Water Air Soil Pollut (2011) 215:349–363
DOI 10.1007/s11270-010-0483-0

Human Health Impact of Exposure to Airborne Particulate Matter in Pearl River Delta, China

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Received: 17 November 2009 / Accepted: 18 May 2010 / Published online: 5 June 2010

Abstract To evaluate the potential public health impact of exposure to airborne particulate matter, concentrations of PM_{10} and $PM_{2.5}$ were measured at 16 monitoring stations in Pearl River Delta. Epidemiological studies were collected, and meta-analysis method was used to get the exposure-response functions for health effects on mortality of residents in China. Chinese studies reported somewhat lower exposure-response coefficients as compared with studies abroad. Both Poisson model and life-table approach were used to estimate the health effects including acute effects and chronic effects. For short-term exposure, 2,700 (95% confidence interval (CI), 2,200–3,400) premature deaths would be prevented annually if PM_{10} daily concentrations reduced to below World Health Organization (WHO) guideline value. Much more benefits would be gained for long-term exposure. The annual avoidable deaths would be 42,000 (95% CI, 28,000–55,000) and 40,000 (95% CI, 23,000–54,000) for PM_{10} and $PM_{2.5}$, respectively, if the particulate matter annual concentrations were reduced to below WHO guideline values. And the average lifespan of residents would prolong 2.57 years for PM_{10} and 2.38 years for $PM_{2.5}$ if reducing the PM annual concentrations. The benefits varied greatly in different areas and different manage strategies should be carried out to protect human health effectively.

Keywords Particulate matter · Pearl River Delta · Avoidable deaths · Life expectancy

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1 Introduction

Compared with other air pollutants, particulate matter measured as either total suspended particle (TSP), PM_{10} (those less than 10 μm), $PM_{2.5}$ (those less than 2.5 μm), or black smoke appears to show most consistent association with human health. A recent World Health Organization review (WHO 2003) concluded that ambient particulate matter was considered responsible for the health effects seen in large epidemiological studies relating ambient particulate matter to mortality and morbidity. Epidemiological studies have consistently shown an association between particulate matter pollution and premature deaths in China and other countries (Wong et al. 2001; Kan et al. 2007; Qian et al. 2007a, b; Daniels et al. 2000; Stieb et al. 2002). There was also abundant evidence associating particulate matter pollution with increase in hospital admissions or outpatients for respiratory and cardiovascular diseases (Ware et al. 1986; Burnett et al. 1997; Wong et al. 1999; Peters et al. 1999; Peng et al. 2008).

The public health impact exposure to particulate matter (PM) included both acute (with short-term effects) and chronic (with long-term effects) effects. Time-series studies identified the health impact of PM pollution in the preceding days, whereas cohort studies analyzed the health effects due to long-term exposure to PM. For mortality, whereas time-series approaches captured only cases in which deaths have been triggered by air pollution exposure incurred shortly before deaths, cohort studies captured all air pollution-related categories of deaths, including deaths of persons whose underlying health condition led to premature deaths without being related to the level of pollution shortly before deaths (Kunzli et al. 2001). Compared with time-series studies, the cohort studies provided more complete assessment of the impact from exposure to air pollution (Kunzli et al. 2001) and represented the full effects of air pollution more accurately.

Health impact assessment (HIA) based on epidemiological study evidence was used widely to estimate the health damage due to PM pollution. Similar assessment studies in Japan, America, Europe, and other areas (Aunan et al. 1998; Levy et al. 2001; Leksell and Rabl 2001; Medina et al. 2004; Yorifuji et al. 2005; Boldo et al. 2006; White et al. 2008) showed quantification estimate results of the impact of PM pollution on human health. In those existed estimated studies, mainly focused on PM_{10}, public health impact of short-term or long-term exposure to airborne particulate matter was valued. There were also some assessment studies in China (Zhang et al. 2007a, b, 2008) assessed the acute health impact due to exposure to PM_{10} in Beijing and other cities and valued the economic loss. Hedley et al. (2006) also valued the acute health effect due to exposure to air pollutants, such as SO_2, NO_2, O_3, and PM_{10}, in Pearl River Delta. Kan and Chen (2002) assessed the impact of long-term exposure to particulate matter (measured as TSP) on life expectancy and survival rate of Shanghai residents. While recent toxicological research suggested potentially important roles for sulfates, particulate acids, metals, and organic compounds in PM toxicity, nevertheless, there was insufficient evidence to identify the independent effects of these correlated compositions. And ambient concentrations of most of the identified particulate constituents would be reduced by control strategies targeting PM_{10} and $PM_{2.5}$ mass. Little heath assessment studies on benefits from controlling chemical composition of particulate matter was available in China and other countries.

To our knowledge, assessment studies on public health impact of exposure to PM_{10} and $PM_{2.5}$, especially for $PM_{2.5}$, were much-needed in Pearl River Delta (PRD). PRD is one of the six most important key economic belts in China. It lies in the south of China. PRD consists of nine prefectures in Guangdong Province and two Special Administrative Regions (SARs). Those prefectures include Guangzhou, Shenzhen, Zhuhai, Dongguan, Zhongshan, Foshan, Huizhou, Jiangmen, and Zhaoqing. And the two SARs are Hong Kong (HK) and Macao Special Administrative Region (MSAR). The region, with an area of 41,700 km^2 (not including HK and MSAR), had a population of about 45.5 million in 2006. The gross production of this area, without HK and MSAR, was about 2161.8 billion Yuan RMB, which accounted for about 10.3% of GDP of China in 2006. Especially in recent 30 years, PRD had a great progress in economic growth but got more terrible air pollution. Energy production and consumption in Guangdong has increased largely. Evaluating the impact on human health attributable to PM pollution in PRD is regarded as an essential step to assess the effectiveness of air pollution control policies in this region.

The Air Quality Monitoring Network of Guangdong and Hong Kong (AQMNGH) which was consisted of 16 monitoring stations started to work in December, 2005. Thirteen stations were in Guangdong province, and the other three stations were in Hong Kong. The network would provide the government and the public more accurate and overall regional air quality data. For long-term observation, it would provide the policy makers useful information, which was necessary to establish effective management strategies to relieve the regional air pollution level in PRD. Unified guidelines for gathering and analyzing data were used to ensure comparability of the data in different areas. More details about AQMNGH could be found in other published work (Zhang et al. 2005).

In this study, the public health impact of exposure to PM_{10} and $PM_{2.5}$ would be assessed, based on the monitoring data of AQMNGH in 2006. The health benefits from reducing the PM concentrations, in terms of number of avoidable deaths and potential gain in life expectancy, would be assessed.

2 Methodology

In this study, HIA provided estimates of avoidable deaths and influence on life expectancy attributable to PM pollution exposure to the target population in PRD, assuming that there was a causal relationship between PM pollution and the observed health effects. The health benefits from reducing PM concentrations in PRD represented the health damage attributed to PM pollution. Both the acute and chronic effects associated with PM exposure were estimated using Poisson model and Life-table method.

The HIA method, similarly used in Japan and Europe (Yorifuji et al. 2005; Boldo et al. 2006), consisted of four steps: specific exposure, health outcomes and exposure response functions, setting HIA scenarios, and calculating the estimated impact in the target population.

2.1 Exposure Measurement

The observation data of PM_{10} and $PM_{2.5}$ based on AQMNGH were selected between January 1 and December 31, in 2006. The original data were measured as 1-h average concentrations. And the daily average concentrations and annual average concentrations were exacted from the original data. Concentrations of PM_{10} were measured at all 16 stations. However, concentrations of $PM_{2.5}$ were only measured at six stations. $PM_{2.5}$ annual concentrations were derived from PM_{10}. Conversion factor 0.7, the average annual concentration ratio of $PM_{2.5}/PM_{10}$ in the six stations, was used. Uncertainties using the factor 0.7 would be discussed later. The observation data were shown in Table 1.

2.2 Health Outcomes and Exposure-Response Functions

The PM-associated health outcomes included mortality, chronic morbidity, hospital admissions and outpatients,

Table 1 Monitoring data of particulate matter in PRD, 2006 (μg/m³)

Areas	Station name	Number of samples[a]	PM_{10}		$PM_{2.5}$	
			Annual mean (μg/m³)	SD (μg/m³)	Annual mean (μg/m³)	SD (μg/m³)
Guangzhou	Tianhu	365	62.4	38.6	46.5	29.9
	Luhu	365	72.8	39.8	–	–
	Wanqingsha	365	89.6	54.4	60.3	37.7
Shenzhen	Liyuan	365	58.8	35.7	–	–
Zhuhai	Tangjia	365	40.5	14.7	–	–
Huizhou	Jinguowan	365	55.9	32.9	34.0	24.3
	Xiapu	365	103.0	46.3	–	–
Jiangmen	Donghu	365	69.7	38.4	–	–
Dongguan	Haogang	152	109.3	109.3	–	–
Zhongshan	Zimaling	365	40.8	26.2	–	–
Foshan	Huijingcheng	365	114.8	66.8	–	–
	Shunde	365	121.7	73.1	–	–
Zhaoqing	Chengzhong	365	78.4	78.4	–	–
Hong Kong	Dongyong	365	56.1	32.4	29.7	24.8
	Quanwan	365	56.6	27.7	40.9	21.0
	Tamen	365	48.1	26.1	34.1	21.2

[a] Here the number of samples means the number of sampling days

and decline in lung function. Among all the health outcomes, death was most notable and contributed largest health damage and economic loss. So, in this study, only the mortality effects due to PM pollution were assessed.

Exposure response functions were used in epidemiologic studies to associate air pollution with adverse health effects. The exposure-response functions in our study were attained from epidemiology studies. Time-series studies identified the short-term health impact of particle pollution, whereas cohort studies analyzed the health effects due to long-term exposure to PM. Time-series studies on mortality from 1990 to 2009 in China were collected, and meta-analysis was used to get the exposure-response functions for short-term exposure. Two major databases, Medline and PubMed, were searched for papers published in international journals. For papers published in local mainland journals, China Academic Journals Full-text Database and Chinese Science Journals Full-text Database were used instead. For long-term exposure, two American cohort studies were used because there were still no published cohort studies on PM_{10} or $PM_{2.5}$ in China. The two studies, American Cancer Society (ACS) study (Dockery et al. 1993) and Harvard Six Cities Study (Pope et al. 1995, 2002) were well-illustrated by many assessment studies in other countries (Martuzzi et al. 2003; Sultan 2007; White et al. 2008; Zhang et al. 2008). Table 2 listed all published epidemiology studies of effects of PM_{10} and $PM_{2.5}$ in China published in English and Chinese. After a systematic literature search, the exposure-response coefficients were estimated by means of a meta-analysis method (inverse variance method), in which the overall coefficients was a weighted average of the individual study coefficients. The weights used in the calculation were the inverse of the study variance (Aunan and

Table 2 Percent increase in mortality per 10 μg/m^3 increase of the concentrations of PM (%)

				Exposure-response coefficients	
	Pollutants	Study resources	Study area	Mean (β)	Standard errors (SE)
Short-term exposure	$PM_{2.5}$	Dai et al. 2004	Shanghai/China	0.85	0.27
		Kan et al. 2007	Shanghai/China	0.36	0.13
		Venners et al. 2003	Chongqing/China	0.00	0.34
	PM_{10}	Dai et al. 2004	Shanghai/China	0.54	0.16
		Kan et al. 2007	Shanghai/China	0.16	0.07
		Wong et al. 2008	Shanghai/China	0.26	0.19
		Kan et al. 2008	Shanghai/China	0.25	0.19
		Kan and Chen 2003	Shanghai/China	0.30	0.10
		Jia et al. 2004	Shanghai/China	0.70	0.18
		Tang et al. 2006	Shanghai/China	0.30	0.13
		Yu et al. 2006	Shanghai/China	0.04	0.02
		Wu and Zhang 2009	Beijing/China	0.17	0.03
		Zhang, Zhang et al. 2007, b	Taiyuan/China	0.25	0.21
		Qian et al. 2007a, b	Wuhan/China	0.36	0.09
		Wong et al. 2008	Wuhan/China	0.43	0.10
		Wong et al. 2008	Hong Kong/China	0.53	0.14
		Wong et al. 2001	Hong Kong/China	0.60	0.28
		Tsai et al. 2003	Kaohsiung/China	0.00	0.41
Long-term exposure	$PM_{2.5}$	.Dockery et al. 1993	USA	13.0	4.5
		Pope et al. 2002	USA	6.2	2.3
	PM_{10}	Dockery et al. 1993	USA	8.5	2.3
		Pope et al. 1995	USA	3.9	1.6

Pan 2004). Homogeneity should be assessed by means of the Q statistic, which was the sum over all studies of the study weight multiplied with the square of the difference between the study coefficients and the weighted average coefficient. After homogeneity test, the fixed-effects model or the random effects model could be chosen (fixed-effects model for homogeneity and random effects model for heterogeneity).The meta-analysis software Revman 4.2.2 was used for statistical integration. More details about the process of meta-analysis could be found in other studies (Schlesselman and Collins 2003; Aunan and Pan 2004; Xie et al. 2009).

2.3 Health Impact Assessment Scenarios

Threshold concentration was defined as the lowest boundary that there was no obvious observed adverse health effect below it. But, there was no such concentration found in existed epidemiological studies. Our aim was to provide useful information for policy decision-makers, the ambient concentration as zero or background concentrations was considered not appropriate as the reference concentration in this study. However, there was no ambient standard of $PM_{2.5}$ in China yet. So, here, the WHO guideline values were chosen as the reference concentrations. The WHO guideline values included 24 h concentration guideline values (25 μg/m^3 for $PM_{2.5}$ and 50 μg/m^3 for PM_{10}) and annual concentrations of $PM_{2.5}$ and PM_{10} (10 μg/m^3 for $PM_{2.5}$ and 20 μg/m^3 for PM_{10}). WHO guideline values of PM were mainly based on published epidemiological studies all over the world and could well protect human health. In our study, the benefits from reducing annual PM concentrations to WHO guideline values represented the health effects attributed to particulate matter pollution.

2.4 Health Impact Assessment Tools

Both avoidable deaths and potential gain in life expectancy were calculated to assess the public health impact of exposure to PM_{10} and $PM_{2.5}$.

(a) Avoidable deaths

Poisson model was often used to quantify the effect of air pollution on morbidity and mortality rates (Zhang et al. 2007a, b). In this study, the simplified linear function was used. The number of avoidable deaths for long-term exposure was calculated as:

$$\Delta H = p \times (E - E_0) = p \times ((1 + \beta \times (C - C_0)) \times E_0 - E_0) \\ = p \times \beta \times \Delta C \times E_0$$

Where β is the exposure-response coefficient from cohort studies, C and C_0 are the ambient particle annual concentrations and reference concentrations (here WHO annual guideline values were used). E and E_0 are the health effects at C and C_0, respectively. The ΔH or the health damage caused by increased pollution can be calculated if β, C, C_0, and E are known.

Similarly, for short-term exposure, the calculation formula treated as:

$$\Delta H = \sum_{i=1}^{365} (p \times \beta \times (C_i - C_0) \times E_0) \\ = \sum_{i=1}^{365} (p \times \beta \times \Delta C \times E_0)$$

Where β is the exposure-response coefficient from time-series study, C_i and C_0 are the ambient particle daily concentrations and reference concentrations (here WHO 24-h guideline values were used).

Health data in PRD, including population and non-accident mortality, was available for 2005 in PRD from the 1% population sampling investigation in Guangdong Province. It was assumed to be applicable to 2006. Health data in Hong Kong were derived from Hong Kong Health Department. Because only adults were included in the two American cohort studies, the estimation of avoidable deaths and the potential gain in life expectancy calculations for long-term exposure were restricted to population older than 30 years. All baseline data were shown in Table 3.

(b) Gain in life expectancy

Because the number of death could not explain the difference between deaths with different ages, so potential gain in life expectancy was also calculated using life table approach in this study. A life table was estimated for a sample population of 100,000 people, who were assumed to be exposed to the current deaths risks in the area of interest for their whole life (Chiang 1968; Nevalainen and Pekkanen 1998). It was constructed with 5-year intervals. For each interval, the number of deaths was estimated for the population

Table 3 Baseline data of mortality and population in PRD

Areas	Population	Population (≥30 years)	Non-accident mortality (‰)	Non-accident mortality (≥30 years) (‰)
Guangzhou	9,500,000	5,200,000	5.13	7.69
Shenzhen	8,310,000	3,190,000	1.17	1.62
Zhuhai	1,430,000	770,000	3.18	4.84
Foshan	5,800,000	3,110,000	4.99	7.04
Jiangmen	4,120,000	2,420,000	5.91	10.28
Zhaoqing	3,680,000	2,000,000	4.82	11.46
Huizhou	3,710,000	1,880,000	3.95	8.72
Zhongshan	2,430,000	1,180,000	5.57	3.89
Dongguan	6,560,000	2,380,000	4.57	7.68
Hong Kong	6,650,000	5,710,000	5.17	7.77

alive in the beginning of the interval. The probability of surviving an interval was estimated as the number of people alive at the end of the interval divided by the number of people alive in the beginning of the interval. The calculation of life expectancy was based on these probability estimates (Chiang 1968; Lee 1992).

Comparing the difference of the actual life table based on actual particulate matter levels with the hypothetical life table in the case of baseline scenario, where the concentrations of particulate matter did not exceed the guideline values suggested by WHO, the potential gain in life expectancy was got. The pooled coefficients from meta-analysis results were used, assuming the same proportional hazard reduction for every age group (age≥30 years).

3 Results

3.1 Concentrations of PM in PRD, in 2006

PM exposure concentrations of areas were extracted from the observation data of monitoring stations. For the areas which had over one station, average concentrations of stations were treated as the exposure concentrations. The PM pollution level in PRD was very high and varied greatly in different areas. Throughout the year, higher daily concentrations of PM were observed from October to March.

Table 4 showed the annual concentrations of PM_{10} and $PM_{2.5}$ in PRD in 2006. Except for Guangzhou and Hong Kong, annual concentrations of $PM_{2.5}$ were converted from PM_{10}, and conversion factor 0.7 was used. The annual mean concentrations of PM_{10} and $PM_{2.5}$ were 73 and 51 μg/m^3, respectively, in PRD, much higher than the guideline values suggested by WHO. In some areas, such as Dongguan, Foshan, and Huizhou, the concentrations of PM_{10} even exceeded 100 μg/m^3 and the concentrations of $PM_{2.5}$ were higher than 80 μg/m^3. Concentrations of PM varied largely in each area. The population in PRD was unevenly distributed, either. In the central and the northeast parts of PRD, such as Foshan, Dongguan, and Huizhou, which were newly developing industrial estates, concentrations of PM_{10} and $PM_{2.5}$ were higher than those in the southeast of PRD, such as

Table 4 Annual concentrations of particulate matter in PRD, 2006 (μg/m^3)

	GZ	SZ	ZH[b]	FS	JM	ZQ	HZ	ZS	DG	HK
PM_{10}	80.6	58.6	40.5	114.8	69.6	78.2	103.0	41.0	94.4	56.4
$PM_{2.5}$	60.3	41.0[a]	28.4[a]	80.3[a]	48.7[a]	54.8[a]	71.7[a]	28.7[a]	66.1[a]	40.3

GZ Guangzhou, *SZ* Shenzhen, *ZH* Zhuhai, *FS* Foshan, *JM* Jiangmen, *ZQ* Zhaoqing, *HZ* Huizhou, *ZQ* Zhongshan, *DG* Dongguan, *HK* Hong Kong

[a] $PM_{2.5}$ concentrations converted from PM_{10}

[b] Because the Jinguowan station in Huizhou was treated as a regional station, the PM concentrations in Huizhou were only extracted from observation data of Xiapu station

Zhuhai and Zhongshan. Here, the conception of population-weighted concentration was used to elucidate this variance. The population-weighted concentration was calculated as:

$$Cpw = \sum (c_i \times p_i) \Big/ \sum p_i$$

Where Cpw is the population-weighted concentration, Ci and pi are the ambient annual concentration and population in each prefecture. The calculation results showed that the population-weighted concentrations of PM_{10} and $PM_{2.5}$ were 77 and 55 μg/m^3, respectively, in PRD, a little higher than the annual concentrations. It suggested that a large number of people were exposed to high level of PM pollution. For example, in some areas, such as Guangzhou, Dongguan, and Foshan, the concentration of particulate matter was high while the population was large too.

3.2 Exposure-Response Functions

The selected ERFs finally used in this study were pooled estimate value by the means of meta-analysis, as shown in Table 5. For short-term exposure, while the daily concentrations of PM_{10} and $PM_{2.5}$ increased 10 μg/m^3, all-course daily mortality of residents increased 0.33% (95% CI, 0.24–0.43%) and 0.42% (95% CI, 0.03–0.81%), respectively. For long-term exposure, all-course annual mortality of adults would increase 5.4% (95% CI, 2.8–7.8%) and 7.6% (95% CI, 3.6–11.6%) for 10 μg/m^3 increase in annual concentrations of PM_{10} and $PM_{2.5}$. Health effects attributable to PM pollution in terms of avoidable deaths and gain in life expectancy were calculated based on these coefficients.

For short-tem exposure, all published epidemiology studies in China from 1990–2009 were collected, and meta-analysis was used to get the exposure-response coefficients. Chinese studies reported somewhat lower exposure-response coefficients as compared with studies abroad especially in developed countries, shown in Fig. 1. In the APHEA2 project (Air pollution and Health-a European Approach), Katsouyanni et al. 2001, 2003 reported 0.6% (95% CI, 0.4–0.7%) increase in daily mortality rate per 10 μg/m^3 increase in PM_{10} daily concentrations based on data from 29 European countries. A meta-analysis study based on 33 epidemiology studies in Europe (Anderson et al. 2004) also showed 0.6% (95% CI, 0.4–0.8%) increase in mortality while PM_{10} daily concentrations increased 10 μg/m^3. A multi-city study of short-term exposure and mortality based on 20 US large cities (Daniels et al. 2000) reported 0.5% (95% CI, 0.3–0.8%) increase in mortality per 10 μg/m^3 increase in PM_{10}. Another NMMAPS (National Morbidity, Mortality, and Air Pollution Study), covering over 90 American cities, indicated a lower increase (0.1–0.4%) in mortality. Burnett et al. (2000) analyzed daily mortality counts and air pollution in nine Canada cities and got the conclusion that daily mortality would increase 0.6% (95% CI, 0.5–0.8%) for 10 μg/m^3 increase in PM_{10} daily concentrations. Meta-analysis studies or multi-city studies on $PM_{2.5}$ were also compared, shown in Fig. 1. A multi-city study based on 112 American cities (Zanobetti and Schwartz 2009) reported 1.0% (95% CI, 0.8–1.3%) increase in mortality per 10 μg/m^3 increase in $PM_{2.5}$ daily concentrations. The studies done in Canada (Burnett et al. 2000) showed 1.2% (95% CI, 0.5–2.0%) increase for $PM_{2.5}$.

For long-term exposure, there were still no cohort studies on $PM_{2.5}$ and PM_{10} in China. The only published cross-sectional study of long-term exposure and mortality, in Benxi (Jing et al. 1999), indicated 8% increase in mortality while total suspended particles (TSP) concentrations increased 100 μg/m^3. It meant 1.3% and 2% increase in mortality per 10 μg/m^3 increase in PM_{10} and $PM_{2.5}$, while the mass concentration conversion factor 0.65 was used (PM_{10}=

Table 5 Percent increase in mortality per 10 μg/m^3 increase of PM concentrations resulting from meta-analysis

	Pollutants	Subjects	Exposure-response coefficients: Mean (β)	95% Confidence interval
Short-term exposure	$PM_{2.5}$	All population	0.42	(0.03, 0.81)
	PM_{10}	All population	0.33	(0.24, 0.43)
Long-term exposure	$PM_{2.5}$	≥30 years	7.6	(3.6, 11.6)
	PM_{10}	≥30 years	5.4	(2.8, 7.8)

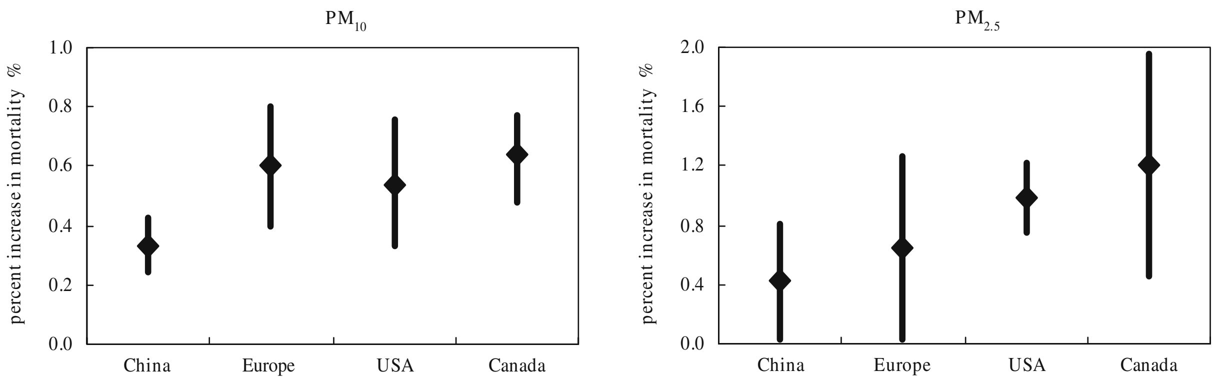

Fig. 1 Percent increase in mortality per 10 μg/m^3 increase of the concentrations of PM in different areas. *Vertical line* means 95% confidence interval. *PM_{10}* China, our study result; Europe, Anderson et al. (2004); USA, Daniels et al. (2000); and Canada, Burnett et al. (2000). *$PM_{2.5}$* China our study result; Europe, Peters et al. (2002) and Neuberger et al. (2007); USA, Zanobetti and Schwartz (2009); Canada, Burnett et al. (2000)

$TSP \times 0.65, PM_{2.5} = PM_{10} \times 0.65$). The exposure-response coefficients were lower than the two American cohort studies.

3.3 Avoidable Deaths Attributable to PM-Exposure in PRD

As shown in Figs. 1 and 2, in terms of avoidable deaths, 2,700 (95% CI, 2,200–3,400) premature deaths for PM_{10} would be prevented annually if the daily concentrations were reduced to below WHO 24-h guideline value in PRD. Areas with higher concentrations and larger populations, such as Foshan and Guangzhou had larger benefits from PM_{10} reductions. Only two areas, Guangzhou and Hong Kong, had the $PM_{2.5}$ daily concentrations data. The annual number of avoidable deaths would be 710 (95% CI, 340–1,100) in Guangzhou and 240 (95% CI, 110–370) in Hong Kong if the $PM_{2.5}$ daily concentrations were reduced to below WHO 24-h guideline value.

The assessment results of chronic effects would be much larger than acute effects. For long-term exposure, 42,000 (95% CI, 28,000–55,000) premature deaths would be prevented annually if the PM_{10} annual concentrations were reduced to below WHO annual guideline value in PRD. And for $PM_{2.5}$, the

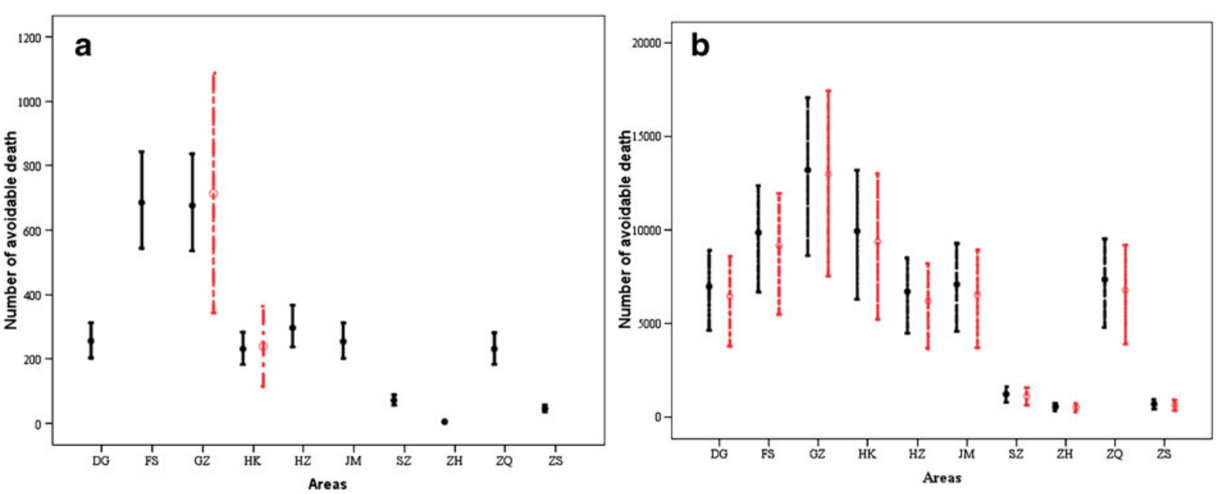

Fig. 2 Number of avoidable deaths reducing PM concentrations below WHO guideline values in PRD (95% confidence limits based on 95% CI of the exposure-response functions). *Black solid points* meant PM_{10} and *red hollow points* meant $PM_{2.5}$. **a** For short-term exposure; **b** For long-term exposure. *DG* Dongguan, *FS* Foshan, *GZ* Guangzhou, *HK* Hong Kong, *HZ* Huizhou, *JM* Jiangmen, *SZ* Shenzhen, *ZH* Zhuhai, *ZQ* Zhaoqing, *ZS* Zhongshan

annual number of avoidable deaths became 40,000 (95% CI, 23,000–54,000). The potential benefits of reducing annual PM levels also varied in different areas. In terms of premature deaths, in Guangzhou, Foshan, and Hong Kong, the benefits of reducing annual PM levels were great, whereas Shenzhen, Zhuhai, and Zhongshan showed much smaller benefits. The influence on mortality was mainly influenced by concentrations of PM, while the avoidable deaths were also influenced by the amount and deaths rate of target population. Some areas, like Guangzhou and Hong Kong, showed large numbers of avoidable deaths for a relative larger population, while the changes in mortality were not very huge. Shenzhen showed small benefits in terms of premature deaths for low death rate of population.

3.4 Gain in Life Expectancy Associated with the Reduction of PM Concentration

In Foshan, Huizhou, and Dongguan, where the PM concentrations were higher, influence on life expectancy would be larger. And in Zhuhai and Zhongshan, influence would be much lower than other areas. The average lifespan of adults in Foshan and Dongguan would prolong more than 3 years when the concentrations of PM in these areas were reduced to below WHO guideline values. But, in Zhongshan and Zhuahai, the average lifespan of adults would prolong less than 1 year.

For PM_{10} and $PM_{2.5}$, the potential gain in person-years lost would be 68,000,000 person-years in PRD if the concentrations of PM_{10} were reduced to below the value of WHO guideline. And for $PM_{2.5}$, the expected gain in person-years lost would be 63,000,000 person-years. The amount of population in PRD was about 26.49 millions, which suggested that the average lifespan in PRD would prolong 2.57 and 2.38 years for PM_{10} and $PM_{2.5}$, respectively. As shown in Fig. 3, Guangzhou and Foshan got great benefit from these reductions due to high concentrations of PM and a large population. Zhuhai and Zhongshan were influenced slightly, due to lower PM pollution levels and a smaller population.

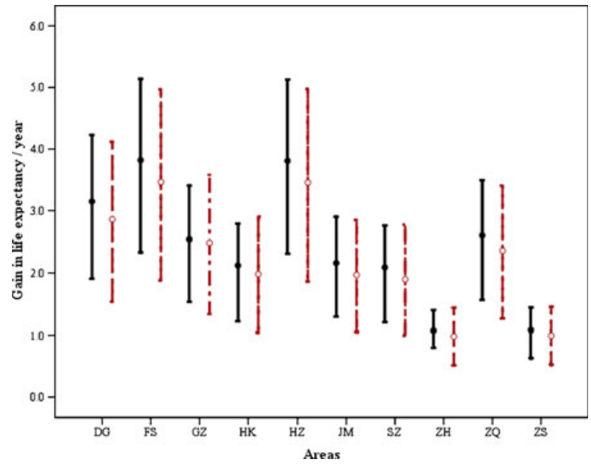

Fig. 3 Gain in life expectancy reducing PM concentrations below WHO guideline values in PRD (95% confidence limits based on 95% CI of the exposure-response functions). *Black solid points* meant PM_{10} and *red hollow points* meant $PM_{2.5}$. *DG* Dongguan, FS: Foshan; GZ: Guangzhou; HK: Hong Kong; HZ: Huizhou; JM: Jiangmen; SZ: Shenzhen; ZH: Zhuhai; ZQ: Zhaoqing; ZS: Zhongshan

4 Discussion

The health impact of exposure to particulate matter in PRD was estimated, in terms of avoidable deaths and gain in life expectancy. Results showed that both PM_{10} and $PM_{2.5}$ contributed to the total burden of mortality in PRD in a non-negligible manner. Health effects due to PM might be explained mainly by $PM_{2.5}$ exposure and coarse particles ($PM_{2.5-10}$) did not show significant association with mortality. This result was consistent with other studies (Yorifuji et al. 2005). In this study, both the acute effects and chronic effects exposure to PM pollution were assessed. Compared with other HIA estimate findings in PRD (Hedley et al. 2006), this study showed large heath impact attributed to PM_{10} pollution because long-term air pollution exposure had greater effect on human health than short-term exposure. In China, the only HIA estimate findings of long-term exposure to airborne particulate pollution (measured as TSP) done in Shanghai (Kan and Chen 2002) showed that 1.34–1.69 years reduction of life expectancy could be attributed to air particulate matter exposure. It seemed a little lower than our results. In that study, the natural background level of TSP (127 $\mu g/m^3$) in Shanghai was chosen as the reference level. Estimated studies done in Europe and America obtained less impact on life expectancy attributed to particulate matter pollution because the pollution level was not as severe as that in PRD (Boldo et al. 2006; Brunekreef 1997).

4.1 Methodological Considerations

In this study, some assumptions about exposure and extrapolation of ERFs and HIA scenarios were set. These assumptions would bring some underlying uncertainties in the assessment of reducing the PM pollution level in PRD.

Regarding exposure data, our HIA findings depended directly on the concentrations of measured particulate matter pollution. As the air pollution in PRD has been paid greater attention in recent several years, there was actually a gentle variation of PM pollution level in PRD, especially from 2004. According to the monitor data promulgated by Guangdong EPA (http://www.gdepb.gov.cn/hjzlyxx/hbzkgb/200906/t20090615_62862.html), the average annual concentrations of PM_{10} in Guangdong Province from 2005 to 2008 were 61, 62, 63, and 58 μg/m^3, respectively. And the average annual concentrations of PM_{10} in Hong Kong from 2005 to 2008 were 59, 60, 63, and 56 μg/m^3, respectively (http://www.epd-asg.gov.hk/english/report/airborne.php). Although, for long-term exposure, available exposure data was just 1 year in this study, our estimate results could elucidate the health impact of long-term exposure attributed to particulate matter in PRD. As the $PM_{2.5}$ measurement data was not available for each area, the conversion factor 0.7 was used to calculate $PM_{2.5}$ concentration from PM_{10}. The conversion factor was got from the average ratio of $PM_{2.5}$/PM_{10} of the six sites where PM_{10} and $PM_{2.5}$ were measured simultaneously. The ratio was consist well with other studies in PRD (Cao et al. 2003, 2004; Niu et al. 2006; Lai et al. 2007; Chen et al. 2008; Liu et al. 2008).

Regarding the exposure-response functions, for short-term exposure, all epidemiology studies from 1990 to 2009 in China were collected, and meta-analysis was used to get the exposure-response coefficients. Our study might be the most systematic review of Chinese epidemiological studies on PM-associated mortality effects especially for fine particles. Results from our study suggested that the exposure response relationship coefficients of PM_{10} and $PM_{2.5}$ in China were a little lower than in USA or Europe, which was consisted with other studies (Xie et al. 2009; Aunan and Pan 2004). For long-term exposure, because there were some methods defects in cross-sectional studies (such as ecological fallacy), it was not suitable to use exposure-response functions from cross-sectional studies to quantify the long-term health effects. Estimating the impact on long-term exposure to PM should be based on cohort studies, for cohort studies provide more complete assessment of the impact from exposure to air pollution. But, there were no cohort studies on PM_{10} or $PM_{2.5}$ available in China or any other developing countries. Two available and well-accepted cohort studies done in America were applied to our study. The PM pollution level in PRD was very high and in most areas, PM concentrations exceeded the range of the referential cohort studies. Although the association between the mortality and the PM pollution was not significantly different from linear associations, the shape of exposure response relationship in cohort studies (Pope et al. 2002) showed that the relative risk of per 10 μg/m^3 increase of PM concentration would decrease slowly when the exposure concentration became too high. The linear assumption about the exposure-response functions would overestimate the health effect. Different internal compositions of PM also existed between PRD and American region. For example, fine particulate mass within the PRD was dominated by organic compounds (24–35%) and sulfate (21–32%). Other important measured constituents included crustal material (7–13%), ammonium (6–8%), elemental carbon (3–8%), and nitrate (1–6%) (Hagler et al. 2006). But, in USA, fine particulate mass was mainly consisted of organic compounds (28%), sulfate (26%), nitrate (12%), and ammonium (11%; Bell et al. 2007), showing higher proportion of nitride and lower proportion of crustal material. Laden et al. (2000) examined $PM_{2.5}$ data from the Harvard Six-Cities study and got the conclusion that both the motor vehicle and coal factors were associated with mortality, with the strongest effect from the former, but the crustal material in $PM_{2.5}$ was not associated with mortality. So, the exposure response relationship coefficient applied in PRD might be a little larger than the real effect. The validity of the extrapolation of exposure response functions to our target population was also a concern, and there were few differences in socio-demographic characteristics among the target population. For example, the proportion of elder people and the proportion of smokers, including current and past smokers, were smaller in PRD. Pope et al. (2002) concluded that although differences across age and sex strata were not generally consistent or statistically significant, the relative risk estimates for both cardiopulmonary and lung cancer mortality were higher for nonsmokers. In all, exposure-response functions based on two American cohort studies might overestimate the real effect of exposure to airborne particulate matter and cohort studies on PM in China should be conducted.

The influence of other co-pollutants should be also discussed. The annual concentrations of sulfur dioxide, nitrogen dioxide, and ozone were 18, 24, and 21 ppb in PRD, in 2006. And in ACS study, the concentrations ranges were 6.7–9.7 ppb for sulfur dioxide, 21.4–27.9 ppb for nitrogen dioxide, and 45.5–59.7 ppb for ozone. It seemed that sulfur dioxide pollution was much severer, and ozone pollution was less serious. Krewski et al. (2000) completed an independent validation and reanalysis of both the Six-Cities and the ACS cohort studies and got the conclusion that the PM effects were not confounded by and were independent of effects of other pollutants. Samat et al. (2001) also got the findings that ambient $PM_{2.5}$ concentrations are suitable surrogates for personal $PM_{2.5}$ exposures and that ambient gaseous concentrations are surrogates, as opposed to confounders, of $PM_{2.5}$.Thus, other co-pollutants might not greatly influence the health effects caused by PM.

The reference exposure level was an especially sensitive parameter in our estimate model. Choosing a lower baseline, the impact of the pollution measurements would increase more. Here, the values of WHO guideline were chosen. But, the exposure concentrations of airborne particulate matter in PRD, even in China, were much higher than some other countries, especially those developed countries in Europe and North America. It would be really a hard to reduce the concentrations of particulate matter to the value of WHO guideline in PRD in a short period. In our study, the health benefits from the 10% reduction in particulate matter were also calculated. In terms of avoidable deaths, 6,600 (95% CI, 4,000–9,400) premature deaths for PM_{10} and 5,900 (95% CI, 3,100–8,800) premature deaths for $PM_{2.5}$ could be prevented annually if 10% reduction in PM annual concentrations was attained. The potential gain in person-years lost would be 8,800,000 and 8,000,000 for PM_{10} and $PM_{2.5}$, respectively, which suggested that the average lifespan of adults in PRD would prolong 0.33 and 0.30 years, respectively. An ambient standard or a guideline of $PM_{2.5}$ concentration in China would be necessary. And the ambient standard of PM_{10} needs to be revised, since the current Chinese ambient daily standard and annual standard of PM_{10} are 150 and 100 μg/m^3, which seem too high to protect human health effectively.

The actual impact of exposure to airborne particulate matter on human health in PRD might be a bit greater than the results from our study because the assessed health impact of particulate matter focused only on mortality but morbidity was not included. Although the death was the most important and notable health outcome, the amount of disease due to PM exposure could be considerable in China and other countries (Qian et al. 2004; Kappos et al. 2004; Ranzi et al. 2004). On the other hand, for long-term exposure, the impact due to PM on mortality of those under age 30 years was not estimated, while more or less health damage could be caused to the younger population, especially in the post-neonatal period (Woodruff et al. 1997).

4.2 Manage Strategies Implications

In our study, the avoidable premature deaths were calculated (shown in Figs. 1 and 2). And the expected gain in life expectancy, seen in Fig. 3, was also estimated. The potential benefits were notable if effective controls were carried out in PRD. Even though the 10% reduction in annual particulate matter concentrations was achieved, the health benefits were considerable in PRD. The benefits from reducing PM concentrations varied greatly in different prefectures. Some areas, such as Foshan, Guangzhou, and Dongguan were greatly benefited from the reductions. However, Zhuhai and Zhongshan were influenced slightly.

Note that the potential benefits were mainly influenced by the PM concentrations, the amount of population and the death rate in each prefecture. Areas, with higher concentrations of particulate matter, larger population and higher mortality, showed higher value of potential benefits. The areas like Guangzhou, Foshan, and Dongguan, where the particulate matter concentrations were very high and the amount of population was large, both avoidable deaths and expected gain in life expectancy from reduction in PM concentrations would be remarkable. The kind of areas was suggested as key-controlling areas. In these areas, the PM pollution was severer and great benefits from PM concentration reduction would be gained. Strict management controls should be carried out immediately to reduce the particulate matter levels for protecting human health. In areas like Dongguan, Jiangmen, Zhaoqing, and Huizhou, where the population was relative small, benefits were also considerable owing to high concentrations of particulate matter. Rational and effective control steps should be implemented to improve the air pollution. In areas like Shenzhen and Hong Kong, where the population was large while the particle pollution was not too severe, the impact of exposure to particulate matter was large. The kind of area was suggested as key-monitoring areas. In these areas, little reduction in particulate matter levels would bring in great benefits. Great attention should be paid to the air pollution and some controls should be made out and implemented to prevent damage to human health there. Zhuhai and Zhongshan showed relatively small benefits from the reduction, where the concentration of particulate matter was much lower and the population was smaller than other areas. Different manage strategies in different types of areas should be carried out to protect human health more effectively.

Our study only gave the potential benefits of PM concentration reductions in PRD, and the internal chemical compositions of PM might influence the particles' toxicity. Getting the chemical compositions of PM and identifying which source had the largest contribution to health impact would be also helpful to policy makers.

5 Conclusion

Our assessment led us to get such conclusions: (1) Annual mean concentrations of PM_{10} and $PM_{2.5}$ were found to reach 73 and 51 μg/m^3, respectively, in PRD. Foshan, Huizhou, and Dongguan had more severe PM pollution. Zhongshan and Zhuhai had a little slighter PM pollution. (2) From the meta-analysis results, Chinese studies reported somewhat lower exposure-response coefficients as compared with internal studies. For short-term exposure, while the daily concentrations of PM_{10} and $PM_{2.5}$ increased 10 μg/m^3, all-course daily mortality of residents increased 0.33% (95% CI, 0.24–0.43%) and 0.42% (95% CI, 0.03–0.81%), respectively. For long-term exposure, all-course annual mortality of adults would increase 5.4% (95% CI, 2.8–7.8%) and 7.6% (95%CI, 3.6–11.6%) for 10 μg/m^3 increase in annual concentrations of PM_{10} and $PM_{2.5}$, (3) In terms of avoidable deaths, for short-term exposure, 2,700 (95% CI, 2,200–3,400) premature deaths would be prevented annually if the PM_{10} daily concentrations were reduced to below WHO 24-h guideline value. Much larger benefits would be gained if the annual concentration did not exceed WHO annual guideline value in PRD. For PM_{10}, 42,000 (95% CI, 28,000–55,000) premature deaths would be prevented annually and for $PM_{2.5}$, the number of deaths avoidable would be 40,000 (95% CI, 23,000–54,000). (4) In terms of gain in life expectancy, the avoidable person-years lost of adults would be 68,000,000 and the average lifespan would prolong 2.57 years for PM_{10}. And for $PM_{2.5}$, the avoidable person-years lost would be 63,000,000 and the average lifespan would prolong 2.38 years if the annual concentrations of PM in PRD reduced to below WHO guideline values. (5) The potential benefits of reducing annual PM levels varied in different prefectures. Different manage strategies should be carried out in different types of prefectures in PRD to improve the air quality.

From our study, the reductions in concentrations of both PM_{10} and $PM_{2.5}$ would bring in remarkable health benefits, especially for long-term exposure. So, it is obligatory to set up an ambient standard or a guideline of $PM_{2.5}$, and the ambient standard of PM_{10} needs to be revised in China to protect human health more effectively.

Acknowledgements This publication supported by the National High Technology Research (863) Program of China (No. 2006AA06A309) and National Basic Research (973) Program of China (No. 2005CB422204). We should give our thanks to the Environmental Monitoring Center of Guangdong Province for providing PM_{10} and $PM_{2.5}$ data in PRD. And we also appreciate the health data provided by Hong Kong Health Department.

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