Using daily excessive concentration hours to explore the short-term mortality effects of ambient $PM_{2.5}$ in Hong Kong

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ABSTRACT

We developed a novel indicator, daily excessive concentration hours (DECH), to explore the acute mortality impacts of ambient particulate matter pollution ($PM_{2.5}$) in Hong Kong. The DECH of $PM_{2.5}$ was calculated as daily concentration-hours >25 μg/m^3. We applied a generalized additive models to quantify the association between DECH and mortality with adjustment for potential confounders. The results showed that the DECH was significantly associated with mortality. The excess mortality risk for an interquartile range (565 μg/m^3*hours) increase in DECH of $PM_{2.5}$ was 1.65% (95% CI: 1.05%, 2.26%) for all natural mortality at lag 02 day, 2.01% (95% CI: 0.82%, 3.21%) for cardiovascular mortality at lag 03 days, and 1.41% (95% CI: 0.34%, 2.49%) for respiratory mortality at lag 2 day. The associations remained consistent after adjustment for gaseous air pollutants (daily mean concentration of SO_2, NO_2 and O_3) and in alternative model specifications. When compared to the mortality burden of daily mean $PM_{2.5}$, DECH was found to be a relatively conservative indicator. This study adds to the evidence by showing that daily excessive concentration hours of $PM_{2.5}$ might be new predictor of mortality in Hong Kong.

Keywords: Excessive concentration hours; $PM_{2.5}$; Mortality; mortality burden; Hong Kong

Capsule: Excessive concentration hours of $PM_{2.5}$, as one new indicator, is significantly associated with increased mortality in Hong Kong.

1. Introduction

Associated with China's rapid social and economic development, ambient air pollution has become the fourth most significant contributor to disability adjusted life years lost (DALYs) in China, behind dietary factors, high blood pressure and tobacco smoking (Yang et al., 2013). Serious air pollution in China, specifically in urban areas like Hong Kong, has increased interest in assessing the health impacts of air pollution (Chen et al., 2013).

The previous studies mainly employed daily mean concentration to represent the exposure (Pope et al., 2006; Schwartz et al., 2017). This approach ignores the enormous variations among different hours within one day (Moreno et al., 2009). A few studies have proposed other indicators, such as daily peak concentration (Delfino et al., 2002; Lin et al., 2016a; Madsen et al., 2012). It is believed that the peak concentration may play a more important role in overwhelming certain body defense mechanisms, and may better capture the adverse effects of outdoor air pollution exposures (Delfino et al., 2002). Both approaches have their own advantages, but neither approach can adequately represent the complex exposure patterns of ambient air pollution, particularly the different exposure intensities and durations among different days even with the same daily mean concentration.

In this study, we developed a novel indicator, daily excessive concentration hours (DECH), to quantify the acute mortality effects of daily $PM_{2.5}$ in Hong Kong, China.

2. Methods

2.1 Air pollution

The hourly monitored concentrations of air pollution were retrieved from Hong Kong Environmental Protection Department between January 1, 1998 and December 31, 2011 (Qiu et al., 2012). A total of 14 stations were operated to monitor the daily concentrations of particulate matter of 10 microns in diameter or smaller (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and ozone (O_3). Hourly concentrations of $PM_{2.5}$ were only monitored in four stations (Central (CL), Tung Chung (TC), Tap Mun (TM), and Tsuen Wan (TW)) (Figure 1). The air pollution data from these four stations were used in this study. Hong Kong covers an area of 1100 km^2, however, most of the population live in the central areas of Hong Kong, which are nearby the four air monitoring stations.

We developed a new indicator, DECH of $PM_{2.5}$, which was calculated as the daily total concentration-hours >25 $\mu g/m^3$. The concentration threshold of 25 $\mu g/m^3$ was chosen according to the guideline of the World Health Organization (WHO) (World Health Organization, 2006). When calculating DECH, any overages of the threshold contributed concentration-hours to the daily total while any concentrations below the threshold did not. For instance, one hour with an hourly concentration of 26.5 $\mu g/m^3$ would contributed 1.5 concentration-hours to the daily total; while hours with the concentrations equal to or lower than 25 $\mu g/m^3$ did not contribute to the daily total.

The daily mean concentrations of ambient NO_2, SO_2 and O_3 were also calculated using the data from these four stations. Daily mean temperature ($^{\circ}C$) and relative humidity (%), were also retrieved from the Weather station of Hong Kong.

2.2 Mortality

Daily count of mortality was retrieved from the Hong Kong Census and Statistics Department over the period of 1998-2011. The causes of death were recorded in accordance with the International Classification of Diseases (ICD), the 9^{th} revision was applied for 1998-2000 and the 10^{th} revision was for 2001-2011. We constructed the daily time series for mortalities for all diseases (ICD-9: 001-799 or ICD-10: A00-R99), cardiovascular diseases (ICD-9: 390-459 or ICD-10: I00-I99) and respiratory diseases (ICD-9: 460-519 or ICD-10: J00-J99). Daily count of hospitalizations for influenza was also utilized to represent the influenza outbreaks.

2.3 Statistical analysis

We employed a generalized additive model (GAM) with a quasi-Poisson to assess the association between DECH of $PM_{2.5}$ and mortality. A penalized spline function was used to adjust the seasonal pattern and long-term trend in daily mortality and the non-linear mortality effects of the weather. The influenza outbreaks was coded as a dummy variable based on whether the weeks with the hospitalization number more than the 75^{th} percentile of a year (Qiu et al., 2012). We also coded both day of the week and public holidays as dummy variables in the model.

In line with previous air pollution time series studies, we conducted the model specification and selected the degrees of freedom (df) for smoothing functions (Peng et al., 2008). For example, we applied a df of 6 per year for temporal trends, a df of 6 for the mean temperature of the same day ($Temp_0$) and average temperature of the previous three days ($Temp_{1-3}$), and a df of 3 the relative humidity ($Humidity_0$) of the same day.

First we examined the concentration-response relationships graphically using a smoothing function. The curves showed an approximately linear relationship, we thus estimated the linear effects with across different lag days. We also investigated the mortality effects using moving averages for the same day (lag_0), previous one day (lag_{01}), two days (lag_{02}), and three days (lag_{03}). We conducted both single-pollutant and two-pollutant models to examine the associations. In the single-pollutant model, DECH of $PM_{2.5}$ was included alone in the model; while in the two-pollutant models, the daily mean contraptions of other air pollutants were included separately in the model, such as SO_2, NO_2 and O_3. However, when two pollutants had a high correlation coefficient (>0.80), they were not be included in the same model simultaneously to avoid the possible multicollinearity (Li et al., 2016b).

To compare the mortality effect of the new indicator with that of daily mean concentration, we also examined the short-term mortality effects of daily mean concentration of $PM_{2.5}$ using the same method as described above.

2.4 Mortality burden attributable to daily mean $PM_{2.5}$ and DECH

To examine the advantage of the new indicator, we compared the mortality burdens attributable to daily DECH of $PM_{2.5}$ and daily mean $PM_{2.5}$ (Li et al., 2016a). Population attributable fraction (PAF) and attributable mortality (AM) were applied (Zhu et al., 2013). The formulas were shown below:

AM= baseline mortality * [exp(β * ΔPC)

PAF= AM/overall mortality

where baseline mortality refers to daily death count at days with reference $PM_{2.5}$

concentration (or zero DECH); ΔPC represents the differences in concentrations between the measured and reference concentrations of $PM_{2.5}$ (or DECH higher than zero μg/m^3*hour); reference is zero μg/m^3*hour for DECH and 25 μg/m^3 for daily mean $PM_{2.5}$, and β represents a coefficient. The difference between the mortality burden of DECH and mean $PM_{2.5}$ was tested by calculating the 95% confidence interval as: $(b_1 - b_2) \pm 1.96 * \sqrt{(SE_1)^2 + (SE_2)^2}$, where b_1 and b_2 were the effect estimates for each variable, and SE_1 and SE_2 were the standard errors (Lin et al., 2016b).

2.5 Sensitivity analysis

The robustness of the key findings was assessed using different degrees of freedom in the smoothing functions. We used "mgcv" package in R to conduct the time series analysis.

3. Results

We obtained 496,042 deaths from all-natural causes in the study population. Among them, there were 138,067 cardiovascular disease deaths and 95,857 respiratory disease deaths. On average, there were 97 all-natural deaths per day, 27 cardiovascular deaths, and 19 respiratory death (Table 1).

There were 44 days without valid monitoring data at CL station, 456 days at TC station, 90 days at TM station, and 190 days at TW station, corresponding to 0.9%, 8.9%,1.8%, and 3.7% of the overall study period, respectively. For all the four stations, there was only one day without valid $PM_{2.5}$ concentrations. The average DECH of $PM_{2.5}$ was 370 μg/m^3*hours, the $PM_{2.5}$ daily mean was 38 μg/m^3. The daily mean concentrations of NO_2, SO_2 and O_3 were

56, 18, and 45 μg/m^3, respectively. The daily mean relative humidity and temperature were 78%. and were 24 °C.

According to the Pearson correlation (Table 2), there was a high correlation of DECH of $PM_{2.5}$ with daily mean $PM_{2.5}$ concentration (r=0.99), and moderate correlation with NO_2 (r=0.79) and SO_2 (r = 0.53). Low to moderate correlations existed between other air pollutants and weather variables.

We observed an approximately linear dose-response relationship between DECH of $PM_{2.5}$ and mortality (Figure 2). Figure 3 shows the linear associations between DECH of $PM_{2.5}$ and mortality across different lag days in models without adjustment for other air pollutants. We found significantly positive associations between DECH of $PM_{2.5}$ and all-cause mortality and cardiovascular mortality across all the lag days. For example, an interquartile range (IQR) (565 μg/m^3*hours) increase in lag_{02} DECH of $PM_{2.5}$ corresponded to a 1.65% (95% CI: 1.05%, 2.26%) increase in all-cause mortality; an IQR increase in lag_{03} DECH of $PM_{2.5}$ was associated with a 2.01% (95% CI: 0.82%, 3.21%) increase in cardiovascular mortality. While the association between DECH of $PM_{2.5}$ and respiratory mortality was only found to be statistically significant at lag 2 day, the corresponding excess risk was 1.41% (95% CI: 0.34%, 2.49%). Table 3 reports the effect estimates from two-pollutant models and the results were comparable and statistically significant.

Figure s1 illustrated the short-term mortality effects of daily mean concentrations of $PM_{2.5}$. The analysis found that daily mean $PM_{2.5}$ was also significantly associated with all-cause mortality, cardiovascular and respiratory mortality. For example, each IQR (27 μg/m^3) increase in daily mean $PM_{2.5}$ at lag_{03} corresponded to 2.13% (95% CI: 1.45%, 2.82%)

increase in all-cause mortality, 2.77% (95% CI: 1.50%, 4.05%) increase in cardiovascular mortality, and 2.07% (95% CI: 0.49%, 3.67%) increase in respiratory mortality.

Table 4 illustrates the estimated AM and PAF associated with both DECH and daily mean concentration of $PM_{2.5}$. We obtained a relatively greater mortality burden attributable to daily mean $PM_{2.5}$ than DECH of $PM_{2.5}$, though the differences were not statistically significant. Based on daily mean concentration of $PM_{2.5}$, we estimated that about 1.14% (95% CI: 0.77%, 1.51%) of all-cause mortality were attributable to higher daily $PM_{2.5}$ concentrations above 25 $\mu g/m^3$, corresponding to 5635 (95% CI: 3821, 7466) attributable deaths; and about 1.04% (95% CI: 0.62%, 1.45%) of the mortality (5142, 95% CI: 3088, 7216) could be attributed to daily DECH in $PM_{2.5}$ in the study population.

The additional analyses with varying DF for the smoothing functions produced consistent results (Table 3). All these sensitivity analyses indicated that the observed associations between DECH of $PM_{2.5}$ and all mortality categories were robust.

4. Discussion

This study developed DECH as a new exposure indicator to measure the short-term mortality impacts of ambient $PM_{2.5}$, which, to our knowledge, was the first time to do so. Using 14 years of data with about half million deaths, our analysis suggested that DECH may serve as an important health predictor of air pollutants.

We observed a high correlation between the DECH of $PM_{2.5}$ and $PM_{2.5}$ daily mean concentrations, and it was hard to exclude the possible confounding effects of daily mean concentration of $PM_{2.5}$. Though some may argue that the observed effects of DECH of $PM_{2.5}$

may possibly serve as one proxy of daily mean concentration of $PM_{2.5}$, our purpose was not to clarify that the mortality effects of daily excessive concentration hours of $PM_{2.5}$ were independent of daily mean $PM_{2.5}$. Instead, the findings of this study may suggest that the previous reported adverse health impacts of daily mean concentration of $PM_{2.5}$ might have been driven by DECH of $PM_{2.5}$. These hourly excessive concentrations should be considered in environmental policy-making to reduce the ambient $PM_{2.5}$ concentrations and in epidemiological health impact analysis (Lin et al., 2016a).

Furthermore, besides providing similar information to the daily mean $PM_{2.5}$, it was likely that the DECH of $PM_{2.5}$ represented additional independent exposure information, making it possible to serve as a new exposure indicator. In addition, the collinearity issue may exist when both $PM_{2.5}$ mean and $PM_{2.5}$ DECH were included in the same model. This could result in effect estimates in two directions, either larger or smaller, especially when several other important covariates were included in the same model.

We did an additional comparison of the mortality burden between these two variables, and observed a relatively conservative effect estimate of daily excessive concentration hours of $PM_{2.5}$. For example, about 1.04% and 1.14% of all-cause mortality was estimated to be attributable to DECH of $PM_{2.5}$ and daily mean $PM_{2.5}$, respectively. This finding may suggest that, compared with daily DECH, daily mean $PM_{2.5}$ might have over-estimated the mortality burden of $PM_{2.5}$ in the study population.

The results of our analysis indicated that days with a greater frequency and severity of higher hourly air pollution level tended to lead to higher mortality risks than those with more moderate hourly air pollution distributions in Hong Kong. The results were in agreement with

previous studies that have used daily mean concentration to examine air pollution-mortality associations (Guo et al., 2013; Lin et al., 2016c; Qiu et al., 2013). For example, a study from Shanghai reported that $PM_{2.5}$ was significantly associated with increased risk of mortality, with a corresponding excess risk for mortality of 0.36% (95% CI: 0.11%, 0.61%) for each 10 $\mu g/m^3$ increase in the daily mean concentration of $PM_{2.5}$ (Kan et al., 2007). One recent Hong Kong study demonstrated that an IQR increase in the daily mean concentration of $PM_{2.5}$ corresponded to a 1.86% (95% CI: 0.85%, 2.88%) increase in cardiovascular morbidity (Qiu et al., 2013). Our recent analysis found the excess risk of cardiovascular mortality was 6.11% (95% CI: 1.76%, 10.64%) for a 31.5 $\mu g/m^3$ increase in the daily mean concentration of $PM_{2.5}$ in Guangzhou, China (Lin et al., 2016c).

The strongest mortality effects of DECH of $PM_{2.5}$ were observed at lag 2 or 3 days' exposure and a 3-day moving average (lag_{02}). Given that the time course of human body response and subsequent mortality risk can be on the order of hours to days for late-stage reactions (Bhaskaran et al., 2011; Yorifuji et al., 2014), this result corresponded with our expectations that the mortality was acutely related to airborne particulate pollution within 3 days of exposures. We further observed slightly stronger associations with a three-day moving average than with single lag days, suggesting cumulative effects to some degree, which was consistent with previous studies (Pun et al., 2014).

A few biological mechanisms supported the observed acute mortality effects of DECH of $PM_{2.5}$. For instance, it was possible that people may inhale higher dose of the fine particles on days with higher DECH of $PM_{2.5}$, as during the hours with higher concentrations of $PM_{2.5}$, as one may inhale air with more dense particles. Another possibility might be that the higher

238 $PM_{2.5}$ exposures may adversely affect the capacity of adapting to the extremely high pollution
239 concentrations during the days with higher DECH of $PM_{2.5}$. Such adaptation capacity may be
240 adversely affected by existing cardiopulmonary conditions. One of our recent studies found
241 that daily peak concentration of $PM_{2.5}$ was significantly associated with increased mortality
242 risk among Chinese population (Lin et al., 2017), thus exposure to high concentrations above
243 the threshold (25 $\mu g/m^3$) may share similar pathways.

244 This study possessed a few advantages. Results of this study supported the necessity of
245 considering relatively higher hourly concentrations of air pollution in both environmental
246 management and air pollution epidemiology studies. Furthermore, harmful effects of air
247 pollution have been observed below the standards/guidelines set by various countries and
248 World Health Organization (WHO) (Chan et al., 2005; Moreno et al., 2009), taking the
249 findings of our study into consideration, it was possible that the effects of high air pollution
250 levels of some hours within one day might have been omitted. More specifically, though the
251 daily mean concentration attained the standards in a given day, some hours may have higher
252 concentrations than the standards, which might have been the underlying reasons for the
253 adverse health effects.

254 A few limitations should also be considered. Being an ecological study, we could not
255 establish the causal relationship. The exposure assessment based on the average of a few
256 stations might have caused non-differential exposure misclassifications, leading to an
257 under-estimation of the association. Furthermore, due to the limited observations with the
258 $PM_{2.5}$ concentrations lower than 25 $\mu g/m^3$ in the study area, making it difficult to examine the
259 health effects of the air pollution lower than the threshold and limit the ability to control for

them in the model.

5. Conclusions

In summary, this study adds to the evidence by showing that daily excessive concentration hours of $PM_{2.5}$ may work as a new predictor of mortality.

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Table 1

Basic characteristics of the daily mortality, weather variables and air pollution in Hong Kong

Variable	Observation days	Mean±SD	Percentile				
			Min	P_{25}	P_{50}	P_{75}	Max
Daily mortality							
All natural	5113	97±17	51	85	95	108	180
CVD	5113	27±7	8	22	26	31	68
Respiratory	5113	19±6	4	14	18	22	58
Air pollution ($\mu g/m^3$)							
$PM_{2.5}$ DECH	5112	370±418	1.0	25	235	590	3398
$PM_{2.5}$	5112	38±20	5.8	22	34	49	170
SO_2	5112	18±11	0.1	11	15	23	120
NO_2	5112	56±21	7.7	40	54	68	150
Ozone	5112	45±24	1.1	26	42	61	140
Weather factors							
Temperature (°C)	5113	24±5.0	8.2	20	25	28	32
Relative humidity	5113	78±10	28	73	79	85	98

Abbreviation: SD, standard deviation; P_x, xth percentile; Min, minimum; Max, maximum; CVD, cardiovascular diseases; DECH, daily excessive concentration hours.

Table 2

Correlation coefficients between daily DECH of $PM_{2.5}$, weather factors and air pollution in

Hong Kong

Pollutants	$PM_{2.5}$ DECH	$PM_{2.5}$ mean	SO_2	NO_2	O_3	Temperature
$PM_{2.5}$ mean	0.99**					
SO_2	0.53**	0.52**				
NO_2	0.79**	0.78**	0.56**			
O_3	0.55**	0.56**	-0.02	0.43		
Temperature	-0.46**	-0.46**	-0.13**	-0.50**	-0.19**	
Humidity	-0.44**	-0.45**	-0.34**	-0.40**	-0.45**	0.13**

Abbreviation: DECH, daily excessive concentration hours. **p< 0.01, * P< 0.05.

Table 3

ER in mortality for an IQR increase in daily excessive concentration hours (DECH) of $PM_{2.5}$ of lag 02 day in different models.

Model	All natural mortality	CVD mortality	Respiratory mortality
Model-single*	1.65 (1.05, 2.26)	2.01 (0.82, 3.21)	1.41 (0.34, 2.49)
Two-pollutant model			
~~With $PM_{2.5}$ mean~~	~~1.48 (0.55, 2.42)~~	~~1.84 (0.19, 3.50)~~	~~2.13 (0.06, 4.25)~~
With SO_2	1.74 (1.11, 2.38)	2.09 (0.86, 3.33)	1.42 (0.35, 2.50)
With NO_2	1.46 (0.78, 2.14)	1.81 (0.51, 3.13)	1.32 (0.24, 2.41)
With O_3	1.62 (0.96, 2.27)	1.80 (0.53, 3.09)	1.59 (0.49, 2.71)
Degree of freedom of temporal trend adjustment			
df=5/year	1.51 (0.91, 2.11)	1.95 (0.75, 3.16)	1.59 (0.52, 2.68)

df=7/year	1.54 (0.93, 2.15)	2.24 (1.05, 3.45)	1.17 (0.09, 2.25)
df=8/year	1.41 (0.81, 2.02)	1.86 (0.66, 3.08)	1.18 (0.10, 2.27)

* Results obtained from single-pollutant models.

Abbreviations: ER, excess risk; IQR, interquartile range; CVD, cardiovascular.

Table 4

The attributable fraction and attributable all natural mortality due to daily excessive concentration hours and daily mean $PM_{2.5}$ in Hong Kong during 1998-2011.

	$PM_{2.5}$ DECHs	Daily mean $PM_{2.5}$	P value
ER * (%)	1.65 (1.05, 2.26)	2.13 (1.45, 2.82)	
Attributable fraction (%)	1.04 (0.62, 1.45)	1.14 (0.77, 1.51)	>0.05
Attributable mortality	5142 (3088, 7216)	5635 (3821, 7466)	>0.05

The reference $PM_{2.5}$ concentrations were the WHO's Ambient Air Quality guidelines (25 $\mu g/m^3$). * ER is the excess risk of mortality for per IQR increase in daily excessive concentration hours of $PM_{2.5}$ (565 $\mu g/m^3$*hours) and in daily mean $PM_{2.5}$ (27 $\mu g/m^3$).

Figure legends:

Figure 1. Geographical distribution of air pollution monitoring stations in Hong Kong.

Figure 2. Exposure-response curves for daily excess concentration hours (DECH) of $PM_{2.5}$

and mortality in Hong Kong. A natural spline smoother with 3 df was applied.

Figure 3. Excess risk of mortality for per IQR increase in daily excess concentration hours (DECH) of $PM_{2.5}$ (565 μg/m^3*hours) at different lag days in single-pollutant models.