Effects of ambient air quality improvement on mortality from acute air pollution exposure in Beijing

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Abstract Exposure to air pollutants increase the mortality of population. Developing countries have taken measures to control air pollution. To explore the effects of air quality improvement on mortality, air quality and acute exposure-response coefficients of excess death in Beijing since the 1990’s were analyzed. It was divided into five stages according to the concentration level of pollutants. Coefficients for period 1990 – 2013 were obtained by retrieving literatures published before December 31, 2019. The coefficients for period 2015 – 2017 were obtained by analyzing the daily data of air pollutant concentration, meteorological and human mortality conducting Poisson Generalized Additive Model (GAM). Meta-analysis of random effect model was used to estimate the integrated coefficient of multiple studies at each stages. Comparative analysis was used to analyze the variation of air quality and coefficients in different stages. The results showed that the concentrations of sulfur dioxide (SO₂), nitrogen dioxide (NO₂), particulate matter with aerodynamic diameter ≤10 μm (PM₁₀) and ≤2.5 μm (PM₂.₅) decreased by up to 50%, 21%, 22% and 15% in different stages. The coefficient of SO₂ on death from respiratory diseases decreased by up to 63.79%. The coefficients of NO₂ on mortality from non-accidental causes, cardiovascular disease, and respiratory disease decreased by up to 0.95%, 1.34% and 0.54%. The coefficients of PM₁₀, PM₂.₅ on mortality from cardiovascular diseases and respiratory disease were decreased by up to 0.19%, 0.31%, 0.65% and 0.36%. Continued improvements in air quality have reduced the acute impact on the health of the local population.

Keywords: Air quality; air pollutants; adverse effects; mortality

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The impacts of air pollutants on human health have been one of the major problems of public health in the world. Air pollutants caused 4.9 million deaths worldwide in 2017, an increase of 5.8% over 2007 (GBD 2017). Studies have found that air pollution prevention and control measures not only reduce concentration of pollutants, but also reduce pollution-related mortality (Peters et al. 2009), which is of great significance in reducing the mortality caused by air pollution worldwide.

China is one of the developing countries with severe air pollution. In recent years, Chinese have been concerned about the health effects of air pollution, and a lot of measures had been taken to control air pollution. Air quality has continued to improve, but air pollutants remain at high levels. At present, there are few studies on the effect of air quality improvement on human mortality at high level of pollution.

Beijing, as the capital of China, had become a national key development area since the middle of the 20th century and had a rapid social and economic development in 21st century. However the serious air pollution had become a major environmental and public health problem at the same time. In order to prevent the further deterioration of air pollution, since the 1990s, Beijing had adopted a series of measures for air pollution prevention and control and carried out a lot of researches on the health effects of air pollution. In order to provide references for Beijing to adopt more targeted air pollution control measures, as well as pollution prevention and control measures for other polluted areas, we chose Beijing as the research site for a longitudinal study. However, at different stages of development, the major pollutants and research hotspots were also different.

In recent decades, Beijing has gone through a gradual transformation of air pollution from coal-burning pollution, coal-burning and vehicle-exhaust mixture pollution to vehicle-exhaust pollution. In view of the different pollution characteristics, targeted air pollution prevention and control measures were also implemented in five stages. First, before 1998, it was mainly coal-burning pollution. Due to the limitation of monitoring data, the research mainly focused on the health impact of total suspended particulates (TSP) and sulfur dioxide (SO₂). Second, since Beijing proposed to bid for the 2008 Olympic Games in 1998, gas had replaced coal as the main domestic fuel. In addition, the increase of number of motor vehicles that use gasoline as fuel increased the concentration of PM₂.₅ and NO₂. The air pollution in Beijing had changed from coal-burning pollution to mixture pollution of coal-burning and vehicle-exhaust pollution (Chen et al. 2004; Wang et al. 2013). In order to reduce the concentration of air
pollutants, Beijing had implemented control measures for the pollution of industrial, civil coal burning, vehicle and dust. Beijing entered the stage of comprehensive air pollution control. With the increase of monitoring indicators of air pollutants, studies on the health effects of particulate matter with aerodynamic diameter ≤10 μm or ≤2.5 μm (PM$_{10}$, PM$_{2.5}$) and nitrogen dioxide (NO$_2$) on population were gradually carried out, which were consistent with international research hotspots (Yang et al. 2018). Third, since 2004, SO$_2$ pollution reached the control target and the annual average concentration was lower than the limit of the national ambient air quality standard in China (60 μg/m$^3$). Although the prevention and control measures at this stage were a continuation of the previous stage, 2004-2008 was made as a separate stage to analyze. Fourth, since 2008, the policy of traffic restrictions and total emission control of motor vehicle policies had been implemented, and the control of automobile exhaust pollution had been strengthened. It had achieved remarkable success in controlling the pollution of NO$_2$ and PM$_{10}$. Especially from 2008 to 2012, the concentration of NO$_2$ and PM$_{10}$ decreased by more than 20%. However, NO$_2$, PM$_{10}$ and PM$_{2.5}$ pollution situations in Beijing are still serious due to the continuous increase of energy consumption and number of vehicles. Fifth, since 2013, the air pollution was dominated by vehicle exhaust pollution. Beijing had implemented the Beijing clean air action plan (2013-2017) aiming at PM$_{2.5}$ control. In order to facilitate the comparison of results in different periods, this study mainly analyzed the research results since 1990. The main particulate pollutants were PM$_{10}$ and PM$_{2.5}$, and the main gaseous pollutants were NO$_2$ and SO$_2$.

This study collected the coefficients of acute effects of air pollution exposure on human mortality in Beijing from published literature. For the stage lacking literature that meet the requirements of analysis, daily data were collected to conduct a supplementary time-series analysis. For the stage with multiple literatures, meta-analysis model was used to estimate the integrated coefficient of multiple studies at each stage. Observing the change tendency of both the atmospheric quality and the coefficients of impact of pollutant exposure on human mortality, researching the health benefits of the improvement of air quality, so as to provide reference on strategies of air pollution prevention and control for developing countries and relevant personnel.
Materials and Methods

Based on the characteristics of pollutants and measures of pollution prevention and control in Beijing, the study was divided into five stages: stage 1 (1990-1997), stage 2 (1998-2003), stage 3 (2004-2007), stage 4 (2008-2012) and stage 5 (2013-2017). Firstly, the acute health impact coefficients of air pollution on human mortality at each stage in Beijing were collected by literature retrieval. For the stage without representative results, supplementary data collection and time-series analysis were conducted. For those with multiple research results in the same stage, meta-analysis was used for quantitative pooled evaluation. By comparing the pollution level and the health impact coefficient of each stage, the influence of the improvement of air quality on the health of the population can be obtained.

Literature Retrieval

A systematic literature search was conducted for epidemiological studies conducted in Beijing China, which were published between 1990 and 2019 in peer-reviewed English and Chinese journals. The on-line electronic databases included China National Knowledge Infrastructure (CNKI), Wanfang Data Knowledge Service Platform (WANFANG DATA), SinoMed, and English databases of the Pubmed, Web of Science. The combinations of following MeSH terms "air pollution" "health hazard" were used in our literature retrieval. Supplementary collection was carried out by key words "air pollutant" "mortality" and by tracing the references of review papers. Literatures meeting the following principles was collected: the studies conducted time-series or case-crossover analysis, in which diseases were classified according to ICD-10, exposure-response coefficient was quantitatively described (such as β, RR, ER), and statistical analysis model controlled the time, temperature, humidity and other confounding factors. There were 54 literatures meeting the above requirements, and research time of those literatures were from 1990 to 2014.

According to the following principles, the exposure-response coefficients were screened or eliminated: ① If there were results of city-level research within the research period, the results of single county research were excluded; ② In view of the stability of the analysis model in time series research, the results from data less than 1 year were excluded; ③ We selected the results with 95% confidence interval, not the
results without confidence interval; ④ Where both Poisson Generalized Additive Model (GAM) and Generalized Additive Mixed Model (GAMM) results were reported, GAM results were selected in order to increase comparability, in view of more literatures reporting GAM results. A total of 15 references were eventually included in the analysis of this study.

Data Collection

The annual average concentrations of atmospheric pollutants (PM$_{10}$, PM$_{2.5}$, NO$_2$ and SO$_2$) in Beijing from 1990 to 2017 were collected from the Environment Bulletin, Statistical Yearbook and published research literatures. The average concentrations in each stage and the percentage of decline were calculated.

In this study, the most recent literature that met the analysis requirements was published in 2017, and it was about the effect of PM$_{2.5}$ exposure on the mortality rate of respiratory diseases in Beijing in 2013. In order to analysis the health effects after 2014, this study collected daily data of concentration of atmospheric pollutants, meteorological and cause-specific death from 2015 to 2017 from the departments of environmental monitoring, meteorological and health. Atmospheric pollutants data include daily concentrations of PM$_{10}$, PM$_{2.5}$, NO$_2$ and SO$_2$. Meteorological data include the daily average temperature (T), relative humidity (RH) and barometric pressure (BP). Data of cause-specific death include daily counts of death from non-accidental (NAD, ICD 10: A00 - R99), cardiovascular disease (CD, ICD 10: I00 - I99) and respiratory disease (RD, ICD 10: J00 - J99). Exposure - response coefficients were obtained by time series analysis of the above data.

Statistical Analysis

Time - series analysis: GAM was used to analyze the exposure-response coefficients of short-term exposure air pollutants to the mortality. The model is as follows:

$log E(Y_i) = \beta Z_i + s(time, df) + s(T_i, df) + s(RH_i, df) + s(BP_i, df) + DOW + intercept$  \hspace{1cm} (1)

Where $E(Y_i)$ is the expected count of death on day $i$; $\beta$ is the regression coefficient of the pollutant; $Z_i$ is the concentrations of pollutant on day $i$; $s(\;\cdot\;)$ is the cubic smoothing spline; $df$ is the degree of freedom of the smooth function; time is a variable for time (6 $df$ per year); $T_i$ is the daily average temperature on day $i$ ($df = 3$); RH is daily average
related humidity at day $i$ ($df = 3$); $BP_i$ is daily average barometric pressure at day $i$ ($df = 3$); DOW denotes the days of week on day $i$.

To better compare with previous studies, we used relative risk (RR) to express the results. The formula for the relationship between RR and $\beta$ is shown below:

$$RR = e^\beta$$

Where $e$ is the nature constant.

The coefficients of exposure-response obtained from the literature also include excess risk (ER, %). ER is also converted to RR. The formula is shown below:

$$RR = \frac{ER}{100} + 1$$

Meta-analysis: Using R3.6 software, Meta random effect model was used to quantitatively estimate the multiple exposure-response coefficients of each stage, so as to obtain the coefficients of air pollution on mortality of population at every stage for trend comparison.

Comparison analysis: Compared to the previous stage, the reduction proportions of both concentrations of pollutant and coefficients of health impact were calculated.

$$Proportion\ of\ change = \frac{x_j - x_{j-1}}{x_{j-1}} \times 100\%$$

Where $x$ is the variable to be compared; $j$ is the stage to be compared, $j-1$ is the stage before stage $j$.

**Results**

**Coefficients of Exposure-response from the Literature**

A total of 45 exposure-response coefficients of environmental air pollutants to mortality of population were obtained from 15 literatures, which met the literature quality requirements of this study (Table1). Most of the studies were about the impact of air pollution from 2004 to 2011 on population mortality. For the same kind of coefficients, if the number of coefficient was 2 or more, meta-analysis will be used to integrate the coefficients. For a stage or a pollutant with few papers, such as SO$_2$ at the first stage, this study used the coefficient of one study to represent the coefficient of this stage or this pollutant. Supplementary analysis was performed for the fifth stage where the raw data could be obtained, which will be described in more detail below.
Table 1. Results from epidemiological studies on the effects of air pollution on mortality in Beijing, China

| Stage | Reference                | Study year | Analysis model | Pollutant | Concentration (Mean±SD, μ g/m³) | RR and 95%CI | RR of CD | RR of RD |
|-------|--------------------------|------------|----------------|-----------|----------------------------------|---------------|----------|----------|
| 1     | Dong et. Al. 1995        | 1990-1991  | PR             | SO₂       | 121±136                          | 1.0202(1.0083,1.0323) | 1.1074(1.0001,1.2262) | 1.0202(0.9965,1.0445) |
| 2     | Chang et al. 2003        | 1998-2000  | GLM            | SO₂       | /                                | 1.0040(1.0014,1.0050) | 1.0042(1.0018,1.0068) |          |
|       | Yang et. Al. 2008        | 2003       | GAM            | PM₁₀      | 140.81±79.09                     | 1.0040(1.0020,1.0060) | /        | /        |
|       |                          |            |                | SO₂       | 60.29±56.15                      | 1.0040(1.0010,1.0080) | /        | /        |
|       |                          |            |                | NO₂       | 71.83±23.5                       | 1.0130(1.0020,1.0240) | /        | /        |
| 3     | Chen, R., et al. 2011    | 2007-2008  | GLM            | PM₂₅      | 82±52                            | 1.0053(1.0037,1.0069) | 1.0058(1.0035,1.0081) | 1.0066(1.0021,1.0111) |
|       | Guo, Y., et al. 2013     | 2004-2008  | GAM            | SO₂       | 48.6±48.1                        | 1.0037(1.0008,1.0067) | /        | /        |
|       |                          |            |                | PM₁₀      | 144.6±91.3                       | 1.0016(1.0006,1.0027) | /        | /        |
|       |                          |            |                | PM₂₅      | 105.1±80.9                       | 1.0014(1.0001,1.0027) | /        | /        |
|       |                          |            |                | NO₂       | 64.2±25.7                        | 1.0054(1.0013,1.0095) | /        | /        |
|       | Li, P., et al. 2013      | 2005-2009  | GAM            | PM₁₀      | 126±87                           | 1.0015(1.0004,1.0022) | 1.0044(1.0012,1.0063) | 1.0008(1.0001,1.0018) |
|       |                          |            |                | PM₂₅      | 75±54                            | 1.0065(1.0029,1.0081) | 1.0138(1.0051,1.0171) | 1.0063(1.0025,1.0083) |
|       | Liu et al. 2014          | 2006-2009  | GAM            | NO₂       | 59.5±24.6                        | 1.0014(1.0001,1.0027) | /        | /        |
|       |                          |            |                | SO₂       | 43.1±44.5                        | 1.0088(1.0034,1.0141) | /        | /        |
|       | Xue et al. 2012          | 2005-2009  | GAM            | PM₁₀      | 139.2                             | 1.0013(1.0008,1.0017) | 1.0012(1.0006,1.0019) | 1.0014(1.0000,1.0027) |
|       | Zhang F, et al. 2011     | 2003-2008  | GAM            | PM₁₀      | 143.1±87.2                       | 1.0019(1.0016,1.0021) | 1.0010(1.0006,1.0015) |          |
|       |                          |            |                | NO₂       | 64.8±24.2                        | 1.0027(1.0009,1.0046) | 1.0095(1.0076,1.0114) |          |
|       |                          |            |                | SO₂       | 112.4±316.9                      | 1.0002(1.0001,1.0003) | 1.0003(1.0002,1.0004) |          |
| 4     | Li et al. 2015           | 2008-2011  | GLM            | PM₂₅      | 173                               | 1.0028(1.0018,1.0041) | 1.0032(1.0016,1.0047) | 1.0031(1.0001,1.0063) |
|       | Yang Yang, et al. 2013   | 2009-2010  | GAM            | PM₁₀      | 121±75                            | 1.0025(1.0017,1.0033) | 1.0024(1.0012,1.0035) | 1.0029(1.0003,1.0054) |
| Stage | Reference   | Study year | Analysis model | Pollutant  | Concentration (Mean±SD, μ g/m³) | RR and 95% CI |
|-------|-------------|------------|----------------|------------|---------------------------------|---------------|
|   5   | Wu et al. 2017 | 2013       | GAMM           | PM_{2.5}   | 92.9±76.9                       | /             |
|       |              |            |                |            |                                 |  /            |
|       |              |            |                |            |                                 | 1.0026(1.0005,1.0047) |
|       | Zhang Y. et al. 2012 | 2008-2009 | GAM            | PM_{10}    | 127.1±77.9                      | 1.0012(1.0000,1.0023) |
|       |              |            |                |            |                                 | /             |
|       |              |            |                |            |                                 | 1.0033(1.0001,1.0061) |
|       | Zhang Y. et al. 2014 | 2008-2009 | GAM            | PM_{10}    | 127.1±77.9                      | /             |
|       |              |            |                |            |                                 | /             |
|       |              |            |                |            |                                 | 1.0047(1.0027,1.0066) |
|       | Zhang Y. et al. 2015 | 2008-2009 | GAM            | PM_{10}    | 127.1±77.9                      | /             |
|       |              |            |                |            |                                 | 1.0089(1.0005,1.0175) |

Note: Data in the table were from literatures and some data were not reported

95%CI: 95% confidence interval
Supplementary Analysis of Time-series

The annual-mean concentrations of SO\textsubscript{2} and NO\textsubscript{2} from 2015 to 2017 in Beijing was below the limit values of national ambient air quality standards in China (60 μg/m\textsuperscript{3} & 40 μg/m\textsuperscript{3}), but PM\textsubscript{10} and PM\textsubscript{2.5} still exceeded the limits (70 μg/m\textsuperscript{3} & 35 μg/m\textsuperscript{3}). The average daily temperature ranges from -15°C to 32°C, and the relative humidity ranges from 8%-95%. The average daily counts of deaths from non-accidental, circulatory diseases and respiratory diseases were 95, 44 and 11 respectively (Table 2).

### Table 2. Summary statistics of ambient air pollutants, meteorological conditions and death cause in Beijing, China, 2015-2017

| Variables          | Ambient air pollutant | Meteorological condition | Death Cause |
|--------------------|-----------------------|--------------------------|-------------|
| PM\textsubscript{10} | 100 ±75               | 13 ±11                   | 95±14       |
| PM\textsubscript{2.5} | 73±66                 | -15                      | 60          |
| SO\textsubscript{2} | 12±13                 | 2                        | 44±9        |
| NO\textsubscript{2} | 51±24                 | 10                       | 11±4        |
| T/°C               | 13 ±11                | 10                       |             |
| RH/%               | 54 ±20                | 8                        |             |
| BP/kPa             | 1011 ±10              | 988                      |             |
| Death Cause        | NAD                   | CD                       | RD          |
|                    |                       |                          |             |

The increasing of concentrations of SO\textsubscript{2} and PM\textsubscript{10} per 10 μg/m\textsuperscript{3} may significantly increase the relative risk of death from non-accidental in the population (Table 3). In particular, exposure to SO\textsubscript{2} may increase the relative risk of death from respiratory disease and exposure to PM\textsubscript{10} may increase the relative risk of death from cardiovascular disease.

### Table 3 RR and 95%CI of cause-specific mortality for per 10 μg/m\textsuperscript{3} increase of pollutants in Beijing, China, 2015-2017

| Pollutant | NAD (RR, 95%CI) | CD (RR, 95%CI) | RD (RR, 95%CI) |
|-----------|-----------------|----------------|---------------|
| SO\textsubscript{2} | 1.0095(1.0003, 1.0188) \* | 1.0028(0.9931, 1.0126) | 1.0464(1.0021, 1.0927) \* |
| NO\textsubscript{2} | 1.0031(0.9995, 1.0067) | 0.9996(0.9945, 1.0047) | 1.0036(0.9942, 1.0131) |
| PM\textsubscript{10} | 1.0015(1.0005, 1.0025) \* | 1.0017(1.0002, 1.0032) \* | 1.0023(0.9998, 1.0048) |
| PM\textsubscript{2.5} | 1.0013(0.9998, 1.0028) | 1.0015(0.9993, 1.0037) | 1.0020(0.9989, 1.0052) |
Meta – Analysis of Multiple Studies

Meta-analysis was performed on quantitative pooled estimates from multiple studies at stage2 – stage5. Except for the effects of SO2 pollution at stage 3, the effects of SO2, PM10, and PM2.5 on the mortality of the population were statistically significant (Table 4).

Table 4. The RR (95%CI) for cause-specific death due to exposure to air pollutant at different stages for meta-analysis in Beijing

| Stage | Pollutant | RR(95%CI) for cause-specific death |
|-------|-----------|-----------------------------------|
|       |           | NAD                               |
| 2     | SO2       | 1.0040(1.0030,1.0050)             |
| 3     | SO2       | /                                 |
|       | NO2       | 1.0093(1.0075,1.0112)             |
|       | PM10      | 1.0014(1.0010,1.0017)             |
|       | PM2.5     | 1.0044(1.0012,1.0076)             |
| 4     | PM10      | 1.0019(1.0006,1.0032)             |
| 5     | PM2.5     | /                                 |

Note: Meta-analysis was only performed for those with 2 or more coefficients

* There was statistical significance (P<0.05).

Change of Air Quality and Coefficients of Health Impact at Different Stages

Fig.1 showed the change trend of concentrations of air pollutants at five stages in Beijing.

As can be seen from Fig 1, SO2 pollution was very serious in stage1. The average concentration of SO2 in stage1 was 116 μg/m³, which was far higher than the current limits of SO2 concentration in the atmosphere of China and WHO. However, the decreasing trend of SO2 concentration was very obvious in each period. Compared with the previous stage, the percentage of decline were by 34%, 34%, 37% and 50% at stage2-5. The annual average concentration of SO2 reached the limit value of Ambient Air Quality Standard in China in stage3, and reached the limit of the WHO air quality guidelines (20 μg/m³) in stage5.

Monitoring data for NO2, PM10 and PM2.5 began in the stage 2. The decrease of NO2 and PM10 were not obvious in the third stage with decrease both by 8%, but it was obvious in the fourth stage with decrease by 21% and 22% respectively. PM10 also decreased by 15% in the fifth stage, but NO2 decreased by only 4%. PM2.5 decreased obviously in stage3 and stage5, by 15% and 11% respectively, but in stage 4, by only 7%.
Fig. 1 Concentrations of atmospheric pollutants in 5 stages in Beijing

Fig 2 and Fig 3 showed RR and 95%CI in 5 stages in Beijing.

At stage 1, the epidemiological study of air pollution on death had just started, and focus on the effects of SO$_2$ exposure. It was found that SO$_2$ had an impact on death, and the influence coefficient was much higher than other stages. At stage 2, the studies found that SO$_2$ still significantly increased the death from cardiovascular and respiratory diseases in the population, and compared with stage 1, the RR decreased by 9.34% and 1.57% respectively. The effect of SO$_2$ on mortality from respiratory diseases was not statistically significant at stage3 when SO$_2$ concentration reached limit of ambient air quality in China. But at stage5, there was statistical significance again.

There was no significant downward trend in the relative risk of death from cardiovascular and respiratory disease due to NO$_2$ exposure at stage2-4. However, compare to stage3, the RR for non-accidental total death increased by 0.71% at stage4. The relative risk of deaths from non-accidental, cardiovascular and respiratory disease due to NO$_2$ exposure at stage5 decreased by 0.93%, 1.32% and 0.53%, respectively.

The relative risk of death due to PM$_{10}$ exposure was decreased by 0.19% in the third stage, compared with the second stage. However, the decreasing trend of stage 3-5 was not obvious. The relative risk of death due to PM$_{2.5}$ exposure had an obvious trend of gradual reduction. Compared with the previous stage, the relative risk of PM$_{2.5}$ to non-accidental total deaths was reduced by 0.16% and 0.15% respectively in the fourth and fifth stages, to deaths from cardiovascular diseases were reduced by 0.64% and 0.17%. The relative risk of death from respiratory diseases was reduced by 0.35% in stage 4.
In stage 5 which of the relatively cleaner atmosphere, the effects of NO$_2$ and PM$_{2.5}$ on deaths of population were not statistically significant, except for the effects of PM$_{2.5}$ on deaths from respiratory diseases. However, the effect of SO$_2$ on the mortality from respiratory diseases was statistically significant.

Note: Fig 3 is the figure after removing the maximum value in stage 1 to show the trend more clearly.
Discussion

The improvement of air quality requires the implementation of pollution control measures for a long time. China formed a complete governance system, which included laws and regulations, administrative management, economy, technology and public participation. Studies had shown that the PM$_{2.5}$ concentration and associated exposure risk were reduced by 40% and 35.7% respectively in China from 2013 to 2017 (Zou et al, 2020). As a key area of development and environmental pollution control in China, Beijing had also undergone the stages of coal-burning pollution control, mixed pollution control and vehicle exhaust pollution control. The results of this study show that Beijing's air quality has been improving continuously since the 1990s. The coefficient of air pollutants on human mortality also showed a downward trend. However, the pollution of NO$_2$, PM$_{10}$ and PM$_{2.5}$ in Beijing is still serious. At present, the contribution of mobile sources from vehicle emissions in Beijing had risen to 45% in local sources, and the importance of vehicle pollution control is becoming increasingly prominent (Beijing, 2019). From the experience of air pollution control in developed countries, Beijing still has a long way to go to control atmospheric photochemical pollution.

Air pollutants can enter the respiratory tract or be deposited in the alveoli through breathing. Some components can even enter the blood through the gas exchange barrier, causing damage to multiple tissues and organs of the human body and causing premature death of high-risk groups. Mechanisms of health hazard include oxidative stress, endothelial injury, systemic inflammation (Chuang, K.J., et al 2007; Aung, N., et al., 2018), thrombosis, autonomic nervous disorders, activation of the hypothalamic-pituitary-adrenal axis and epigenetic changes, etc. The reduction of the concentration of air pollutants will inevitably reduce the dose of pollutants into the human body, thus reducing the damage to human health. The results of this study show that continuous improvement in air quality benefited human health even at higher concentrations, which were consistent with the previous report (Zhang et al. 2011). Studies had shown that reducing the use of fossil fuels could effectively improve air quality (Shindell et al. 2019), and phasing out fossil fuels could avoid 3.61 million (4.52 million - 6.52 million) excess deaths from global outdoor air pollution (Lelieveld et al. 2019). The results of this study showed that the influence coefficients of SO$_2$ and NO$_2$ on death of respiratory
diseases, PM$_{10}$ on death of cardiovascular diseases, and PM$_{2.5}$ on death of both all decreased had a downward trend with the decrease of pollution level.

The atmosphere is a complex mixture. The composition of atmosphere varies with the source of pollution, and so as to affect the coefficient of impact on human health. In stage 4, the pollution caused by automobile exhaust in Beijing gradually aggravated, and the percentage of NO$_2$ in the atmosphere increased. Although the concentration of NO$_2$ decreased, its influence coefficient on human health did not change much. In addition, the health damage caused by PM from different sources, different particle sizes and different components were also significantly different. Particulate matter of smaller size (e.g., PM$_{0.5}$) has a greater adverse impact on the health of the population (Dong, W., et al., 2018). In stage 4, an increase in the proportion of sources of automobile exhaust in the atmosphere may lead to an increase in the proportion of fine particles in aerodynamically sized particles with diameters of less than 10 microns. This may lead to a decrease in the concentration of Stage 4 PM$_{10}$ pollution, but the coefficient of influence on the excess mortality of the population increased.

The main sources of pollution determined the pollutants to be monitored. In stage 1 with coal burning as the main source of pollution, the monitoring pollutants for air pollution were TSP, SO$_2$ and nitrogen oxide (NOx). With the change of pollution characteristics, Beijing began to monitor NO$_2$, PM$_{10}$ and PM$_{2.5}$, and canceled TSP and NOx in 2002. In order to extend the length of the analysis, this study mainly focuses on SO$_2$, NO$_2$, PM$_{10}$ and PM$_{2.5}$. However, there were still some stages with no data for analysis. Some stages only had one qualified research result for analysis. The study year did not cover the whole stage, so the representativeness of the results was not enough. For the stages with results of more than one study, although quantitative combined estimation was made by Meta-analysis method, the stability of the Meta analysis model was also affected due to the small sample size. In addition, the results of some studies with the time spanned two stages were all classified into the previous stage for Meta-analysis, so the coefficient of this stage may be underestimated. In order to avoid the influence of high co-linearity among pollutants on the stability of the model, the coefficients compared in this study were all the results of the single-pollutant analysis model. The internal relationship between different pollutants was not considered, which may overestimate the impact of pollutants on death. With the development of the economic, Beijing continued to expand the scope of jurisdiction, and the scope of research had gradually expanded from the two municipal districts in the last century to
16 municipal districts. The expansion of the scope of jurisdiction would inevitably lead to the change of the population structure. In addition, with the development of economy, the continuous improvement of people's life condition and healthy behaviors may lead to differences in the sensitivity of people in different periods. All of above would lead to some deficiencies in trend study.

The positive correlation between health impact coefficient and pollutant concentration further demonstrated that air pollution was one of the causes of increased risk of death. Even in the fifth stage with the best air quality, significant effects of air pollution on human mortality were still found. In addition, regional transmission was also an important cause of air pollution in Beijing. In 2013, 28% ~ 36% of PM$_{2.5}$ in Beijing came from regional transmission (Beijing, 2019). Concentrations of nitrogen dioxide and particulate matter in Beijing remain high and continue to increase the risk of premature death from respiratory and cardiovascular diseases. Beijing still needs to continue to reduce the proportion of fossil fuels in the energy structure, to strengthen the control of vehicle exhaust pollution and to improve the regional joint mechanism of air pollution control, in order to further reduce the air pollution level and reduce the acute health impacts on excess death of the crowd.

Continuous improvement of air quality obviously decreased the degree of acute health effects of local people. The prevention and control measures of atmospheric pollution can be used for reference with serious polluted countries and regions. However, it is also necessary to expand the scope of health impact research. It should be carried out multicenter longitudinal research in the similar areas with consistent level of economic development, living habits and demographics but different pollution levels in the future. Research on the changing rules of the health impact of air pollution on the population according to different pollution levels, and Comprehensive evaluation of improvement of atmospheric quality and effects of population health, could provide scientific basis for adjusting the policy and measures for pollution control and health protection.

**AUTHOR CONTRIBUTIONS**

The corresponding author had full access to all study data and was responsible for the decision to submit for publication. Study concept and design: XU Dongqun, HAN Jingxiu, MENG Congshen, LIU Jingyi. Acquisition of data: HAN Jingxiu, MENG
Congshen, Chunyu Xu, Zhe Liu, Wang Qin and Yue Liu. Statistical analysis and interpretation of data: HAN Jingxiu. Drafting of the manuscript: XU Dongqun and HAN Jingxiu. All authors read and approved the manuscript.

DISCLOSURE STATEMENT

The authors declared that they have no conflicts of interest to this work.

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