Mortality benefits of vigorous air quality improvement interventions during the periods of APEC Blue and Parade Blue in Beijing, China

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ABSTRACT

Vigorous air pollution control measures were implemented during the 2014 Asia-Pacific Economic Cooperation and a large-scale military parade (described here as "APEC Blue" and "Parade Blue" periods) in Beijing, China. A natural experiment was conducted in a health impact assessment framework to estimate the number of deaths attributable to $PM_{2.5}$, using concentration-response functions derived from previous studies conducted in Beijing, combined with the differences in $PM_{2.5}$ concentrations between intervention and reference periods. Substantial reductions in daily $PM_{2.5}$ concentrations were observed during both intervention periods. Using the same dates from the prior year as a reference, daily $PM_{2.5}$ concentration decreased from 98.57 μg/m^3 to 47.53 μg/m^3 during "APEC Blue", and from 59.15μg/m^3 to 17.07μg/m^3 during the "Parade Blue". We estimated that 39 to 63 all-cause deaths (21 to 51 cardiovascular, 6 to 13 respiratory deaths) have been prevented during the APEC period; and 41 to 65 deaths (22 to 52 cardiovascular, 6 to 13 respiratory deaths) have been prevented during the Parade period. This study shows that substantial mortality reductions could be achieved by implementing stringent air pollution mitigation measures.

Capsule: There were about 50% reductions in daily $PM_{2.5}$ concentrations during the APEC and Parade Blue periods compared with the reference periods, and we estimated that the air pollution improvement intervention measures resulted in substantial mortality reductions.

Keywords: Air pollution; Intervention; APEC Blue; Mortality; Beijing

1. Introduction

Air pollution is regarded as an important environmental risk factor of morbidity and mortality around the world (Krall et al. 2013, Landrigan et al. 2015). The World Health Organization (WHO) estimated that 3.7 million premature deaths in 2012 were attributable to ambient air pollution (World Health Organization 2014).

Several biological mechanisms support the short-term association between ambient fine particulate matter air pollution ($PM_{2.5}$) exposure and mortality. For example, inhaled particles, deposited in the pulmonary tract, can elicit and exacerbate both pulmonary and systemic inflammation and oxidative stress, resulting in direct pulmonary and vascular damage, atherosclerosis, and autonomic dysfunction (Dockery and Stone 2007). In a quasi-experimental study examining the air pollution control program during the 2008 Beijing Olympics, the investigators found that the diminished air pollution concentration was followed by acute changes in the systemic inflammation biomarkers in healthy adults (Rich et al. 2012).

Such links between air pollution and adverse health outcomes have prompted governments to develop effective environmental policy and air quality legislation in order to safeguard the public's health (Ministry of Environmental Protection of China 2012). In recent years, anthropogenic air pollution control programs have been implemented in a number of countries, particularly during large-scale events, such as the Olympic Games, the Asian Games, and some political events (Friedman et al. 2001, Li et al. 2010, Tao et al. 2015). These programs have provided unique opportunities to quantitatively evaluate the public health impacts resulting from environmental regulatory policies (Rich et al. 2012, Lin et al. 2014), also known as accountability research, a necessary component of governmental policy development and evaluation (Dominici et al. 2007, Henschel et al. 2012).

Vigorous air pollution control measures were put into effect in Beijing, the capital of China, during the Asia-Pacific Economic Cooperation (APEC) Summit in 2014, and the 2015 China large-scale military parade (Johnston et al. 2013, Zheng et al. 2016). This effort significantly improved the ambient air quality, which was coined as "APEC Blue" and "Parade Blue", respectively (Wen et al. 2015, Shi et al. 2016). Yet, to what extent air pollutants, especially particulate matter equal to or less than 2.5 µm in diameter ($PM_{2.5}$), were reduced because of these measures, and how these reductions were associated with mortality reduction during these two intervention periods remained unclear. Therefore, as an accountability analysis, this study compared the $PM_{2.5}$ concentrations during the intervention periods with the reference periods and evaluated the potential mortality reduction based on a health impact assessment framework. We hypothesized that reduced air pollution by the intervention measures could significantly reduce mortality risk during the intervention periods.

2. Materials and methods

2.1 Setting

Beijing, located in northern China, is the capital of the People's Republic of China and one of the most populous cities in the world. Its population in 2013 was 21.2 million. The typical climate in Beijing is a combination of temperate and continental monsoon climates with four distinct seasons. The summer is hot and humid and the hottest month is July with an average temperature of 26 °C (79 °F). The winter is cold and dry with the coldest month of January presenting an average temperature of -4 °C (25 °F).

Alongside its rapid economic development, in recent years Beijing has become infamous for serious air pollution problems (Rich et al. 2012). It is no strange for its sky to be completely shrouded by a filthy film of gray smog. Six urban districts in Beijing with elevated air pollution levels were selected for this study because they were more likely to be affected by the air pollution control measures described below, which provided the opportunity to conduct the current study in the context of a "natural experiment" design.

2.2 APEC Blue

On November 5th through the 11th, 2014, China hosted the APEC Leaders' Meeting in Beijing. To improve the city's air quality, the government enforced strict air pollution control measures in Beijing and neighboring regions from November 1st to the 12th, 2014. The detailed emission control measures have been described elsewhere (Li et al. 2015a).

In brief, the targeted sources included emission control for point source (construction, paint, and solvent use), area source (industry, steel factories, chemical factories, power plants, etc), and on-road mobile source (vehicle emissions). As a result, air quality was greatly improved, and the phrase "APEC Blue" was coined to refer to the blue sky during this period (Li et al. 2015b).

2.3 Parade Blue

On August 20th, 2015, the Chinese authorities implemented air pollution control measures to ensure a blue sky for the 2015 China Victory Day Parade, which was held on September 3rd, 2015 to celebrate the 70th anniversary of the end of the Second World War. Control measures included restrictions on construction, factory production, and car use. During this period, limited car use affected five million car owners; hundreds of factories were closed; 40,000 construction sites in and around Beijing were shut down. On August 20th, air pollution levels in Beijing dropped dramatically, resulting in the city's usually smoggy skies to be "picture-perfect blue", which was entitled "Parade Blue" (Shi et al. 2016).

2.4 Estimates of mortality effects of a unit change in daily $PM_{2.5}$ concentration

To estimate the changes in mortality associated with decreased $PM_{2.5}$ concentrations during the APEC and the Parade periods, we conducted a health impact assessment using an approach proposed by the WHO (World Health Organization 2001a, World Health Organization 2001b). The health impact assessment was conducted based on exposure-response function and data about population size, baseline mortality, and air pollution concentrations during the intervention period and reference period. We based our analysis on a log-linear relationship between daily particulate matter air pollution concentrations and mortality in China (Chen et al. 2012, Lin et al. 2016b). The WHO also advised that the air pollution-health relationship is approximately linear (World Health Organization 2003).

We obtained the all-cause mortality risk (excluding injury and poisoning), cardiovascular mortality, and respiratory mortality from previously published time-series studies conducted in Beijing. According to one study (Li et al. 2015c), a 10 μg/m^3 increase in daily $PM_{2.5}$ concentration in Beijing would lead to a 0.28% [95% confidence interval (CI): 0.18%-0.41%] increase in all-cause mortality, a 0.32% (95% CI: 0.16%-0.47%) increase in cardiovascular mortality, and a 0.31% (95% CI: 0.01%-0.63%) increase in respiratory mortality. Another study (Li et al. 2014) found that the excess mortality risk for every 36 μg/m^3 $PM_{2.5}$ increase was 1.52% (95% CI: 1.07%-1.99%) in Beijing. Table 1 shows the estimates of the short-term association between $PM_{2.5}$ and mortality from all-cause, cardiovascular, and respiratory diseases in Beijing among these studies, from which we also calculated a range of estimates of the number of preventable deaths.

Table 1 The association between daily $PM_{2.5}$ and mortality obtained from previous studies in Beijing, China

Death cause	Study period	$PM_{2.5}$ concentrati n (μg/m^3)	ER (95% CI)	β (95% CI, *10^{-4})
All-cause				
Guo, 2013(Guo et al. 2013)	2004-2008	94	2.5 (0.6, 4.5)	2.63 (0.64, 4.68)
Li, 2014(Li et al. 2014)	2005-2009	36	1.52 (1.07-1.99)	4.19 (2.96, 5.47)
Li, 2015(Li et al. 2015c)	2008-2011	10	0.28 (0.18-0.41)	2.80 (1.80, 4.09)
CVD mortality				
Dong, 2013(Dong et al. 2013)	2007-2008	10	0.78 (0.07-1.49)	7.77 (0.70, 14.79)
Li, 2015(Li et al. 2015c)	2008-2011	10	0.32 (0.16-0.47)	3.19 (1.60, 4.69)
Respiratory mortality				
Li, 2013(Li et al. 2013)	2004-2009	10	0.69 (0.54-0.85)	6.88 (5.39, 8.46)
Li, 2015(Li et al. 2015c)	2008-2011	10	0.31 (0.01-0.63)	3.10 (0.10, 6.28)

Note: No. of units means number of units (in μg/m^3) for the corresponding excess risk of mortality reported in the original study; ER refers to excess mortality risk; and β and its 95% CI refer to coefficients and corresponding 95% CI for the association between daily $PM_{2.5}$ (1 μg/m^3) and mortality.

2.5 Change in $PM_{2.5}$ concentration compared with reference period

We used two different reference periods to calculate the changes in air pollution concentration relative to the intervention periods. The first reference period (Reference I) was the average concentration during the same calendar dates of the previous year:

November 1st to the 12th , 2013, for the APEC period and August 20th to September 3rd , 2014, for the Parade period. The second reference period (Reference II) was the near-term reference period with the same distribution of days of the week: October 18th to the 29th , 2014, for the APEC period and July 30th to August 13th, 2015, for the Parade period. We collected daily air pollution data in Beijing, including the levels of $PM_{2.5}$, sulfur dioxide (SO_2), and nitrogen dioxide (NO_2) from the Chinese Environmental Monitoring Center (http://www.cnemc.cn/). Additionally, daily meteorological data for the same period, including daily mean temperature (°C) and relative humidity (%) data, were obtained from the Chinese National Weather Data Sharing System (http://cdc.cma.gov.cn/home.do).

2.6 Baseline number of outcome events

We assumed that the size of the baseline population changed minimally within the study period so that the person-time units in the denominators of the mortality rates remained constant; this allowed us to compare the daily mortality counts in the intervention and reference periods using rate ratios (RRs), which is defined as the ratio of the number of deaths in the intervention period and the number of deaths during the reference periods. We calculated the daily mortality count based on the population and the mortality rate in Beijing. According to the sixth census data, there were 12.76 million residents in 6 urban districts in Beijing. Based on an overall annual mortality rate of seven per thousand, the daily mortality count would be 245. According to a previous study (Ma et al. 2015), among the overall mortalities, the proportions of cardiovascular mortality and respiratory mortality were 43.74% and 12.32%, respectively; so it was estimated that there were about 107 and 30 deaths from cardiovascular and respiratory diseases respectively each day in the study areas.

2.7 Statistical analysis

Measures of $PM_{2.5}$-mortality association is reported as relative risk (RR) or excess risk (ER). To determine the increase in $PM_{2.5}$, concentrations were first converted into a regression coefficient (β) for each μg/m^3 change using the formula: β = ln(RR)/unit =

ln(1+ER)/unit; and the 95% confidence interval for β: β_{lower} = ln(RR_{lower})/unit = ln(1+ER_{lower})/unit, β_{upper} = ln(RR_{upper})/unit = ln(1+ER_{upper})/unit. Where RR_{lower} and RR_{upper} are the lower and upper limits of the 95% CI of RR, and ER_{lower} and ER_{upper} are the lower and upper limits of the 95% CI of ER. We then calculated the number of prevented deaths attributed to the decreased $PM_{2.5}$ concentrations based on the following formula (Lin et al. 2016a):

$$\Delta\text{number of mortality} = \text{baseline mortality} * [\exp(\beta * \Delta PC) - 1]$$

The 95% CI of the mortality benefits was estimated using the following formula(s):

$$\Delta\text{lower limit of number of mortality} = \text{baseline mortality} * [\exp(\beta_{lower} * \Delta PC) - 1]$$

$$\Delta\text{upper limit of number of mortality} = \text{baseline mortality} * [\exp(\beta_{upper} * \Delta PC) - 1]$$

Where Δnumber of mortality is the estimated change in the number of deaths, β is the coefficient of association between daily $PM_{2.5}$ concentrations (per 1μg/m^3 increase) and mortality, and ΔPC is the change in ambient $PM_{2.5}$ concentrations (i.e., the difference between the reference and intervention periods).

3. Results

Table 2 summarizes the daily air pollution and meteorological conditions during the intervention and the reference periods in Beijing. Significant reductions were observed during the intervention periods when compared with the reference periods for both the "APEC Blue" and the "Parade Blue" events.

Table 2 Comparison of air pollutants and meteorological variables between intervention and reference periods

Variable	Intervention	Reference I		Reference II	
		Baseline	Change	Baseline	Change
APEC Blue (12 days)					
Air pollutants					
$PM_{2.5}$ (μg/m^3)	47.53	98.57	51.04	138.19	90.66
SO_2 (μg/m^3)	9.90	20.58	10.68	13.57	3.67
NO_2 (μg/m^3)	50.64	69.47	18.83	91.33	40.69
Meteorological					
Temperature (°C)	6.46	7.05	0.59	11.37	4.91

Humidity (%)	45.33	52.81	7.48	65.06	19.73
Parade Blue (15 days)					
Air pollutants					
$PM_{2.5}$ (μg/m^3)	17.07	59.15	42.08	70.09	53.02
SO_2 (μg/m^3)	4.91	6.27	1.36	7.73	2.82
NO_2 (μg/m^3)	21.64	34.83	13.19	53.21	31.57
Meteorological					
Temperature (°C)	25.15	25.07	-0.08	27.17	2.02
Humidity (%)	65.06	64.47	-0.59	65.47	0.41

During the "APEC Blue" period in 2014, daily $PM_{2.5}$ concentrations fell to 47.53 μg/m^3, attaining WHO's air quality guideline Interim Target II (50 μg/m^3), corresponding to a 51.78% reduction compared to the same calendar dates of the previous year (Reference I, 98.57 μg/m^3) and a 65.61% reduction compared to the pre-intervention period (Reference II, 138.19μg/m^3). The reduction of daily SO_2 and NO_2 concentrations was 51.90% and 27.11% compared to Reference I, and 27.04% and 44.55% compared to Reference II. The daily mean temperature during the intervention period was similar to that during the Reference I period, but lower than that during the Reference II period.

During the "Parade Blue" period in 2015, daily $PM_{2.5}$ concentration decreased 71.14% from 59.15 μg/m^3 on the same calendar dates in 2014 (Reference I) to 17.07 μg/m^3 and 75.65% from 70.09 μg/m^3 during the pre-intervention period (Reference II) to 17.07 μg/m^3 (Table 2). The $PM_{2.5}$ concentrations during this period attained the ultimate goal of the WHO's air quality guideline (25 μg/m^3). A decreasing pattern was also observed for other air pollutants, such as SO_2 and NO_2. The daily mean temperature was similar during the intervention period and the Reference I period, but lower than that of the Reference II period.

Table 3 Estimated mortality benefits from air pollution controlling interventions during AEPC Blue and Parade Blue periods in Beijing, China

	Reference I		Reference II	
	Δ Mortality	**95% CI**	**Δ Mortality**	**95% CI**
APEC Blue (12 days)				
All-cause mortality				
Guo, 2013	39	9-70	70	15-125

Li, 2015	42	23-61	75	40-109
Li, 2014	63	44-82	112	77-146
CVD mortality				
Li, 2015	21	11-31	37	20-55
Dong, 2013	51	5-97	90	9-172
Respiratory mortality				
Li, 2013	13	10-16	22	17-28
Li, 2015	6	0-12	10	0-20
Parade Blue (15 days)				
All-cause mortality				
Guo, 2013	41	10-72	51	12-91
Li, 2015	43	28-63	54	35-80
Li, 2014	65	46-85	82	58-107
CVD mortality				
Li, 2015	22	11-32	27	14-40
Dong, 2013	52	5-100	66	6-126
Respiratory mortality				
Li, 2013	13	10-16	16	13-20
Li, 2015	6	0-12	7	0-15

Note: 95% CI: 95% confidence interval.

Table 3 illustrates the reductions in daily mortality as a result of a reduction in $PM_{2.5}$ levels during the intervention periods in Beijing. We estimated that, during the APEC period, the reductions in all-cause mortality ranged from 39 to 63 compared to the Reference I period, and from 70 to 112 compared to the Reference II period. The estimated number of prevented cardiovascular deaths ranged from 21 to 51 (Reference I), and from 37 to 90 (Reference II). The reduction in respiratory mortality ranged from 6 to 13 (Reference I), and from 10 to 22 (Reference II).

Significant premature mortality reductions were also observed during the Parade intervention period in Beijing. During the 15-day intervention period, 41 to 65 deaths and 51 to 82 deaths were estimated to be prevented compared to the Reference I period and the Reference II period, respectively. The prevented cardiovascular mortality was estimated to range from 22 to 52 (Reference I), and from 27 to 66 (Reference II); the reduction in respiratory mortality would range from 6 to 13 (Reference I), and from 7 to 16 (Reference II).

4. Discussion

The results of our study suggested that air pollution control measures implemented in Beijing during the discrete time periods described as "APEC Blue" and "Parade Blue" were associated with substantial mortality reductions. Similar temporary and strict air quality improvement policies have been conducted during several large-scale events in China, such as the 2008 Beijing Olympic Games (Jia et al. 2009), the 2010 Guangzhou Asian Games (Lin et al. 2014, Tao et al. 2015), and more recently, the APEC meeting and the military parade in Beijing as described (Li et al. 2015b). Evaluation of the mortality benefits of air pollution control measures in the context of natural experiments such as the current study provided compelling evidence that extensive control measures are both feasible and essential for improving public health (Bell et al. 2011, Fann et al. 2012).

Alongside the economic development, China has been facing severe air pollution problems, which has gained international attention in recent years (Chen et al. 2013). Evidence of the association between particulate air pollution and increased mortality has been accumulating in the past decades. Both time-series studies and case-crossover studies have demonstrated short-term effects of particulate air pollution on human health (Kan et al. 2007, Peng et al. 2012, Lin et al. 2016b). Based on this, our study estimated the health benefits from lowering particulate air pollution concentrations by controlling air pollution emissions through citywide transportation regulation and industrial emission controls. We estimated that about 39-112 (1.33%-3.81% of daily mortality) and 41-82 (1.20%-2.39% of daily mortality) premature deaths were prevented during the APEC period and the Parade period, respectively. The results were consistent with a number of previous studies. Friedman and colleagues observed a substantial reduction in hospital admissions during the 1996 Olympic Games when the alternative transportation policy was put into effect to reduce vehicle exhaust (Friedman et al. 2001). Significant health benefits, including asthma morbidity reduction, improved cardiac autonomic function among young healthy adults, acute changes in biomarkers of inflammation and thrombosis, and measures of cardiovascular physiology were reported during the 2008 Beijing Olympic Games (Li et al. 2010, Wu et al. 2010, Rich et al. 2012). Short-term beneficial effects were also observed during the Asian Games in Korea, as well as the one in China (Lee et al. 2007, Lin et al. 2014). Using a health impact assessment framework, we illustrated that significant reductions in premature mortality could be achieved by lowering daily $PM_{2.5}$ levels in a heavily polluted Chinese city. Our results highlighted the need for continuous and persistent efforts to improve ambient air quality in China.

A few limitations should be noted. First, this study estimated only the association between prevented mortality and acute ambient $PM_{2.5}$ reductions obtained by temporary air quality improvement activities. We were likely to underestimate the health benefits of $PM_{2.5}$ reduction in Beijing, as various other medical conditions, which could benefit from air quality improvement, were not evaluated in our analysis (Bell and Davis 2001, Liu et al. 2016). As chronic medical conditions were common among the population, a large number of residents were likely to be affected by pollution exacerbating milder symptoms, which could not be investigated due to our limited access to the datasets. Furthermore, even though our analysis focused on $PM_{2.5}$, significant reductions of other mortality-associated air pollutants, such as SO_2 and NO_2 (Lin et al. 2013), were also observed following the air pollution control measures (Table 2). Therefore, there might be more health benefits related to vigorous air pollution intervention measures.

Second, ambient air pollution concentration served as a proxy for individual exposure level. As previously reported, studies assessing air pollution by a fixed air monitoring station might have underestimated the health effect (Mindell and Joffe 2004). However, it was important to use the same measurement of exposure in the health impact assessment as in the studies where the exposure-response functions were derived (World Health Organization 2000). A simulation study on air pollution exposure assessment showed that for $PM_{2.5}$ concentrations measured by fixed local air monitoring stations were adequate surrogates for personal exposures (Schwartz et al. 2007). In addition, $PM_{2.5}$ tended to be spatially homogeneous, indicating the representativeness of monitor-based pollution levels for personal exposure (Monn 2001). Hence, the association between residents' actual $PM_{2.5}$ exposures and the measurement by a fixed air monitor might not be substantially different in urban Beijing.

Third, different studies have used different model approaches, making it difficult to compare results across studies of environmental health effects; in this respect, we obtained coefficients of $PM_{2.5}$-mortality association in Beijing, by using results from major studies done in the study city of Beijing. Doing so allowed us to estimate the health co-benefits of $PM_{2.5}$ reductions.

This study has important implications for environmental management and public health protection. As air pollution becomes a severe problem for daily life, the growing public concerns need to be addressed by a strong governmental response. Nationwide policy development and implementation are needed to tackle air pollution problems and to protect public health. Our results provided quantitative estimates of the mortality benefits resulting from the air quality control measures that may support policy changes. For example, in Australia, policy goals to achieve a daily mean $PM_{2.5}$ of 8 $\mu g/m^3$ have been set and actions to improve air quality have been taken since 2003. Goals to reduce daily mean $PM_{2.5}$ in China will have important implications for improving public health, as proposed by the scientific community and the WHO (World Health Organization 2006).

In conclusion, our findings suggest that substantial mortality benefits could be achieved by lowering air pollution concentrations, particularly during large-scale events. Air pollution control measures should be adopted as a regular practice to better safeguard public health.

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None declared.

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