WITHDRAWN: The association between short-term exposure to PM1 and daily hospital admission and related expenditures in Beijing

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EDITORIAL NOTE:

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The association between short-term exposure to PM$_1$ and daily hospital admission and related expenditures in Beijing

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Abstract

Ambient particulate matter (PM) pollution has been a leading environmental health threat throughout the world. PM with aerodynamic diameter ≤ 1.0 μm, also known as PM$_1$, has been implicated in the morbidity and mortality of several cardiorespiratory and cerebrovascular diseases. However, previous studies have mostly focused on analysing fine PM (PM$_{2.5}$) associated disease metrics including emergency department visits and mortality. Here, using air pollution and hospital admission (HA) data in Beijing from 2015 to 2017, we performed a time-series analysis and meta-analysis to evaluate the association between short-term PM$_1$ exposure and HA of all-cause, chronic obstructive pulmonary disease (COPD) and respiratory infection (RI) diseases. It was found that as per 10 μg/m$^3$ increase of PM$_1$ concentration, all-cause disease HA increased by 0.07% (95% CI: [0, 0.14%]) in Beijing during 2015-2017, while COPD and RI-related HA was not significantly associated with short-term PM$_1$ exposure. We then estimated the attributable number of HA and hospital expenditure related to all-cause diseases. An average of 6644 (95% CI: [351, 12917]) cases of HA were found to be attributable to ambient PM$_1$, which was estimated to associate with 106 (95% CI: [5.6, 207]) million CNY increase in hospital expenditure every year, accounting for 0.32% (95% CI: [0.02, 0.62%]) of the annual total expense. The findings reported here highlights the underlying impact of ambient PM pollution on health risks and economic burden to the society, which also indicates the need for further policy actions on public health.

Keywords: PM$_1$, hospital admission, hospital expenditures, COPD, and Beijing
1. Introduction

Ambient particulate matter (PM) pollution has been one of the leading environmental health threats in the world, especially in developing countries (Burnett et al. 2018; Cohen et al. 2017; Xie et al. 2021). Existing epidemiological studies have associated ambient exposure of PM$_{10}$ (PM with aerodynamic diameter \( \leq 10 \, \mu \text{m} \)), PM$_{2.5}$ (fine PM with aerodynamic diameter \( \leq 2.5 \, \mu \text{m} \)) and PM$_{1}$ (PM with aerodynamic diameter \( \leq 1.0 \, \mu \text{m} \)) with morbidity and mortality of conditions such as cardiorespiratory and cerebrovascular diseases (Luo et al. 2023; Wu et al. 2022; Xie et al. 2021). As reported, the global attributable mortality associated with air pollution including ambient PM exposure accounted for approximately 2.92 million female deaths and approximately 3.75 million male deaths, where Asian countries including China remain the highest health risk associated with air pollution (Collaborators 2020). In particular, low- and middle-income countries account for 62.6% of global pulmonary disease burdens, including chronic obstructive pulmonary disease (COPD) and lung cancer (Diseases and Injuries 2020). These evidences therefore indicate an urgent need to understand the underlying causes of PM-associated health risk and provide indications for public health officials regarding air pollution control.

Previous studies have mostly focused on the effect of short-term exposure of PM$_{2.5}$ and PM$_{10}$ with various morbidity and mortality outcome (Hasegawa et al. 2023; H Liu et al. 2018; Yin et al. 2020), while recent studies have pointed out that the smaller size may trigger higher risk, such as PM$_{1}$. As known, PM$_{1}$ is a type of health-damaging particle mainly sourced from chemical combustion and secondary aerosol materials in China (Chen et al. 2018; Huang et al. 2014a). PM$_{1}$ has a higher surface area : volume ratio which allows it to easily penetrate the lungs and potentially induce more adverse health effects, compared to other PMs (Valavanidis et al. 2008; Yin et al. 2020). It was found that PM$_{1}$ accounts for 80% of PM$_{2.5}$ mass contents (Chen et al. 2018), indicating that PM$_{2.5}$-related health effects is likely dependent on the existence of PM$_{1}$. In fact, short-term PM$_{1}$-dependent effects have been previously implicated in the cause of various diseases by assessing relative health risk metrics. This includes emergency ambulance call, emergency department visits (EDV), and mortality (GB Chen et al. 2017a; Hu et al. 2022; H Lin et al. 2018; LJ Liu et al. 2021; Wang et al. 2021a; Yin et al. 2019; Zhang et al. 2020b). Recently, studies have mostly focused on the implications of short-term PM$_{1}$ exposure in hospital admissions related to cardiovascular diseases and strokes (Liu et al. 2022; Tian et al. 2023; Zheng et al. 2023; Zhou et al. 2023), less is understood on the impact on respiratory disease hospitalisations (Li et al. 2023; Zhang et al. 2020a).
In addition, the associated health impact is accompanied by economic loss, the amount of which is estimated to account for 1% of GDP in 2060, with additional health expenditures having the largest impact (Lanzi et al. 2018). This therefore indicates the urgent need for further study to elucidate the underlying impact. Based on a time-series analysis in China, PM$_{2.5}$ exposure was attributable to an increase of 362,007 hospital admission (HA) cases and 3.68 billion CNY expenditures (Xie et al. 2021), highlighting the health and economic burden of ambient PM pollution. However, the hospital expenditures associated to PM$_1$ exposure remains unclear.

Here, we performed a time-series analysis to study the impact of short-term PM$_1$ exposure on hospital admission of non-accidental, COPD and respiratory infection (RI) diseases during 2015-2017 among 16 districts of Beijing, China. We then estimated the attributable number of HA and expenditure increase to elucidate the potential socio-economic burden of ambient PM$_1$ pollution. Study presented here may shed some light in air pollution mitigation.

2. Materials and Methods

This study aimed to investigate the association of ambient PM$_1$ exposure with hospital admissions (HA) and total hospital expenses of three cause-specific diseases: all non-accidental causes (all-cause), respiratory infections (RI) and chronic obstructive pulmonary disease (COPD) in Beijing, China. Air pollutant and health data of sixteen administrative districts in Beijing during the study period of January 1, 2015, to December 31, 2017 were used for the present study.

2.1 Air pollutant and health data preparation

Four sets of data for each of the sixteen districts in Beijing were collected: daily air pollutant concentration, daily meteorological data, daily HA and daily total hospital expense. The process of data collection and preparation have been described in previous studies (Wang et al. 2021a; Yin et al. 2020). In general, hourly ambient PM$_1$ concentrations were collected from four monitoring stations in Beijing, as part of the Atmosphere Watch Network (CAWNET) (Guo et al. 2020a; Guo et al. 2020b; Zhang et al. 2019) and averaged to obtain daily levels based on previously described methods (GB Chen et al. 2017a; Zhang et al. 2020b). Temperature and humidity levels were obtained from the China Meteorological Data Service Centre (http://data.cma.cn/) (L Liu et al. 2018; Yin et al. 2020). Additionally, daily HA and hospital expense data were obtained from Beijing Municipal Health Big Data and Policy Research Center (http://www.phic.org.cn/) and categorised using the Tenth Revision of
the International Classification of Diseases codes: all-cause diseases (codes A00-R99), RI (codes J00–J98) and COPD (codes J41- J44) (Yin et al. 2020).

2.2 Determination of PM\textsubscript{1}-associated effects on daily HA

We conducted a two-stage approach to elucidate the association between PM\textsubscript{1} exposure and daily HA risk of all-cause diseases, COPD and RI in Beijing, in line with previous studies (Wang et al. 2021a; Xie et al. 2021). Briefly, time-series analyses using generalised linear models (Chen et al. 2020; Jiao et al. 2019) were performed in the first stage to assess PM\textsubscript{1}-associated effects on daily HA for non-accidental diseases, COPD and RI of each district in Beijing. Daily HAs ($y$) were estimated assuming a Poisson regression model (Chen et al. 2020; Jiao et al. 2019), where $\mu$ is the parameter representing the expected number of HA in the specific district of Beijing on a specific day. The concentration of PM\textsubscript{1} ($P$) in the specific district of Beijing within a three-day moving average was used as attribute variable. Given that previous studies have generally shown significant PM-associated effects on health variables at lag0-2 days (labelled as lag0-2), district analyses of lag0-2 PM\textsubscript{1}-associated relative risks for daily HA in Beijing were performed. In order to control against potential variations, other factors were considered in the model, including 1) the variable “day of the week” (DoW) to account for possible variations within a week (RJ Chen et al. 2017); 2) a natural spline smoothing function for calendar day with 7 degrees of freedom per year (Yrdf) to control long-term temporal trends of HA risk (Yin et al. 2020); 3) a natural spline smoothing function for temperature (Temp) and relative humidity (H) with six degrees of freedom for a three-day moving average to exclude potential non-linear and delayed impacts of meteorological conditions on HA risk (Zhang et al. 2020a; Zhang et al. 2020b). The model is expressed as below:

$$y \sim \text{Poisson}(\mu)$$

$$\log(\mu) \sim P + \text{DoW} + \text{Yrdf} + \text{Temp} + H$$

In addition to lag0-2 estimations, delayed effects of PM\textsubscript{1} exposure and HA risk were controlled by using single lag days (labelled as lag0, lag1 and lag2), four- and five-day moving average (labelled as lag0-3 and lag0-4).

Secondly, after obtaining the district-specific HA risk data in the first stage, meta-analysis was performed to assess the overall effect of PM\textsubscript{1} exposure on each disease in Beijing. Using random-effect models, the lag0-2 effect data were estimated for overall HA risk, referred to as relative risk (RR) and represented as mean and related 95% confidence interval (95% CI) per 10 μg/m\textsuperscript{3} uptick of PM\textsubscript{1} concentration. Percentage differences in HA
risk with a 10 μg/m$^3$ increase in PM$_1$ concentration were then calculated as (RR-1)*100.

Two-sided $p<0.05$ was considered statistically significant.

2.3 Estimation of PM$_1$-associated daily HA and total hospital expense change

Overall effect estimates of HA risk from the meta-analysis were utilised to calculate attributable number (AN) and attributable fraction (AF) of daily HA and total hospital expenses due to PM$_1$ exposure for all-cause diseases, based on previously demonstrated methods (Wang et al. 2021b; Xie et al. 2021). The above estimated RR at lag0-2 was first used to calculate RR$_i$ for each year $i$, as below:

$$RR_i = e^{(β \times \frac{P_i}{10})}$$  \hspace{1cm} (3)$$

where $P_i$ indicates PM$_1$ concentration of year $i$, and $β$ represents the estimated coefficient of daily HA per 10 μg/m$^3$ uptick of PM$_1$ concentration from the meta-analysis.

AN$_i$ of daily HA of each year $i$ for Beijing was then calculated as (Gasparrini et al. 2012; Tian et al. 2019):

$$AN_i = \frac{RR_i - 1}{RR_i} \times C_i$$  \hspace{1cm} (4)$$

where $C_i$ indicates the total number of daily HA in year $i$ for Beijing. Annual AN$_i$ values were then averaged to calculate three-year average AN. AF$_i$ of daily HA of each year $i$ for Beijing were therefore obtained by dividing annual AN$_i$ by the sum of HA over three years in Beijing. Additionally, the upper and lower limit values of 95% CI of $β$ were used to calculate the 95% CI values of ANs and AFs using the above formulas (GB Chen et al. 2017b).

Furthermore, we calculated the AN of total hospital expense for all-cause diseases in each year $i$ in Beijing (referred to as AN$_{ei}$), shown as below (Wei et al. 2019):

$$AN_{ei} = E_i \times AN_i$$  \hspace{1cm} (5)$$

where $E_i$ is the average expense of all all-cause HA in year $i$ for Beijing.

AF of total hospital expense for all-cause diseases in each year $i$ in Beijing (labelled as $AF_{ei}$) were calculated by dividing $AN_{ei}$ by the sum of total hospital expenses over three years in Beijing.

District-specific AN and AF of daily HA and total hospital expenses for all-causes diseases in Beijing were estimated, respectively using $β$, RR, daily HA and total hospital expenses of each specific district in Beijing.

All data analyses and graph plotting were performed using packages dlnm and metafor in the R software (version 4.2.1). All data were presented as mean ± 95% CI or as indicated.

3. Results
Table 1 summarises PM pollutant concentrations for Beijing during 2015-2017. PM$_{1}$ concentration levels experienced a 24.01% annual average reduction throughout the study period in Beijing, with a three-year average of 48.23±44.51 μg/m$^3$. Similar decreasing temporal trend was also observed in PM$_{2.5}$ and PM$_{10}$ pollutant levels. Figure 1 shows PM$_{1}$ concentration in each of the 16 districts of Beijing from 2015 to 2017. In general, the six urban districts (Dongcheng, Xicheng, Haidian, Chaoyang, Fengtai and Shijingshan) demonstrated higher three-year average PM$_{1}$ concentration levels, compared to the other rural districts. The highest average PM$_{1}$ level was reported in Dongcheng district (50.93±50.05 μg/m$^3$) throughout the study period, and the lowest in Shunyi district (42.91±38.78 μg/m$^3$), 15.74% lower than that in Dongcheng.

Daily average HA of all-cause, RI and COPD patients were also summarised in Table 1. In total, 5,847,285 cases of all-cause, 125,772 cases of RI and 86,597 cases of COPD HA were recorded, corresponding to a daily average HA of 333±369 cases for all-cause, 7±6 cases for RI and 5±5 cases for COPD over the study period in Beijing. Interestingly, daily average HA of all-cause experienced an increasing temporal trend during 2015-2017, which raised by 19.73% in 2017 (358±286 cases), compared to that in 2015 (299±241 cases). Moreover, total hospital expenses for all-cause reached 100,535 million CNY from 2015 to 2017 in Beijing, with a daily average of 5.73±5.38 million CNY (Table 1).

Pooled estimations of PM$_{1}$-associated effects on daily HA at different lag days during the study period in Beijing are illustrated in Figure 2. Percentage increases of HA per 10 μg/m$^3$ uptick of PM$_{1}$ concentration are significant for all-cause admissions at lag0-2 and lag0-4 days. COPD and RI admissions, however, failed to demonstrate significant PM$_{1}$-associated risk increase. As illustrated in Figure 3, per 10 μg/m$^3$ rise of PM$_{1}$ concentration was associated with 0.07% (95% CI: [0, 0.14%]) increase in daily HA for all-cause during 2015-2017. Twelve out of 16 districts, including 4 urban and 8 rural districts, had significant PM$_{1}$-associated effects on all-cause admissions during the study period. The strongest increment was seen in Mentougou district corresponding to a 0.21% [-0.29, 0.72%] increase in daily HA for all-cause, and the lowest observed in Fangshan district (0.03%, [-0.37, 0.43%]), although without significance. The significant association between other dose metrics (for example the PM$_{2.5}$ and PM$_{10}$) and all-cause admissions were not demonstrated in this study.

We then proceeded with the all-cause lag0-2 data for the estimation of HA and total hospital expenses attributable to ambient PM$_{1}$ in Beijing during 2015-2017 (Table 2). The percentage increase of all-cause HA associated with ambient PM$_{1}$ decreased over time by
years, with an average percentage of 0.34% [0.02, 0.67%] from 2015 to 2017 in Beijing. This is estimated as a daily average of 6644 [351, 12917] admissions attributable to ambient PM$_1$, corresponding to 0.11% [0.01, 0.22%] related to PM$_1$ exposure within the all-cause disease group. As for attributable hospital expense estimations of all-cause diseases (Table 2), a three-year average number of 106 [5.6, 207] million CNY was estimated to be associated with ambient PM$_1$ in Beijing during the study period, represented by a fraction of 0.32% [0.02, 0.62%] attributable to PM$_1$ exposure. In particular, district analysis (shown in Table 3) revealed the strongest PM$_1$-associated effect on all-cause associated HA and total hospital expense increase in Chaoyang district. It is estimated that 3540 [187, 6881] daily HA cases can be attributable to ambient PM$_1$ pollution. This is found to result in 63.68 [3.37, 123.79] million CNY increase in hospital spending, accounting for 18.37% of the city-wide attributable increase in hospital expenses.

4. Discussion

In this time-series analysis, we analysed PM$_1$-associated hospitalisation risks on all-cause, COPD and RI in Beijing, China during 2015-2017. We demonstrated that ambient PM$_1$ exposure was associated with an increase in all-cause HA but has no significant effect on COPD or RI-related hospitalisation in Beijing. The average, estimated hospital expenditure for non-accidental diseases attributable to PM$_1$ exposure would be 106 million CNY in Beijing, which accounts for 0.32% of the total estimated city expense. These findings indicate that short-term PM$_1$ exposure could lead to remarkable health and economic burden in Beijing, China.

Ambient exposure to PMs including PM$_1$, PM$_{2.5}$ and PM$_{10}$ has long been implicated in various non-accidental clinical conditions, including RI, cardiovascular diseases (Liu et al. 2019; Tian et al. 2020; Wang et al. 2021b), stroke (Wu et al. 2022), sleeping disorder (Lawrence et al. 2018), liver diseases (Guo et al. 2022), kidney functions (Li et al. 2021), gene damage (Byun et al. 2013), reproductive disease (Yu et al. 2022) and obesity (MJ Liu et al. 2021). Recent studies have demonstrated significant epidemiological evidence on PM$_1$-related health risks for all non-accidental diseases in China, including data on emergency department visits (EDV) (GB Chen et al. 2017a; Hu et al. 2022; HL Lin et al. 2018; LJ Liu et al. 2021; Wang et al. 2021a; Zhang et al. 2020b) and mortality (Hu et al. 2018; Wang et al. 2021b; Yin et al. 2020). It was also reported that short-term PM$_1$ exposure could lead to increased hospitalisation related to ischemic stroke and cardiovascular diseases among China (Liu et al. 2022; Tian et al. 2023; Zheng et al. 2023; Zhou et al. 2023). However, few have
focused on changes in non-accidental and respiratory related HA due to ambient PM$_1$ exposure. Here, we reported 0.07% increase in all-cause HA per 10 μg/m$^3$ increase of PM$_1$ concentration. Similar trends were recapitulated in all-cause EDVs and mortality that were associated with PM$_1$ pollution in China. Wang et al reported 0.47% (95% CI: 0.35, 0.59%) increase of all-cause EDVs related to PM$_1$ exposure in Beijing from 2016 to 2017 (Wang et al. 2021a). Similarly, Zhang et al reported 2.2% (95% CI: 1.8, 2.6%) and 1.7% (95% CI: 1.0, 2.4%) increase in all-cause EDVs per 10 μg/m$^3$ increase of PM$_1$ concentration in Guangzhou and Shenzhen from 2015 to 2016, respectively (Zhang et al. 2020b). The stronger estimates were possibly caused by lower PM$_1$ level compared to Beijing and the usage of different lag periods during statistical analysis (Peng et al. 2006; Zhang et al. 2020b). Additionally, patients with acute diseases may not develop into more serious diseases that requires admission into hospitals and further treatments, even they have visited the emergency department. Pooled analysis of all-cause mortality data in Beijing from 2014 to 2017 also showed 0.19% (95% CI: 0.09, 0.28%) increase due to ambient PM$_1$ exposure (Yin et al. 2020). The reasons for such spatial heterogeneity and more significant estimates on PM$_1$-related all-cause hospitalisation risks could be due to different PM pollution sources, climate conditions including seasonal temperature and humidity, variable population vulnerability, access to healthcare and socioeconomical status (Pui et al. 2014). Previous PM-related health analysis have mostly focused on PM$_{2.5}$ and PM$_{10}$. In 2019, a 35% reduction in PM concentration of Beijing was reported (UN Environment, 2019). We also showed a decreasing temporal trend of the of PM$_1$, PM$_{2.5}$ and PM$_{10}$ pollutant levels from 2015 to 2017 in Beijing. Studies have shown that PM$_1$ accounts for around 60% of PM$_{10}$ components and 80% of PM$_{2.5}$ particles across Chinese cities (Chen et al. 2018; Wang et al. 2015), indicating that ultrafine particles are the main compositions of PM mass pollutants. Previous estimations demonstrated that PM$_1$, PM$_{2.5}$ and PM$_{10}$ exposure had similar or lower effects on all-cause hospitalisation risks. Peng et al reported that from 2014 to 2017, as PM$_1$, PM$_{2.5}$ and PM$_{10}$ concentration increase 10 μg/m$^3$, non-accidental mortality elevated by 0.19% (95% CI: 0.09, 0.28%), 0.18% (95% CI: 0.08, 0.27%) and 0.17% (95% CI: 0.01, 0.24%), respectively (Yin et al. 2020). PM$_1$ is a health-damaging particle, which can easily penetrate the lungs and enter systemic circulation (Valavanidis et al. 2008). It was found that PM$_1$ carries more toxic molecules including metals and organic compounds than other PMs, which potentially induces adverse lung injury and genetic changes (Huang et al. 2014b; Tao et al. 2012; Yang et al. 2019). Compared to other PMs, PM$_1$ trigger more significant pro-inflammatory responses and oxidative stress (Valavanidis et al. 2008; Yang et al. 2022).
Given the implications of PM$_{2.5}$ and PM$_{10}$ in various respiratory and cardiovascular diseases (Hasegawa et al. 2023; Luo et al. 2023; Yang et al. 2019), it is likely that the rising hospitalisation risks associated with PM$_{2.5}$ and more coarse PM particles are mainly attributed to their PM$_1$ compositions.

Despite significant effects shown for all-cause PM$_1$-related hospitalisation risks, HA associated with RI was not found to be significantly impacted by ambient PM$_1$ exposure in Beijing from 2015 to 2017. In contrast, a case crossover study in Shenzhen reported that 10 $\mu$g/m$^3$ increase of PM$_1$ exposure was associated with 0.09% (95% CI: 0.04%, 0.14%) increase of RI-related HA during 2015-2016, with a stronger effect observed during the cold seasons (Zhang et al. 2020b). Similar results were reported in the Beibu Gulf area of China, where 3.0% (95% CI: 2.7%, 3.2%) were found to be attributable to PM$_1$ pollution from 2013 to 2016 (Li et al. 2023). This is possibly due to the composition of PM$_1$ particles, as the main source of PM$_1$ is mobile emission in southern China (Yin et al. 2020), which causes more severe effects on lung functions, compared to non-vehicle pollutants (Lepeule et al. 2014). A study in Hanoi, Vietnam also showed that the components of PM pollutants affect the degree of heath impairment (Luong et al. 2017). PM$_1$-associated increase of RI-related HA lost its significance after adjusting NO$_2$ as a confounding variable during the time-stratified case-crossover analysis (Luong et al. 2017). Additionally, short-term exposure to PM$_1$ were found to increase the risk of acute respiratory conditions, as evident by the significant correlation between PM$_1$ exposure and respiratory HA during 2007 to 2012 in Beijing (Xiong et al. 2015), and PM$_1$-related increase of respiratory EDVs in Guangzhou (LJ Liu et al. 2021) and Beijing (Wang et al. 2021a). However, a meta-analysis of hospitalisation, EDV and prevalence data from China, Vietnam and America published between 2004 and 2021 showed that PM$_1$ exposure had no significant association with increase in RI hospitalisation risks (Hu et al. 2022). Therefore, there is still a lack of understanding regarding how PM$_1$ exposure contributes to the development of respiratory diseases and how long it takes for disease progression, which may also explain the inconsistency of results reported here.

As one of the most common chronic respiratory diseases, we found that the hospitalisation risk of COPD was not significantly associated with ambient PM$_1$ exposure. Although exposure to ultrafine particles including PM$_1$ was significantly implicated in COPD mortality in Shanghai (Yin et al. 2019) and COPD HA in Shenzhen (Zhang et al. 2020b), Mei et al previously found that COPD incidence levels were not significantly correlated with increase of PM level and were less easily impacted by fine PM particles, compared to other respiratory conditions such as asthma (Mei et al. 2022). Liu et al mentioned that COPD
prevalence differs significantly among different cities in China as COPD may be affected by various disease causes such as age, smoking and exposure to biofuels and dusts (Liu et al. 2017; Zhong et al. 2007). We also noticed a large heterogeneity of HA among different districts in Beijing for non-accidental diseases including COPD. This large variation was recapitulated in an estimation analysis for EDVs in Beijing during the same study period, possibly due to differences in population vulnerability between age groups (Wang et al. 2021a). It was reported that COPD is more prevalent in rural areas of China (Zhong et al. 2007), and given also Beijing has one of the best-quality healthcare system in China, patients from rural areas frequently visits the hospitals. Therefore, given the variation of demographic vulnerability to PM pollution, the underlying mechanisms of the week association between PM$_1$ exposure and RI and COPD remain to be investigated.

Health expenditure has been one of the largest socioeconomical burden worldwide. It was reported that the government health expenditure experienced a 3-fold increase from 2008 to 2017 in China (Yip et al. 2019). PM pollution has been recognised as one of the leading environmental cause for socio-economic burden in the world (Landrigan et al. 2018). Previous studies have mostly focused on the effect of PM$_{2.5}$ pollution on healthcare expenditure related to non-accidental diseases. It was reported that PM$_{2.5}$-associated mortality may result in 101.39 billion US dollar, around 0.91% of China total GDP in 2016 (Maji et al. 2018). A more recent nation-wide study in China also found that 220 million CNY increase of healthcare expenditure was attributable to PM$_{2.5}$-associated hospitalisation risk of lower RI during 2016 to 2017. Here, we estimated a significant healthcare expense associated with PM$_1$-related hospitalisation increase in Beijing, and reducing the pollutant levels of PM particles could largely avoid the economic loss due to the related health risk. Collectively, as industrialisation and rapid modernisation of cities worsens air quality, our findings could provide guidance for public policy makers and healthcare officials to reduce economic burden.

Nonetheless, the present study is still limited by the lack of ground measurements of PM$_1$ concentration. We only utilised ambient PM$_1$ concentration from fixed-site monitoring stations, which failed to include individual heterogeneity regarding pollution exposure due to different outdoor activity times and habits and living conditions. We also did not analyse the confounding effects caused by other stimulants such as NO$_2$, O$_3$ and pollen exposure, which may not significantly shape the results (Luong et al. 2017).

5. Conclusion
In summary, using the data on daily HA in Beijing during 2015-2017, our study provides evidence for PM$_1$-associated impacts on all-cause HA increase. Meanwhile, our data also showed that short-term PM$_1$ exposure leads to additional hospital expense in Beijing, which increases the health and economic loss. The findings therefore highlights the necessity for effective air quality regulation and public health policies in developing countries such as China.

6. Conflict of interest
All authors declare no competing interests.

7. Acknowledgements
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8. References


<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean (SD)</th>
<th>Median (IQR)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2015</td>
<td>2016</td>
</tr>
<tr>
<td><strong>Air Pollutant Concentration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PM$_1$</td>
<td>54.47 (49.08)</td>
<td>48.82 (43.58)</td>
</tr>
<tr>
<td>PM$_{2.5}$</td>
<td>71.66 (50.76)</td>
<td>63.18 (42.36)</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>114.71 (85.67)</td>
<td>100.80 (68.20)</td>
</tr>
<tr>
<td><strong>Temperature (°C)</strong></td>
<td>12.7 (10.83)</td>
<td>12.57 (11.42)</td>
</tr>
<tr>
<td><strong>Humidity (%)</strong></td>
<td>55.57 (20.17)</td>
<td>54.44 (19.91)</td>
</tr>
<tr>
<td><strong>Hospital Admissions</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All-cause</td>
<td>299 (241)</td>
<td>343 (274)</td>
</tr>
<tr>
<td>RI</td>
<td>6 (5)</td>
<td>8 (6)</td>
</tr>
<tr>
<td>COPD</td>
<td>4 (4)</td>
<td>5 (5)</td>
</tr>
<tr>
<td><strong>Average Hospital Expense</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(All-cause, million CNY/day)</td>
<td>4.92 (4.58)</td>
<td>5.83 (5.41)</td>
</tr>
</tbody>
</table>

Abbreviations: SD, standard deviation; IQR, Interquartile range
Table 2. Attributable numbers and fractions of hospital admissions and total hospital expenses of all-cause diseases associated with ambient PM$_1$ at lag0-2 in Beijing during 2015-2017.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Year</th>
<th>Percentage differences in % (95% CI)</th>
<th>Attributable number (95% CI)</th>
<th>Attributable fraction in % (95% CI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hospital admissions (cases/day)</td>
<td>2015</td>
<td>0.38 (0.02, 0.75)</td>
<td>6697 (354, 13 016)</td>
<td>0.11 (0.01, 0.22)</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td>0.34 (0.02, 0.67)</td>
<td>6856 (363, 13 328)</td>
<td>0.12 (0.01, 0.23)</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td>0.31 (0.02, 0.67)</td>
<td>6382 (338, 12 408)</td>
<td>0.11 (0.01, 0.21)</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>0.34 (0.02, 0.67)</td>
<td>6644 (351, 12 917)</td>
<td>0.11 (0.01, 0.22)</td>
</tr>
<tr>
<td>Total hospital expense (million CNY)</td>
<td>2015</td>
<td></td>
<td>103 (5.4, 200)</td>
<td>0.36 (0.02, 0.70)</td>
</tr>
<tr>
<td></td>
<td>2016</td>
<td></td>
<td>109 (5.7, 211)</td>
<td>0.32 (0.02, 0.62)</td>
</tr>
<tr>
<td></td>
<td>2017</td>
<td></td>
<td>107 (5.7, 209)</td>
<td>0.28 (0.02, 0.55)</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td>106 (5.6, 207)</td>
<td>0.32 (0.02, 0.62)</td>
</tr>
</tbody>
</table>
Table 3. Attributable numbers and fractions of hospital admissions and hospital expenses of all-cause diseases associated with ambient PM$_{1}$ at lag0-2 of each district in Beijing during 2015-2017.

<table>
<thead>
<tr>
<th>District</th>
<th>Hospital Admissions (cases/day)</th>
<th>Total hospital expense (million CNY)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percentage differences in % (95% CI)</td>
<td>Attributable number (95% CI)</td>
</tr>
<tr>
<td>Changping</td>
<td>0.36 (0.02, 0.69)</td>
<td>1444 (76, 2807)</td>
</tr>
<tr>
<td>Chaoyang</td>
<td>0.36 (0.02, 0.70)</td>
<td>3540 (187, 6881)</td>
</tr>
<tr>
<td>Daxing</td>
<td>0.36 (0.02, 0.71)</td>
<td>1736 (92, 3375)</td>
</tr>
<tr>
<td>Dongcheng</td>
<td>0.37 (0.02, 0.72)</td>
<td>1195 (63, 2323)</td>
</tr>
<tr>
<td>Fangshan</td>
<td>0.36 (0.02, 0.70)</td>
<td>1411 (75, 2742)</td>
</tr>
<tr>
<td>Fengtai</td>
<td>0.36 (0.02, 0.71)</td>
<td>2256 (119, 4386)</td>
</tr>
<tr>
<td>Haidian</td>
<td>0.36 (0.02, 0.70)</td>
<td>2420 (128, 4703)</td>
</tr>
<tr>
<td>Huairou</td>
<td>0.33 (0.02, 0.65)</td>
<td>412 (22, 801)</td>
</tr>
<tr>
<td>Mentougou</td>
<td>0.36 (0.02, 0.7)</td>
<td>492 (26, 956)</td>
</tr>
<tr>
<td>Miyun</td>
<td>0.33 (0.02, 0.64)</td>
<td>486 (26, 945)</td>
</tr>
<tr>
<td>Pinggu</td>
<td>0.33 (0.02, 0.64)</td>
<td>585 (31, 1137)</td>
</tr>
<tr>
<td>Shijingshan</td>
<td>0.36 (0.02, 0.7)</td>
<td>762 (40, 1481)</td>
</tr>
<tr>
<td>Shunyi</td>
<td>0.31 (0.02, 0.61)</td>
<td>855 (45, 1662)</td>
</tr>
<tr>
<td>Tongzhou</td>
<td>0.34 (0.02, 0.67)</td>
<td>1145 (61, 2226)</td>
</tr>
<tr>
<td>Xicheng</td>
<td>0.36 (0.02, 0.71)</td>
<td>1621 (86, 3151)</td>
</tr>
<tr>
<td>Yanqing</td>
<td>0.36 (0.02, 0.69)</td>
<td>312 (17, 607)</td>
</tr>
</tbody>
</table>
Figure 1. Heatmap illustrating the average PM$_1$ concentrations (μg/m$^3$) for each district in Beijing (A) average throughout 2015 to 2017; (B) in 2015; (C) in 2016; (C) in 2017.
Figure 2. The percentage differences of hospital admissions per 10 μg/m³ uptick of PM$_{1}$ exposure at different days of moving average during 2015-2017 in Beijing for (A) all-cause, (B) COPD and (C) RI diseases.
Figure 3. The forest plot for percentage differences of hospital admissions per 10 μg/m³ uptick of PM₁₀ exposure during 2015-2017 in each district at lag0-2 days for (A) all-cause, (B) COPD and (C) RI diseases.