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Interaction Between Ambient Particles and Ozone and Its Effect on Daily Mortality[1]

GUO-HAI CHEN[*], GUI-XIANG SONG[#], LI-LI JIANG[#], YUN-HUI ZHANG[†], NAI-QING ZHAO[‡], BING-HENG CHEN[†], AND HAI-DONG KAN[†,2]

[*]Shanghai Environmental Monitoring Center, Shanghai 200030, China; [#]Shanghai Municipal Center for Disease Control and Prevention, Shanghai 200336, China; [†]Department of Environmental Health, School of Public Health, Fudan University, Shanghai 200032, China; [‡]Department of Health Statistics, School of Public Health, Fudan University, Shanghai 200032, China

Objective To examine the effect of particulate matter (PM) less than 10 microns in diameter (PM_{10}) and ozone (O_3) on daily mortality in Shanghai, China. **Methods** A generalized additive model with penalized spline function was used to observe the acute effect of PM_{10} and O_3 on daily mortality. **Results** Higher PM_{10} significantly increased the effect of O_3 on total mortality, and O_3 also increased the effect of PM_{10} although the estimated increment was statistically insignificant. **Conclusion** Our findings provide further evidence for the effect of PM_{10} and O_3 on daily mortality.

Key words: Air pollution; Mortality; Interaction; PM; Ozone

INTRODUCTION

Ambient air pollution is due to a complex mixture of particulates and gaseous pollutants. Particulate matters (PM) less than 10 microns in diameter (PM_{10}) and ozone (O_3) are two essential components generally found in ambient air pollution. Both ambient PM and O_3 are independently associated with daily mortality[1]. Recent multi-city analyses provided substantial evidence to support coherence and plausibility of their acute effect on cardio-respiratory system[2-3]. In real human life, exposure to ambient air pollution usually involves more than one pollutant, and biological responses to the inhaled pollutants likely depend on the interaction between individual pollutants[4]. For example, co-exposure to inhaled particles and O_3 causes a synergistic effect on airway responsiveness and allergic inflammation in mice[5]. Ambient concentrations of O_3 can increase the biological potency of diesel exhaust particles (DEP)[6]. Exposure to O_3 can also alter regional function and particle dosimetry in human lung[7]. Moreover, combined exposure to O_3 and dust in office air could cause significantly stronger effects than either O_3 or dust exposure alone. To our knowledge, only one time-series study has examined the combined effect of ambient PM and O_3 on mortality[8].

In the present study, we examined the effect of ambient PM_{10} and O_3 on daily mortality in Shanghai, China.

MATERIALS AND METHODS

Data

Daily mortality data (excluding accidents & injuries) of residents living in the nine urban districts of Shanghai from January 1, 2001 to December 31, 2004 were collected from the database of Shanghai Municipal Center for Disease Control and Prevention (SMCDCP). SMCDCP is a government agency in charge of health data collection in Shanghai. Similar mortality data have been used to examine the acute health effects of outdoor air pollution[9]. The death report system in Shanghai was initiated in 1951, and has been computerized since 1990. For both in-home and in-hospital deaths, physicians complete the death certificate cards. The information on the cards is then sent to SMCDCP through its internal computer network. As required by law, the database for 2001

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[2]Correspondence should be addressed to Hai-Dong KAN. Tel: 1-(919)-316-4506. Fax: 1-(919)-541-2511. E-mail: haidongkan@gmail.com

Biographical note of the first author: Guo-Hai CHEN, male, senior engineer, Shanghai Environmental Monitoring Center, majoring in air quality monitoring.

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and 2002-2004 was coded according to International Classification of Diseases, Revision 9 (ICD-9) and 10 (ICD 10), respectively. The mortality data were classified into deaths due to all non-accidental causes (ICD-9 <800; ICD-10 A00-R99), cardiovascular diseases (ICD-9 390-459; ICD-10 I00-I99) and respiratory diseases (ICD-9 460-519; ICD-10 J00-J98).

Daily data on levels of PM_{10}, SO_2, NO_2, and 8-hour averaged O_3 (from 10 AM to 6 PM) were retrieved from the database of the Shanghai Environmental Monitoring Center (SEMC). The daily concentrations for each pollutant were averaged from the available monitoring results of six fixed-field stations located in urban areas of Shanghai and covered by China National Quality Control. We abstracted the 24-hour average concentrations for PM_{10}, SO_2, NO_2, and 8-hour (from 10 AM to 6 PM) average concentration for O_3. The 8-hour time zone was used because it is the average time recommended by the World Health Organization to reflect the most health-relevant exposure to O_3.

To adjust the effect of weather conditions on mortality, meteorological data (daily minimum, maximum and mean temperature, relative humidity, and dew point temperature) from January 1, 2001 to December 31, 2004 were obtained from the database of the Shanghai Meteorological Bureau (SMB). The weather data were measured at a fixed-field station located in Xuhui District of Shanghai.

All daily mortality, pollutant and meteorological data were validated by an independent auditing team assigned by the Institute of Health Effects (IHE), a funding agency of this study. The team checked the original death certificates and monitoring records, and validated the generation progress of mortality, weather, and air pollution data used for the time-series analysis.

Statistical Methods

Since the review of daily mortality data typically follows a Poisson distribution and the relations between mortality and explanatory variables are mostly nonlinear, the core analysis was performed using a generalized additive model (GAM) with log link and Poisson error accounting for smooth fluctuations in daily mortality. We first built the basic models for mortality outcomes excluding air pollution and weather variables. We incorporated smoothed spline functions of time, which can accommodate nonlinear and non-monotonic patterns between mortality and time, offering a flexible modeling tool. Partial autocorrelation function (PACF) was used to guide the selection of *df* until the absolute values of sum of PACF for lags up to 30 reach minimum. After having established the basic models, we introduced the pollutant and weather variables and analyzed their effects on mortality outcomes.

Briefly, we fit the following log-linear GAM to obtain the estimated pollution log-relative rate β in Shanghai:

$$logE(Yt) = \beta Zt + DOW + ps(time,df) + ps(temperature,3) + ps(humidity,3) + intercept \quad [1]$$

Where $E(Y_t)$ represents the expected number of deaths on day t, β represents the log-relative rate of mortality associated with a unit increase of air pollutants, Z_t indicates the pollutant concentrations on day t, *DOW* is day of the week effect, *ps(time, df)* is the penalized spline function of calendar time, and *ps(temperature/humidity, 3)* is the penalized spline function for temperature/humidity with 3 *df*.

To examine the interaction between PM_{10} and O_3, we observed the acute effect of PM_{10} and O_3 on daily mortality. Compared with other methods to detect the interaction effect (e.g. response surface), stratified analysis uses fewer parameters and gives a simple and quantitative comparison of the estimated effects of pollutants in the various covariate strata[10]. Ninety-five percent upper and 5% lower PM_{10}/O_3 were defined as the cut-points for each strata.

All analyses were conducted in R 2.1.1 using the MGCV package.

RESULTS

From 2001 to 2004, a total of 173 911 deaths were registered in the study population. On average, there were 119.0 non-accidental deaths per day, including 44.2 due to cardiovascular diseases and 14.3 respiratory diseases. Cardiopulmonary disease accounted for 49.1% of the total non-accidental deaths among urban residents in Shanghai.

During our study period, the mean daily average concentrations of PM_{10} and O_3 were 102.0, and 63.4 $\mu g/m^3$, respectively. Meanwhile, the respective mean daily average temperature and relative humidity were 17.7℃ and 72.9%, reflecting the subtropical climate in Shanghai.

In the single-pollutant analysis which did not consider the stratified effect of co-pollutant, daily mortality was significantly associated with both PM_{10} and O_3. For example, an increase of 10 $\mu g/m^3$ of PM_{10} and O_3 corresponded to 0.23% (95% CI 0.11%-0.35%) and 0.43% (95%CI 0.15%-0.71%) increase of total mortality, respectively.

For total mortality, stratified analysis showed that the effect of both PM_{10} and O_3 generally increased in the 95% upper co-pollutant strata (Table 2). Significant interaction was observed only for O_3 in the 95% high PM_{10} strata. For cardiovascular

TABLE 1

Summary Statistics of Daily Deaths, Air Pollutant Concentrations, and Weather Conditions in Shanghai (2001-2004)

	$\bar{x} \pm s$	Min	P(25)	Median	P(75)	Max
Daily Deaths						
Total (non-accident)	119.0 ± 22.5	51.0	103.0	115.0	133.0	198.0
Cardiovascular	44.2 ± 11.0	11.0	36.0	43.0	51.0	85.0
Respiratory	14.3 ± 6.4	3.0	10.0	13.0	17.0	45.0
Air Pollutants Concentrations						
PM_{10} (μg/m^3)	102.0 ± 64.8	14.0	56.3	84.0	128.3	566.8
O_3 (μg/m^3)	63.3 ± 36.7	5.3	37.6	56.1	82.7	251.3
Meteorological Measures						
Mean Temperature (℃)	17.7 ± 8.5	−2.4	10.3	18.3	24.7	34.0
Relative Humility (%)	72.9 ± 11.4	33.3	65.5	73.5	81.0	97.0

TABLE 2

Percentage Change in Mortality Outcomes and 95% Confidence Intervals (CI) Per 10 μg/m^3 Increment in PM_{10} and O_3

		Strata*	% Change	95% CI	P Value**
Total Mortality	PM_{10}	95% Upper O_3	0.37	0.08, 0.67	0.26
		5% Lower O_3	0.24	0.00, 0.48	0.83
		5%-95% O_3	0.21	0.10, 0.33	
	O_3	95% Upper PM_{10}	0.87	0.39, 1.35	0.02***
		5% Lower PM_{10}	0.66	0.00, 1.32	0.40
		5%-95% PM_{10}	0.40	0.11, 0.68	
Cardiovascular Mortality	PM_{10}	95% Upper O_3	0.47	0.05, 0.90	0.22
		5% Lower O_3	0.14	−0.22, 0.51	0.64
		5%-95% O_3	0.22	0.05, 0.40	
	O_3	95% Upper PM_{10}	0.87	0.15, 1.59	0.18
		5% Lower PM_{10}	0.82	−0.18, 1.81	0.45
		5%-95% PM_{10}	0.46	0.04, 0.89	
Respiratory Mortality	PM_{10}	95% Upper O_3	0.21	−0.49, 0.92	0.97
		5% Lower O_3	0.34	−0.29, 0.97	0.69
		5%-95% O_3	0.22	−0.06, 0.51	
	O_3	95% Upper PM_{10}	0.41	−0.80, 1.62	0.63
		5% Lower PM_{10}	1.37	−0.32, 3.07	0.12
		5%-95% PM_{10}	0.16	−0.59, 0.92	

Note. * PM_{10}: 5% cut-point 36.6 μg/m^3, 95% cut-point 225.7 μg/m^3; O_3: 5% cut-point 36.6 μg/m^3, 95% cut-point 225.7μg/m^3. ** P value for lower and upper strata compared with 5%-95% strata. *** Statistical significant (P<0.05).

and respiratory mortality, no significant interaction was observed between PM_{10} and O_3.

DISCUSSION

Potential interaction between ambient PM and gaseous pollutants has been proposed for a long time[4,11] and is supported by several toxicological studies[5-6,12]. However, due to the high correlation between PM, SO_2 and NO_2, outcomes of the interaction analyses should be interpreted with caution. Unlike other ambient gaseous pollutants (e.g. SO_2 and NO_2), O_3 is weakly correlated with PM, which provides a good opportunity to investigate the interaction between particulates and gaseous pollutants.

Our study has shown that high levels of PM_{10} might intensify the health hazards of O_3, which is consistent with the reported data[8]. O_3 is also found to increase the effect of $PM_{10,}$ although the estimated increment is statistically insignificant. The underlying mechanisms of PM_{10}-O_3 interaction may involve physical adsorption, chemical reaction in the exposure atmosphere or on particle surface, and alternation of the pulmonary environment[4]. Gaseous pollutants can adsorb PM_{10} in the air, and consequently high concentrations of PM_{10} may carry more ambient O_3 into the airways. In addition, due to the highly oxidizing capability of O_3, this pollutant may react with some constituents present on PM which may thereafter increase the toxicity of particles[6].

Of course, the findings of the present study need to be further replicated, especially in areas with different air pollution patterns. However, if substantiated, they may have implications for the development of strategies aiming at controlling health effects of air pollution.

REFERENCES

1. Goldberg M S, Burnett R T, Stieb D (2003). A review of time-series studies used to evaluate the short-term effects of air pollution on human health. *Rev Environ Health* **18**, 269-303.
2. Bell M L, McDermott A, Zeger S L, *et al.* (2004). Ozone and short-term mortality in 95 US urban communities, 1987-2000. *JAMA* **292**, 2372-2378.
3. Samet J M, Dominici F, Curriero F C, *et al.* (2000). Fine particulate air pollution and mortality in 20 U. S. cities, 1987-1994. *N Engl J Med* **343**, 1742-1749.
4. Schlesinger R B (1995). Interaction of gaseous and particulate pollutants in the respiratory tract: mechanisms and modulators. *Toxicology* **105**, 315-325.
5. Kobzik L, Goldsmith C A, Ning Y Y, *et al.* (2001). Effects of combined ozone and air pollution particle exposure in mice. *Res Rep Health Eff Inst* **106**, 5-29.
6. Madden M C, Richards J H, Dailey L A, *et al.* (2000). Effect of ozone on diesel exhaust particle toxicity in rat lung. *Toxicol Appl Pharmacol* **168**, 140-148.
7. Foster W M, Silver J A, Groth M L (1993). Exposure to ozone alters regional function and particle dosimetry in the human lung. *J Appl Physiol* **75**, 1938-1945.
8. Ponka A, Savela M, Virtanen M (1998). Mortality and air pollution in Helsinki. *Arch Environ Health* **53**, 281-286.
9. Zhang Y, Huang W, London S J, *et al.* (2006). Ozone and daily mortality in Shanghai, China. *Environ Health Perspect* **114**, 1227-1232.
10. Roberts S (2004). Interactions between particulate air pollution and temperature in air pollution mortality time series studies. *Environ Res* **96**, 328-337.
11. Pierson W E (1992). System interactions of air pollutants. *Otolaryngol Head Neck Surg* **106**, 733-735.
12. Goldsmith C A, Ning Y, Qin G, *et al*. (2002). Combined air pollution particle and ozone exposure increases airway responsiveness in mice. *Inhal Toxicol* **14**, 325-347.

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