	6.0	15.0	19.0	25.0	66.0
Sunshine duration (h)		6.5	4.1	0	2.9	7.7	9.7	14.1

a: unit: 10 thousand Chinese Yuan (CNY)

**Table 2 Spearman's correlation coefficients between the daily levels of air pollutants and meteorological variables in Beijing, 2013-2105.**

	PM <sub>2.5</sub>	PM <sub>10</sub>	SO <sub>2</sub>	NO <sub>2</sub>	CO	O <sub>3</sub>	Temp	RH
PM <sub>2.5</sub>	1	0.89*	0.58*	0.78*	0.81*	-0.2*	-0.21*	0.47*
PM <sub>10</sub>		1	0.52*	0.75*	0.73*	-0.16*	-0.17*	0.32*
SO <sub>2</sub>			1	0.72*	0.7*	-0.32*	-0.55*	-0.02
NO <sub>2</sub>				1	0.81*	-0.45*	-0.39*	0.24*
CO					1	-0.41*	-0.43*	0.37*
O <sub>3</sub>						1	0.67*	-0.08*
Temp							1	0.23*
RH								1

\*  $p < 0.05$ ; Temp: temperature; RH: relative humidity.

**Table 3 Percentage change (95% CI) in HAs for MDs associated with a 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> in different models.**

	RRI (95%CI)		RRI (95%CI)
Co-pollutant <sup>#</sup>		df for time <sup>§</sup>	
+SO <sub>2</sub>	3.71(0.07,7.47)*	df=4	2.83(0.02,5.72) *
+NO <sub>2</sub>	1.59(-2.25,5.59)	df=5	3.46(0.60,6.41) *
+CO	3.15(-0.78,7.22)	df=6	3.46(0.56,6.44) *
+O <sub>3</sub>	3.56(0.63,6.57) *	df=7	3.55(0.67,6.51) *
df for temperature <sup>†</sup>		df=8	3.45(0.56,6.41) *
df=6	3.71(0.78,6.71) *	df=9	3.35(0.42,6.37) *
df=9	3.59(0.75,6.51) *	df=10	3.42(0.50,6.42) *
Adjusted model <sup>¶</sup>	3.32(0.36,6.37) *		

<sup>#</sup>Percentage change (95% CI) in HAs for MDs associated with a 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> at lag11 using two-pollutant models.

<sup>†</sup>Percentage change (95% CI) in HAs for MDs associated with a 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> at lag11 under varying degrees of freedom for the smooth function of daily mean temperature using single-pollutant models.

<sup>¶</sup>Effect estimates of PM<sub>2.5</sub> at lag11 on MDs in the adjusted model (add wind speed and sunshine duration into the model).

<sup>§</sup>Percentage change (95% CI) in HAs for MDs associated with a 10µg/m<sup>3</sup> increase in PM<sub>2.5</sub> at lag11 under varying degrees of freedom for the smooth function of time trend using single-pollutant models.

\**p*<0.05.

**Table 4 The attributable number of HAs and the related economic cost due to exceeding PM<sub>2.5</sub> exposure using WHO and China air quality standard in Beijing, 2013-2015.**

Year	WHO's air quality guideline			China grade II standard		
	AN <sub>y</sub>	AC <sub>ytotal</sub> <sup>*</sup>	AC <sub>ypocket</sub> <sup>*</sup>	AN <sub>y</sub>	AC <sub>ytotal</sub> <sup>*</sup>	AC <sub>ypocket</sub> <sup>*</sup>
2013	613(135, 973)	12.18(2.68, 19.33)	2.88(0.64, 4.58)	410(90, 653)	8.15(1.79, 12.97)	1.93(0.42, 3.07)
2014	977(222, 1 531)	17.97(4.08, 28.17)	4.43(1.01, 6.94)	658(151, 1 027)	12.11(2.78, 18.89)	2.98(0.68, 4.66)
2015	1,019(234, 1 567)	21.70(4.98, 33.38)	4.78(1.10, 7.36)	751(172, 1158)	16.00(3.66, 24.67)	3.53(0.81, 5.44)
Total	2,609(591, 4 071)	51.86(11.75, 80.87)	12.10(2.74, 18.88)	1,819(413, 2 838)	36.25(8.23, 56.53)	8.44(1.92, 13.17)

\*unit: million CNY. The annual economic costs were measured at the constant price in 2018.

Note: AN<sub>y</sub> represents the number of HAs that could be attributable to exceeding PM<sub>2.5</sub> exposure in year *y*. AC<sub>ytotal</sub> and AC<sub>ypocket</sub> represent the total hospital admission cost and out-of-pocket cost that could be attributable to exceeding PM<sub>2.5</sub> exposure in year *y*. AN<sub>y</sub>, AC<sub>ytotal</sub> and AC<sub>ypocket</sub> were calculated based on the largest effect estimates in single pollutant models. The total HAs were 4,597, 6,008, and 6,647 person-times in 2013, 2014, and 2015, respectively, and the related total medical expenses were 83.45, 103.02, and 133.81 million CNY, respectively.