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# Daily exceedance concentration hours: A novel indicator to measure acute cardiovascular effects of $PM_{2.5}$ in six Chinese subtropical cities

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ABSTRACT

*Background:* Daily mean concentration cannot fully address the hourly variations of air pollution within one day. As such, we proposed a new indicator, daily exceedance concentration hours (DECH), to explore the acute cardiovascular effects of ambient $PM_{2.5}$ (particles with aerodynamic diameters less than 2.5 μm). The DECH in $PM_{2.5}$ was defined as daily total concentration-hours > 25 μg/m$^3$.
*Methods:* A generalized additive model with a quasi-Poisson link was applied to estimate the associations between day-to-day variation in $PM_{2.5}$ DECH and day-to-day variation in cardiovascular mortality in six subtropical cities in Guangdong Province, China.
*Results:* The analysis revealed significant associations between $PM_{2.5}$ DECHs and cardiovascular mortality. A 500 μg/m$^3$∗h increase in $PM_{2.5}$ DECHs at $lag_{03}$ was associated with an increase of 4.55% (95% confidence interval (CI): 3.59%, 5.52%) in cardiovascular mortality, 4.45% (95% CI: 2.81%, 6.12%) in ischemic cardiovascular mortality, 5.02% (95% CI: 3.41%, 6.65%) in cerebrovascular mortality, and 3.00% (95% CI: 1.13%, 4.90%) in acute myocardial infarction mortality. We further observed a greater mortality burden using $PM_{2.5}$ DECHs than daily mean $PM_{2.5}$ (6478 (95% CI: 5071, 7917) VS 5136 (95% CI: 3990, 6305)).
*Conclusion:* This study reveals that $PM_{2.5}$ DECH is one important exposure indicator of ambient $PM_{2.5}$ to measure its cardiovascular mortality effects in Pearl River Delta region; and that using daily mean concentration could under-estimate the mortality burden compared with this new indicator.

## 1. Introduction

Increasing evidence has demonstrated a consistent linkage between day-to-day variation in concentrations of ambient $PM_{2.5}$ and day-to-day variation in cardiovascular mortality (Shang et al., 2013; Lee et al., 2015; Lin et al., 2016c). A majority of these studies used daily mean concentration as the exposure metric; one concern is that daily mean concentration ignores the large variation of air pollution concentrations between different time points within one day (Yorifuji et al., 2014); a new exposure indicator might be needed to fully address the different hourly concentrations in one day.

Furthermore, previous studies have reported significant harmful health effects from ambient air pollution even when daily mean concentrations were lower than daily concentration standards/guidelines proposed by various countries and WHO (Samoli et al., 2008; Shi et al., 2015). For example, when restricting to the concentrations below 10 μg/m$^3$, one US study observed that each 10 μg/m$^3$ increase in 2-day lagged $PM_{2.5}$ was associated with 2.14% increase in mortality, and that

*Abbreviations:* DECH, daily exceedance concentration hours; $PM_{2.5}$, airborne particulate matter smaller than 2.5 μm; CI, confidence interval; PRD, Pearl River Delta; ICD, International Classification of Diseases; CVD, cardiovascular diseases; IHD, ischemic heart diseases; AMI, acute myocardial infarction; CBD, cerebrovascular diseases; WHO, World Health Organization; $NO_2$, nitrogen dioxide; $SO_2$, sulfur dioxide; $O_3$, ozone; GAM, generalized additive model; PH, public holidays; DOW, day of the week; AM, attributable mortality; PAF, population attributable fraction

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comparable effect magnitude was found when further restricting to below 6 μg/m$^3$ (Shi et al., 2015). Similarly, a great number of previous studies have reported an approximately linear concentration-response relationship between short-term $PM_{2.5}$ exposure and mortality across the entire concentration range (Kan et al., 2007; Qiu et al., 2013; Lin et al., 2016d), also indicating a significant effect in the low concentration. This, to our understanding, might be partly attributable to exceeding hourly concentrations (Lin et al., 2017b). This notion is predicated on the observation that when daily mean concentration is lower than the standard/guideline, the hourly concentrations in a given day may still exceed the reference concentration, resulting in adverse health effects (Delfino et al., 2002).

It is therefore possible that using daily mean concentration may underestimate the disease burden of air pollution. As such, one more appropriate indicator may be warranted to fully consider the exceedance hourly concentrations. We thus propose such a novel indicator, daily exceedance concentration hours (DECH), and explore in the present study the acute cardiovascular mortality effect of the new indicator in six subtropical cities of Pearl River Delta (PRD) in southern China. Further, we estimate the mortality burden attributable to exceeding hourly $PM_{2.5}$ concentrations and compare results with those using the daily mean $PM_{2.5}$. The findings from this analysis will contribute new insights to the environmental epidemiology studies on air pollution and formulation of air quality standards.

## 2. Materials and methods

### 2.1. Study area

Six subtropical Chinese cities, Guangzhou, Shenzhen, Zhuhai, Foshan, Dongguan, and Jiangmen (Table 1), were selected from PRD region in Guangdong Province (Fig. 1). These cities have a typical subtropical and monsoon climate with an annual temperature of 23 °C and an annual relative humidity of 76%; the summer is wet and hot, and the winter is dry, and cool. The characteristics of population and industrial structure are different among the six cities. As the capital city of Guangdong Province, Guangzhou is the largest city and center of economic, education, and culture in southern China with a population of 16.7 million in 2015; Shenzhen is located immediately north of Hong Kong, and is one of the fastest-growing cities in the world during the past decades partly due to the policy of "reform and opening", it has the most high-tech companies in China and has a population of 10.8 million; Zhuhai borders Macau to the south, is one of the original Special Economic Zones of China established in the 1980s, and one of China's premier tourist destinations, it has 1.6 million residents; Dongguan is a major manufacturing hub for electronics and communications equipment, has the fourth largest amount of experts among Chinese cities, and has about 8.3 million residents; Foshan, located in the central Guangdong Province, has a great number of electronical appliance factories responsible for more than half of the world's air conditioners and refrigerators, it has 7.2 million residents; and Jiangmen's economy mainly relies on manufacturing sectors, including motorcycles, household appliances, electronics, paper, food processing, synthetic fibers and garments, it has 4.5 million residents.

### 2.2. Mortality data

The daily mortality time series data were derived from the death registration system of the health department of Guangdong Province during the period between January 19, 2013 and June 30, 2015. The death certificate recorded the information of age, sex, education, and cause of death. All physicians at various levels of the health system are legally obliged to report any death on the death certificate. Data quality is ensured by standard quality assurance and quality control (Lu et al., 2007). According to the Tenth Revision of the International Classification of Diseases (ICD-10), the mortality data used in this analysis were classified into: cardiovascular diseases (CVD, ICD10: I00–I99), ischemic heart diseases (IHD, ICD10: I20–I25), acute myocardial infarction (AMI, ICD10: I21), and cerebrovascular diseases (CBD, ICD10: I60–I69).

### 2.3. Air pollution data

The hourly concentrations of ambient $PM_{2.5}$ were monitored in the six cities from January 19, 2013 through June 30, 2015. Among the six cities, varying numbers of air monitoring stations were used to regularly monitor the ambient air quality: eleven in Guangzhou and Shenzhen, four in Zhuhai and Jiangmen, eight in Foshan, and five in Dongguan. Besides $PM_{2.5}$, these air monitoring stations also regularly monitor the daily concentration of other air pollutants, including nitrogen dioxide ($NO_2$), sulfur dioxide ($SO_2$) and ozone ($O_3$). Previous studies indicated that the monitoring stations acceptably represent the general air pollution situation in these cities (Lin et al., 2016c).

The DECH in $PM_{2.5}$ was defined as daily total concentration-hours > 25 μg/m$^3$. For example, 1 h with a mean concentration of 28.5 μg/m$^3$ contributes 3.5 concentration-hours to the daily total; and hours with average concentrations of lower than 25 μg/m$^3$ (e.g., 24 μg/m$^3$) contribute zero concentration-hours to the daily total. We chose 25 μg/m$^3$ as the concentration threshold because it is proposed as the daily concentration guideline by the WHO (World Health Organization, 2006).

We also collected the daily 24-h average concentrations of various gaseous air pollutants, such as $NO_2$, $SO_2$ and $O_3$, from these air monitoring stations. During the study period, there were 35 days with missing data for $PM_{2.5}$, $SO_2$, and $NO_2$, and 53 days with missing data for $O_3$. Daily meteorological data, including mean temperature (°C) and relative humidity (%), were collected from the National Weather Data Sharing System.

### 2.4. Statistical analysis

A two-stage statistical approach was applied to estimate the

**Table 1**
Descriptive statistics of daily cardiovascular mortality, ambient $PM_{2.5}$, and mean temperature in the six Chinese cities, 2013–2015.

| City | Daily no. of deaths | | | | $PM_{2.5}$ DECHs, μg/m$^3$*h | | | Daily $PM_{2.5}$, μg/m$^3$ | Mean temperature (°C) |
|---|---|---|---|---|---|---|---|---|---|
| | CVD | IHD | CBD | AMI | Min | Mean | Max | | |
| Dongguan | 15 | 6 | 4 | 3 | 0 | 511.69 | 4025.20 | 43.82 | 22.87 |
| Foshan | 21 | 8 | 6 | 4 | 0 | 564.22 | 3763.74 | 45.89 | 21.30 |
| Guangzhou | 52 | 22 | 16 | 10 | 0 | 590.91 | 3151.88 | 47.89 | 21.66 |
| Jiangmen | 40 | 14 | 15 | 11 | 0 | 561.48 | 4340.67 | 45.43 | 22.71 |
| Shenzhen | 13 | 3 | 3 | 1 | 0 | 346.08 | 2507.28 | 35.14 | 23.20 |
| Zhuhai | 6 | 2 | 2 | 2 | 0 | 382.15 | 2802.93 | 35.57 | 23.13 |
| Overall | 25 | 9 | 8 | 5 | 0 | 493.08 | 4340.67 | 42.23 | 22.49 |

DECH, daily exceedance concentration hours; CVD, cardiovascular mortality; IHD, ischemic heart diseases; CBD, cerebrovascular diseases; AMI, acute myocardial infarction.