Potential reductions in premature mortality attributable to PM$_{2.5}$ by reducing indoor pollution: a model analysis for Beijing-Tianjin-Hebei of China

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ABSTRACT

**Background:** China has one of the highest PM$_{2.5}$ (particulate matter with an aerodynamic diameter
smaller than 2.5 μm) pollution levels in the world. It might still be long before air quality reaches the National Class II standard 35 μg/m³.

**Objective:** We aim to estimate the potential reduction in premature mortality by reducing indoor PM$_{2.5}$ levels in the Beijing-Tianjin-Hebei (BTH) region and compared it with reducing outdoor levels.

**Methods:** We combined outdoor PM$_{2.5}$ outdoor-to-indoor particle transport model and the Global Burden of Disease 2016 methodology to estimate potential reductions in premature mortality attributable to PM$_{2.5}$ by reducing indoor PM$_{2.5}$ to National Class I standard of 15 μg/m³, and compared with reducing outdoor PM$_{2.5}$ to Government 2020 Interim target of 64 μg/m³ or National Class II standard of 35 μg/m³.

**Results:** A total of 74,000 (95% confidence interval (CI): 43,000-111,000) premature deaths were attributable to PM$_{2.5}$ exposure in 2013. Thirty percent, or 22,000 (95% CI: 17,000-32,000) deaths, would have been averted if indoor PM$_{2.5}$ had reached the National Class I standard. The benefit is greater than that from reaching the Government 2020 Interim target for outdoor PM$_{2.5}$ [22%, or 16,000 (95% CI: 12,000-23,000), deaths], although still smaller than that from reaching the National Class II standard [42%, or 31,000 (95% CI: 24,000-45,000), deaths].

**Conclusions:** Reaching the National Class I level of indoor PM$_{2.5}$ at current outdoor pollution levels could bring considerable health benefits, which are comparable to those from reaching the Government 2020 Interim target for outdoor PM$_{2.5}$.

**Key Words:** PM$_{2.5}$; human exposure; premature mortality; indoor cleaning; outdoor cleaning

**Main Findings:** The avertable premature deaths gained from cleaning indoor PM$_{2.5}$ to National
Class I standard level would be greater than reducing outdoor PM$_{2.5}$ to Government 2020 target.

**Introduction**

Air pollution is responsible for 6.5 million deaths, or 20.1% of the total deaths, globally in 2015, making it the single largest environmental risk factor (Forouzanfar et al., 2016). In China, outdoor PM$_{2.5}$ (fine particulate matter with an aerodynamic diameter smaller than 2.5 μm) pollution levels are 10-100 times those in Europe and North America (Kulmala, 2015). The exposure to PM$_{2.5}$ is associated with a number of adverse health outcomes, including acute lower respiratory illness (ALRI), cerebrovascular disease, ischemic heart disease (IHD), chronic obstructive pulmonary disease (COPD), and lung cancer (LC) (Anenberg et al., 2010; Brauer et al., 2012; Burnett et al., 2014; Lim et al., 2012; Pope et al., 2009; van Donkelaar et al., 2010; Wu et al., 2014), and it was responsible for 25.2 million disability-adjusted life-years (DALYs) lost in China in 2010 (Yang et al., 2013).

In 2013, only three of the 74 cities (4.1%) with PM$_{2.5}$ monitoring data in China had an annual mean level below the National Class II standard 35 μg/m$^3$, with mean PM$_{2.5}$ concentration of 72 μg/m$^3$ across all the cities (Ministry of Environment Protection of People's Republic of China, 2014). A year later, more cities (161) had data on PM$_{2.5}$ monitoring, but only 18 (11.2%) met the National Class II standard (Ministry of Environment Protection of People's Republic of China, 2015). Many of the heavily polluted cities are in the Beijing-Tianjin-Hebei (BTH) region; eight of the top 10 most polluted cities were from this region in 2014 (Ministry of Environment Protection of People's Republic of China, 2015). The Chinese government has set out coordinative plans for the BTH
region to reduce its annual PM$_{2.5}$ concentration to 64 μg/m$^3$ by 2020 (National development and reform commission, 2015). Beijing also announced its plan to further reduce to the National Class II standard of 35 μg/m$^3$ by 2030 (Huang et al., 2017). Both targets are still much higher than the World Health Organization (WHO) guideline level of 10 μg/m$^3$.

Several studies have quantified the health benefits of outdoor particle control in China (Guo et al., 2013; Huang et al., 2017; Pan et al., 2007; Voorhees et al., 2014; Yin et al., 2017). A study estimated the short-term associations between ambient PM$_{2.5}$ and mortality using a time-series approach in six Chinese cities, and the results shown that 1661 (95% CI: 1,379-1,946) and 11,176 (95% CI: 9,261- 3,120) all-cause premature mortalities were attributable to PM$_{2.5}$ using China's and WHO's air quality standards as the reference, respectively (Lin et al., 2016). Another study projected the life years gained if urban China were to reach National Class II standard (35 μg/m$^3$) using Cardiovascular Disease Policy Model–China (Huang et al., 2017). The study found that achieving the National Class II standard would yield greater health benefits (992,000; 95% CI: 790,000–1,180,000 life-years) than World Health Organization–recommended goals of 25% improvement in systolic hypertension control and 30% reduction in smoking combined (928,000; 95% CI: 830,000–1,033,000 life-years) (Huang et al., 2017). However, the time scales of the government plans mentioned earlier imply that these benefits are not achievable in the short term. On the other hand, people spend 87% of their time indoors in China (Ministry of Environment Protection of People's Republic of China, 2013); indoor particle of outdoor origin accounting for 81% to 89% of the total increase in mortality associated with exposure to outdoor particle (Ji and Zhao, 2015b). And outdoor particle penetration into buildings is affected by the ventilation conditions and the structures of
cracks on buildings, e.g. between walls and windows (Chen and Zhao, 2011; Shi et al., 2017), therefore, the exposure to outdoor PM$_{2.5}$ predominantly occur indoors when the outdoor PM$_{2.5}$ migrates indoor via the ventilation (Anenberg et al., 2014).

Creating a cleaner indoor environment, e.g. using air cleaners, might prove effective to mitigate the hazard of outdoor particulate air pollution. Previous studies did show health benefits from use of air cleaners indoors in experimental settings (Chen et al., 2015; Fisk, 2013; Li et al., 2017; United States Environmental Protection Agency, 2018). Several studies have quantified the health benefits of reducing indoor particulate air pollution (Bekö et al., 2008; Fisk and Chan, 2017; MacIntosh et al., 2010; Zhao et al., 2015), however, none of them compared the health benefits between indoor and outdoor cleaning or took into account the difference between indoor and outdoor PM2.5 concentrations and its impact on exposure. And majority studies focused on public health benefits of reducing particle pollution in China focused on the PM$_{10}$ rather than PM$_{2.5}$ or used a uniform PM$_{2.5}$ concentration for all study areas without city distinctions (Guo et al., 2013; Huang et al., 2017; Lin et al., 2016; Pan et al., 2007; Voorhees et al., 2014; Yin et al., 2017).

In this study, we aimed to estimate the potential reduction in premature mortality by reducing indoor PM$_{2.5}$ levels of outdoor origin in the BTH region and compared it with reducing outdoor levels.

**Methods**

**Study population and scenarios**

The BTH region consists of the Beijing (BJ) and Tianjin (TJ) municipalities and the adjacent
province of Hebei with 11 cities, i.e. Baoding (BD), Cangzhou (CZ), Chengde (CD), Handan (HD), Hengshui (HS), Langfang (LF), Shijiazhuang (SJZ), Tangshan (TS), Qinhuangdao (QHD), Xingtai (XT) and Zhangjiakou (ZJK). A total of 105 million residents lived in 2,903 districts in the BTH region (Long et al., 2014). It is home to eight of the 10 cities with the worst PM$_{2.5}$ pollution in China in 2014 (Ministry of Environment Protection of People's Republic of China, 2015), but it also has a considerable intra-region variability. Three cities in the north of the region, i.e. ZJK, CD and QHD, had average annual PM$_{2.5}$ levels below 64 μg/m$^3$, much lower than the range of 86-131 μg/m$^3$ seen elsewhere.

We used a Monte Carlo exposure assessment model to estimate the population distributions of PM$_{2.5}$ exposure in both urban and rural areas of the BTH region in 2013 and in an intervention scenario where indoor PM$_{2.5}$ concentration is lowered to 15 μg/m$^3$ (it is technically feasible to use air cleaners to keep indoor pollution at 15 μg/m$^3$ as shown in the supplementary materials (SM)), as per the National Class I standard for outdoors, which is also the WHO Interim Target 3 level (China, 2015). The effect of lowering indoor PM$_{2.5}$ was compared with that of reducing outdoor PM$_{2.5}$ concentration to the Government 2020 Interim target of 64 μg/m$^3$ and National Class II standard of 35 μg/m$^3$, which is also the WHO Interim Target 1 level, and the Government Target for 2030 respectively (Huang et al., 2017; National development and reform commission, 2015). The indoor cleaning and outdoor cleaning intervention scenarios are theoretical, assuming that the current technology can realize the interventions, and the interventions’ costs are affordable.
Using the population distribution of PM\textsubscript{2.5} exposure, we estimated the population attributable fraction (PAF) of premature mortality attributable to PM\textsubscript{2.5} exposure if PM\textsubscript{2.5} was reduced to an alternative scenario. The alternative scenarios included one with a theoretical minimum PM\textsubscript{2.5} level of 2.9 μg/m\textsuperscript{3} and ones where outdoor and indoor PM\textsubscript{2.5} was reduced as mentioned earlier. Causes of deaths included IHD, stroke, COPD and LC for people aged 25 years or over, and ALRI for children aged 5 years or under, based on evidence of causal associations with PM\textsubscript{2.5} exposure (Burnett et al., 2014). We did the analysis separately for thirteen age groups (<5 years, every five years as an age group between 25 to 80 years, and 80 years or older) by district.

**Estimating population exposure to PM\textsubscript{2.5}**

We calculated PM\textsubscript{2.5} exposure as the time-weighted average of PM\textsubscript{2.5} concentration in outdoor and indoor environments throughout the whole year, and derived its population distribution using Monte Carlo simulation. The daily PM\textsubscript{2.5} exposure concentration (z) was used to determine the exposure which was defined as the average indoor and outdoor concentrations weighted by the time people spend in each environment:

\[
z = \frac{C_{in}(24-t_{out})+C_{out}t_{out}}{24} \quad (1)
\]

where \(t_{out}\) is the time people spend outdoors (h), which varies by age (Ministry of Environment Protection of People's Republic of China, 2013); \(C_{in}\) is the daily indoor PM\textsubscript{2.5} concentration (μg/m\textsuperscript{3}), while \(C_{out}\) is the daily outdoor PM\textsubscript{2.5} concentration (μg/m\textsuperscript{3}).

The daily district indoor PM\textsubscript{2.5} concentration was calculated using an outdoor-to-indoor particle transport model for particulate matter migration from outdoors to indoors to account for the lower indoor PM\textsubscript{2.5} concentration compared to the outdoor concentration. Indoor PM\textsubscript{2.5}
concentration is influenced by factors including building characteristics, residents’ behaviors, and meteorological conditions (Shi et al., 2017). Air change rate, PM$_{2.5}$ penetration rate and time period when windows are closed or open, respectively, PM$_{2.5}$ deposition rate and outdoor PM$_{2.5}$ concentration were considered to determine the indoor PM$_{2.5}$ concentration. PM$_{2.5}$ generated by indoor sources were not included in the model, since the outdoor particles are the main contributor of indoor particles, and that PM$_{2.5}$ generated from indoor sources is different in composition from outdoor PM$_{2.5}$ (Allen et al., 2012; Ji and Zhao, 2015a; Meng et al., 2007). Assessment of exposure to PM$_{2.5}$ from both sources is beyond the scope of our study. Mathematically, the indoor PM$_{2.5}$ concentration model is:

$$C_{in} = \frac{a_{wc} P_{wc} C_{out} t_{wc} + a_{wo} P_{wo} C_{out} t_{wo}}{a_{wc} + K t_{wc} + a_{wo} + K t_{wo}}$$

(2)

where $a_{wc}$ is air change rate when windows are closed (h$^{-1}$), $a_{wo}$ is the air change rate when windows are open (h$^{-1}$), $P_{wc}$ is the PM$_{2.5}$ penetration rate when windows are closed, $P_{wo}$ is the penetration rate when windows are open, $K$ is the PM$_{2.5}$ deposition rate (h$^{-1}$), $C_{out}$ is the outdoor concentration ($\mu$g/m$^3$), $t_{wc}$ is the time period when windows are closed (h), while $t_{wo}$ is the time period when windows are open (h), both of which varies by season and region (Ministry of Environment Protection of People's Republic of China, 2013), and $t_{wc} + t_{wo} = 24$ hours.

In brief, in the indoor PM$_{2.5}$ reduction scenario, the outdoor concentration level is the original outdoor concentration level and the indoor concentration is 15 $\mu$g/m$^3$. In the two outdoor PM$_{2.5}$ reduction scenarios, if outdoor concentration is larger than 64 or 35 $\mu$g/m$^3$, it would be reduced to 64 or 35 $\mu$g/m$^3$, respectively, and if outdoor concentration is less than 64 or 35 $\mu$g/m$^3$, it would
remain unchanged. In the two outdoor PM$_{2.5}$ reduction scenarios, the indoor concentration was calculated by equation (2).

All weather and human behavioral parameters used in the model were season-specific and were from studies done in the BTH region. Each parameter was assumed to be either (log)normally or uniformly distributed. The means and standard deviations (for (log)normally distributed parameters) or the ranges (for uniformly distributed parameters) determined are as described in the SM. We performed 5,000 draws (which is sufficient for Monte Carlo sampling as shown in the SM, Table S3, Fig. S1) from the distribution of each parameter and calculated the annual mean exposure concentration at the draw level for each of the 2903 districts. Population PM$_{2.5}$ exposure distribution was then determined as the distribution of the annual mean exposure concentration.

**Attributable and avertable premature mortality**

Premature mortality attributable to PM$_{2.5}$ exposure was estimated using the population attributable fraction (PAF). The PAF measures the proportional reduction in mortality if PM$_{2.5}$ exposure was reduced to alternative scenarios. In the Monte Carlo simulation, it was calculated using the formula below, separately for each cause (Murray et al., 2003):

\[
PAF = \frac{\sum RR(z_i) - \sum RR(z'_i)}{\sum RR(z_i)}
\]  

(3)

where $z_i$ is the PM$_{2.5}$ exposure of $i^{th}$ individual in the simulation, $z'_i$ is the PM$_{2.5}$ exposure of $i^{th}$ individual in the simulation in the alternative scenario, and $RR(x)$ is relative risk at PM$_{2.5}$ exposure of $x$ and was calculated using an improved exposure response function developed for very high PM$_{2.5}$ exposures (Burnett et al., 2014).

\[
RR = 1 + a\left[1 - \exp\left(-b(z - z_{cf})^p\right)\right]
\]  

(4)
where $z_{cf}$ is the counterfactual concentration ($\mu g/m^3$) below which we assume that there is no additional risk. The $z_{cf}$ used here is a set of uniformly distributed value ranging from 2-6 $\mu g/m^3$. The relative risk was derived based on Monte Carlo simulations, with 1,000 sets of coefficient and exposure response functions for each of the exposures.

The attributable fraction of, or potential reduction in, premature mortality was the product of the baseline mortality and the PAF calculated above. The calculation was done by age group. For each age group $j$, premature mortality can be calculated using the following equation:

$$PD = PAF \cdot y_0 \cdot Population \quad (5)$$

where the $y_0$ is the age-, cause-specific mortality rates in 2013 in the BTH. We aggregated the results using population for reporting and aggregated cause-specific PAFs using cause-specific mortality to report total PAFs for all the causes considered. We used 1,000 iterations in the Monte Carlo simulation, and reported the 95% confidence interval as the 2.5th to 97.5th percentile of the results across all iterations.

**Data sources**

We obtained daily outdoor PM$_{2.5}$ concentrations at district level from April 2013 to March 2014 from a database based on ground observations and remote sensing images (Long et al., 2014). We derived cause-specific mortality by age group for each city using national age-specific, cause-specific mortality in 2013 by five-year age groups and the age structure, cause-specific mortality in each city (Du and Peng, 2014; National health and family planning committee, 2013; Xia, 2014; Yin, 2010; Zhang, 2010). Seasonal and geographical specific parameters used in the exposure
assessment model were from surveys done in the BTH region for air change rate, PM$_{2.5}$ penetration factor, deposition rate, window opening time, and human outdoor activity time.

**Results**

*PM$_{2.5}$ exposure distribution at sub-district level in the BTH*

The baseline and intervention annual mean PM$_{2.5}$ exposure concentrations at district level are shown in Fig.1. The baseline annual mean exposure concentration was between 22 and 77 μg/m$^3$ in the 2903 district with a mean of 54 μg/m$^3$. If indoor PM$_{2.5}$ had reached the National Class I standard, the annual mean exposure in the 2903 district level would have been reduced to 19-35 μg/m$^3$ with a mean exposure of 28 μg/m$^3$. In comparison, the annual mean exposure at district level would have been reduced to 23-36 μg/m$^3$ either with a mean exposure of 33 μg/m$^3$ or 18-20 μg/m$^3$, or with a mean exposure of 18 μg/m$^3$, if outdoor PM$_{2.5}$ had reached the Government 2020 Interim target or National Class II standard.

*The population PM$_{2.5}$ exposure distribution in the BTH*

At baseline, the annual population PM$_{2.5}$ exposure concentration could reach 130 μg/m$^3$ due to the heavy outdoor PM$_{2.5}$ pollution (Fig.2), which was 13 times the WHO guideline of 10 μg/m$^3$. Over 80% of the BTH population had an annual exposure concentration higher than 35 μg/m$^3$. If indoor PM$_{2.5}$ had reached the National Class I standard, the exposure concentration for over 85% of the BTH population would have been below the national standard of 35 μg/m$^3$, while 63% would have achieved the target if outdoor PM$_{2.5}$ had reached the Government 2020 Interim target. And 95% of the population would have achieved an annual exposure below 25 μg/m$^3$ if outdoor PM$_{2.5}$ had
reached the National Class II standard.

**Premature deaths attributable to PM$_{2.5}$ pollution**

In 2013, PM$_{2.5}$ pollution was responsible for 74,000 [95% confidence interval (CI): 56,000-94,000] premature deaths from IHD, stroke, COPD, LC, and ALRI in BTH. IHD was responsible for the most attributable deaths (28,000; 95% CI: 23,000-35,000) with stroke (24,000; 95% CI: 19,000-28,000) ranking closely behind. About one in five deaths (19%; 95% CI: 11-29%) in BTH were attributable to PM$_{2.5}$ pollution in 2013, and the proportional contribution is higher for ALRI (31%; 95% CI: 23-39%) and LC (30%; 95% CI: 18-42%) and lower for stroke (16%; 95% CI: 8-25%) (Fig.3).

If indoor PM$_{2.5}$ had reached the National Class I standard, 22,000 (95% CI: 17,000-32,000) of the total premature deaths could have been averted, with the largest reduction in the number of deaths due to stroke (6,000; 95% CI: 5,000-9,000). In comparison, if outdoor PM$_{2.5}$ had reached the Government 2020 Interim target or National Class II standard, 15,839 (95% CI: 12,256-23,441) or 31,000 (95% CI: 24,000-45,000) of the deaths could have been averted, respectively, with the largest benefit again seen with stroke in both scenarios. Reducing indoor PM$_{2.5}$ to 15 $\mu$g/m$^3$ brought smaller benefits than reducing outdoor PM$_{2.5}$ to 64 $\mu$g/m$^3$, but the benefits were larger than brought by reducing outdoor PM$_{2.5}$ to 35 $\mu$g/m$^3$. (Table 1 and Fig.4).

**The PAFs attributable to outdoor PM2.5 pollution in BTH region**

The PAFs varied significantly between cities. Across cities in the baseline, XT had the largest PAFs for all five causes, followed by SJZ and HD (Fig.3). These three cities also had the highest PM$_{2.5}$ levels. At the other extreme, ZJK had the lowest PAF for IHD and stroke while CD had the
lowest for LC, COPD, and ALRI. The inter-city variations in PAFs for IHD and stroke were relatively small, with differences between the largest and the least PAFs smaller than six percentage points. However, the differences for LC, COPD, and ALRI were more than twice as much (between 12 and 16 percentage points). XT consistently had the largest potential reductions in number of deaths from all causes in all scenarios, while CD consistently had the smallest potential reductions (Fig.5). It was due to the fact that XT had the highest pollution level before intervention and CD had the lowest. Reducing indoor PM$_{2.5}$ to 15 μg/m$^3$ yielded larger reductions than reducing outdoor PM$_{2.5}$ to 64 μg/m$^3$ except for LC in XT.

The reductions in the number of deaths were larger by reducing indoor PM$_{2.5}$ to 15 μg/m$^3$ than by reducing outdoor PM$_{2.5}$ to 64 μg/m$^3$ in all cities. The differences between these two interventions were largest in the moderately polluted cities (BJ, TJ, and TS) in that order (Table 1). In the heavily polluted cities (XT, SJZ, HS, and HD), the advantage of reducing indoor PM$_{2.5}$ to 15 μg/m$^3$ was not obvious compared to reducing outdoor PM$_{2.5}$ to 64 μg/m$^3$ (Table 1). BJ had the largest potential reductions in premature deaths, followed by TJ, due to the size of their population (Table 1).

If indoor PM$_{2.5}$ had reached 15 μg/m$^3$, ALRI had the largest PAFs (14%; 95% CI: 8-21%) among the five diseases, the next largest reductions were for COPD (PAF=11%; 95% CI: 7-13%) and LC (PAF=11%; 95% CI: 7-20%). Compared to reducing indoor PM$_{2.5}$ to 15 μg/m$^3$, by reducing outdoor PM$_{2.5}$ to 64 μg/m$^3$, the PAFs was 2-92%, 1-92%, 0-91%, 3-91%, and 7-91% smaller for IHD, stroke, LC, COPD, and ALRI among the 13 cities. However, by reducing outdoor PM$_{2.5}$ to 35 μg/m$^3$, the PAFs was 35-62%, 34-57%, 30-45%, 28-46%, and 21-36% larger for IHD, stroke, LC, COPD, and ALRI among the 13 cities (Fig.5).
The ALRI PAFs ranged from 6% to 19% across the cities if indoor PM$_{2.5}$ had reached 15 μg/m$^3$; and COPD PAFs ranged 5-15%, LC 4-14%, stroke 2-6%, while IHD ranged 2-6%. A similar situation also occurred if outdoor PM$_{2.5}$ had reached 64 μg/m$^3$ or 35 μg/m$^3$. By reducing indoor PM$_{2.5}$ to 15 μg/m$^3$, the potential reductions were larger and smaller by reducing outdoor PM$_{2.5}$ to 64 μg/m$^3$ or 35 μg/m$^3$, respectively, for all five causes of death. (Fig.5) However, when it comes to the number of premature deaths, most deaths attributable to PM$_{2.5}$ were from IHD, followed by stroke, LC, COPD, and ALRI; the largest number of avertable premature deaths were due to stroke, followed by IHD, LC, COPD, and ALRI if the PM$_{2.5}$ exposure had been reduced for the three interventions.

If indoor PM$_{2.5}$ had reached 15 μg/m$^3$, IHD and stroke PAFs would vary little across cities, with <4% difference between the least and largest PAFs. However, the variations in PAFs for LC, COPD, and ALRI could reach 10-13%. There would be larger variations in PAFs for all five diseases if outdoor PM$_{2.5}$ had reached the Government 2020 Interim target or National Class II standard (Fig.6) with a 5-6% difference between the least and largest IHD and stroke PAFs and 14-19% for LC, COPD, and ALRI. (Fig.5)

The PAFs were higher in the younger age groups for IHD and stroke, but similar across ages for LC and COPD. PM$_{2.5}$ exposure accounted for 39% of IHD deaths in people aged 25-30 years, and only accounted for 15% of the IHD deaths in those aged ≥80 years. The same pattern was also observed for stroke (with PAFs ranging from 32% for 25-30-year-olds to 12% for ≥80 years). However, PAFs were similar across age groups for LC and COPD with smaller variations than one percentage point across age groups, and the largest PAFs for LC and COPD were in the age group
of >45 and ≤60. (Fig.6) And this trend was consistent across the three interventions. The PAFs for IHD and stroke for people aged 25-30 years were about three times that for people aged ≥80 years in all three interventions. (Fig.6) And the difference between the largest and smallest PAFs for LC and COPD across age groups would be between 0.2 and 1 percentage point in the three interventions. (Fig.6) The health benefits to the youngest population on IHD and stroke were about three times those to the eldest population for all interventions. This suggests that young people with IHD and stroke should pay special attention to reducing their exposure to PM$_{2.5}$.

**Discussions**

The mortality attributable to air pollution in BTH region are approximately 74.3 thousand for adults and infants, accounted for one-fifth of the deaths related to the five diseases and 12% of the total deaths in 2013 in BTH. The number of deaths attributable to air pollution was four times that caused by traffic accidents. (National health and family planning committee, 2013) Reducing PM$_{2.5}$ exposure can significantly decrease the number of PM$_{2.5}$ related premature deaths. If indoor PM$_{2.5}$ had reached the National Class I standard, 6% (95% CI: 4%-10%) of the premature deaths would have been averted in BTH in 2013; hence, 32% of the PM$_{2.5}$ related premature deaths could have been averted. Moreover, if outdoor PM$_{2.5}$ had reached the Government 2020 Interim target or National Class II standard, 4% (95% CI: 3%-8%) or 8% (95% CI: 5%-15%) of the premature deaths, respectively, would have been averted and these account for 21% and 42% of the PM$_{2.5}$ related premature deaths that could have been averted.

Comparing to reducing indoor PM$_{2.5}$ to National Class I standard, the potential reduction was
27% smaller and 47% larger by reducing outdoor PM$_{2.5}$ to Government 2020 Interim target or National Class II standard (the government target for 2030), respectively. As reported, cleaning up the polluted atmosphere in cities very often demands changes in policy and social norms, which requires a long time to take effect (Samet, 2016). Stringent and sweeping laws and programs are crucial to address air pollution like the United States and United Kingdom have done in the past few decades (Davis, 2002; Samet, 2011; Samet, 2016). London, Los Angeles and Donora, Pennsylvania were all former heavily polluted areas and once triggered well-known major pollution incidents, but their air quality has been greatly improved through policy actions. In London, the annual mean PM$_{10}$ levels closer to 30 μg/m$^3$ than the 300 μg/m$^3$ 50 years ago (and approximately 3,000 μg/m$^3$ in December 1952), while the annual PM$_{2.5}$ was 15 μg/m$^3$ in 2013 (Davis, 2002; 2016). The Los Angeles and Donora air of today is far better than that the mid-20th century, with the PM$_{2.5}$ concentration holding at 11 and 10 μg/m$^3$ in 2014, respectively (Samet, 2011; 2016). The Clean Air Act was passed in 1956 in United Kingdom and in 1970 in the United States, both of which provided a broad regulatory framework (covering air-pollution standards, various stationary and mobile sources et al.) and has led to progressive reductions in levels of criteria pollutants over the 40 years (Samet, 2016). While it is unarguably crucial to permanently clean up the outdoor air, an effective short-term solution would benefit the hundreds and millions of people living and breathing in the cities today. Unlike the outdoor environment, it is possible to achieve a substantial reduction in PM$_{2.5}$ indoor using air filters or cleaners provided that they are installed and maintained properly. Our results demonstrated that cleaning the indoor environment is an effective short-term solution to PM$_{2.5}$ pollution in the BTH region. In addition, indoor cleaning can also very quickly remove
pollutants generated by indoors activity including cooking, smoking and pets allergen (Butz et al., 2011; Sulser et al., 2009). Several studies have shown that indoor cleaning can not only greatly reduce the outdoor PM$_{2.5}$ exposure, but also significantly reduce the indoor PM$_{2.5}$ exposure caused by indoor sources, and achieve large health benefits (Bekő et al., 2008; Butz et al., 2011; Fisk, 2013; Sulser et al., 2009). If we take into account the PM$_{2.5}$ generated by indoor sources in our calculations, the health benefits of indoor cleaning will further improve relative to the outdoor cleaning.

With fast economic growth over the past three decades, China has become the world’s second largest economy in terms of gross domestic product (GDP) in 2010 and was the world’s biggest energy consumer in 2009(Chen et al., 2013). The rapid coal-dependent industrialization and the dramatic increase number of motor vehicles make China become one of the most air-polluted regions in the world. The first National Action Plan on Air pollution Prevention and Control was released in 2013 by Chinese government and required US$277.5 billion be invested over the next 5 years to reduce PM$_{2.5}$ concentration in BTH, Yangtze River Delta and Pearl River Delta by 25%, 20% and 15% respectively compared to the 2012 level. A modelling study estimated the cost-effectiveness of different policies (energy-saving and emission-reduction measures) in this action plan. The study found that total cost and total benefit were 118.39 and 748.15 billion Yuan, respectively, and the estimated benefit cost ratio was 6.32 in integrated policies scenario (Gao et al., 2016). Another study estimated the value of avoided cases of mortality in Shanghai assuming the outdoor PM achieve National Class II air quality standards in 2010-2012, and found the avoided cases of all-cause mortality had an value ranging from US$40.5 million to US$285.7 million (Voorhees et al., 2014). We have shown that this has resulted in huge avoidable premature deaths
attributable to PM$_{2.5}$ exposure in the BTH region. However, reducing outdoor PM$_{2.5}$ in the BTH region also benefits other regions, considering the long-range transport of PM$_{2.5}$. The benefits to other regions were not part of the comparison of this paper, therefore merits from reducing outdoor PM$_{2.5}$ are underestimated. Cleaning outdoor environment also reduces people’s exposure to PM$_{2.5}$ during outdoor activities and improves indoor environments. Moreover, using air cleaners increases total energy consumption in the region, leading to higher emissions from power generation, which is mainly from coal in China, hence worse pollution. Finally, because indoor cleaning requires the possession and correct operation of an additional device in all households, education campaigns and government subsidies are necessary to ensure effective and equitable implementation in the population, which adds to the cost of indoor cleaning besides its installation and operational costs. Indoor cleaning should never be considered as an alternative to outdoor cleaning, but rather merely a short-term compromise to mitigate the harm to health when outdoor pollution is being cleaned up.

**Strength and limitations**

Detailed population PM$_{2.5}$ exposure was estimated as the sum of exposures in indoor and outdoor environments by district, with an outdoor-to-indoor particle transport model for particulate matter migration from outdoors to indoors, where weather and human behavioral parameters were season-specific and were from studies done in the BTH region (Ministry of Environment Protection of People's Republic of China, 2013). The physical model based on the Monte Carlo framework has been verified, and according to our previous research (Shi et al., 2017), the model was sensitive to the following parameters: human outdoor activity time period, air exchange rates, window opening time period and PM$_{2.5}$ penetration rates and deposition rates. Therefore, we have been very careful
when deciding the distributions of these parameters and did measurements where data were missing from literature. The detailed PM$_{2.5}$ exposure level was combined with the detailed population density at district level to assess the health benefits for both indoor and outdoor cleaning. Overall, thirteen age groups and five PM$_{2.5}$-related diseases were also considered to account for variations in population exposure and health benefits. To our best knowledge, no study has quantified the population-level PM$_{2.5}$ exposure and health benefits of indoor PM$_{2.5}$ cleaning in such detail and compared it with outdoor cleaning.

However, there were no city-, case-, or age-specific mortality rates for the 13 cities at present. Hence, we used the city- and case-specific mortality rate and age group structures of Beijing, Tianjin, and Hebei province to adjust the city-, case-, and age-specific mortality rate of the entire China to derive the mortality rates in the 13 cities. City-specific air change rates, time period when windows were opened, and time spent outdoors were unavailable for the 11 cities in Hebei province; hence, the distributions of these parameters for Hebei Province as a whole were used for all cities in Hebei when available, and distributions for Beijing were used when the former were unavailable. Only residential buildings were considered in the paper. This was mainly restricted by the availability of data necessary for simulating other indoor environments for the BTH region. However, in BTH region, people spend over three quarters of their time in outdoor and residential indoor environments combined (Shi et al., 2017), which are the two microenvironments considered in this paper. Furthermore, the potential difference in infiltrations in commercial vs residential environments is mainly due to the difference in their air exchange rates (indoor sources are not included in our study), and our previous study (Zhou and Zhao, 2012) found that air exchange rates are similar in these two
environments. Therefore, our current assessment of exposure concentration based on outdoor and residential indoor environments could reflect their characteristics to a large extent. As well, we assumed that the outdoor PM$_{2.5}$ concentrations were reduced to less than a constant concentration (theoretical intervention scenario, 64/35 μg/m$^3$), and using PAF to quantitatively estimate health effects at population level without considering individual differences.

**Conclusions**

This study is the first to indicate that the avertable premature deaths gained from cleaning indoor PM$_{2.5}$ to National Class I standard level would be greater than those reducing outdoor PM$_{2.5}$ to Government 2020 Interim target, but would be lesser than those achieved by reducing outdoor PM$_{2.5}$ to National Class II standard. Strategies to balance the indoor and outdoor cleaning would help achieve the short-term target of PM$_{2.5}$ exposure reduction and protect the health of people.

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**Declarations of interest:** none.

**Ethical approval:** This article does not contain any studies with human participants or animals
performed by any of the authors.

Reference
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Guo, Y., Li, S., Tian, Z., Pan, X., Zhang, J., Williams, G., 2013. The burden of air
pollution on years of life lost in Beijing, China, 2004-08: retrospective regression analysis of daily deaths. bmj 347, f7139.


## Table 1. Potential reductions in premature mortality of three interventions (numbers in parentheses are the 95% confidence interval of the estimates)

<table>
<thead>
<tr>
<th>City</th>
<th>IHD</th>
<th>Stroke</th>
<th>COPD</th>
<th>LC</th>
<th>ALRI</th>
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<tbody>
<tr>
<td></td>
<td>S2</td>
<td>S3</td>
<td>S4</td>
<td>S2</td>
<td>S3</td>
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<td>520</td>
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<td>(413,709)</td>
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IHD, ischemic heart disease; LC, lung cancer; COPD, chronic obstructive pulmonary disease; ALRI, acute lower respiratory illness; BTH, Beijing-Tianjin-Hebei

S2: if indoor PM$_{2.5}$ concentration had been reduced to National Class I standard; S3: if outdoor PM$_{2.5}$ concentration had been reduced to Government 2020 Interim target; S4: if outdoor PM$_{2.5}$ concentration had been reduced to National Class II standard.
Fig.1. Population exposure distribution at the baseline scenario and at the three interventions. S1: exposure concentration (μg/m³) at baseline; S2: exposure concentration (μg/m³) if indoor PM$_{2.5}$ had been reduced to National Class I standard; S3: exposure concentration (μg/m³) if outdoor PM$_{2.5}$ had been reduced to Government 2020 Interim target; S4: exposure concentration (μg/m³) if outdoor PM$_{2.5}$ had been reduced to National Class II standard.
**Fig.2.** Population distribution of annual mean PM$_{2.5}$ exposure concentration at the baseline scenario and at the three interventions.

S1: baseline scenarios in 2013; S2: if indoor PM$_{2.5}$ concentration had been reduced to National Class I standard; S3: if outdoor PM$_{2.5}$ concentration had been reduced to Government 2020 Interim target; S4: if outdoor PM$_{2.5}$ concentration had been reduced to National Class II standard.
Fig. 3. The PAFs in the baseline scenario

IHD, ischemic heart disease; BTH, Beijing-Tianjin-Hebei; LC, lung cancer; COPD, chronic obstructive pulmonary disease; ALRI, acute lower respiratory illness; PAF, population attributable fraction
Fig. 4. Potential reductions in premature mortality attributable to PM$_{2.5}$ at district level in the BTH region in 2014 (person/each district)

S1: avertable premature deaths if indoor PM$_{2.5}$ had been reduced to National Class I standard; S2: avertable premature deaths if outdoor PM$_{2.5}$ had been reduced to Government 2020 Interim target; S3: avertable premature deaths if outdoor PM$_{2.5}$ had been reduced to National Class II standard; S4: difference of premature deaths avoided between reducing indoor PM$_{2.5}$ to National Class I standard and reducing outdoor PM$_{2.5}$ to Government 2020 Interim target.
Fig. 5. The PAFs of the three interventions

(A) Reducing indoor PM$_{2.5}$ concentration to National Class I standard; (B) Reducing outdoor PM$_{2.5}$ concentration to Government 2020 Interim target; (C) Reducing outdoor PM$_{2.5}$ concentration to National Class II standard.

IHD, ischemic heart disease; BTH, Beijing-Tianjin-Hebei; LC, lung cancer; COPD, chronic obstructive pulmonary disease; ALRI, acute lower respiratory illness; PM$_{2.5}$, fine particles; PAF, population attributable fraction
Fig. 6. The PAFs of different age groups in the baseline and intervention scenarios

(S1) The PAFs of different age groups in the baseline scenario; (S2) The PAFs of reducing the indoor PM2.5 concentration to National Class I standard; (S3) The PAFs of reducing the outdoor PM$_{2.5}$ concentration to Government 2020 Interim target; (S4) The PAFs of reducing the outdoor PM$_{2.5}$ concentration to National Class II standard.