Original Contribution

Short-Term Associations of Cause-Specific Emergency Hospitalizations and Particulate Matter Chemical Components in Hong Kong

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Initially submitted August 16, 2013; accepted for publication January 24, 2014.

Despite an increasing number of recent studies, the overall epidemiologic evidence associating specific particulate matter chemical components with health outcomes has been mixed. The links between components and hospitalizations have rarely been examined in Asia. We estimated associations between exposures to 18 chemical components of particulate matter with aerodynamic diameter less than 10 μm (PM10) and daily emergency cardiorespiratory hospitalizations in Hong Kong, China, between 2001 and 2007. Carbonaceous particulate matter, sulfate, nitrate, and ammonium accounted for two-thirds of the PM10 mass. After adjustment for time-varying confounders, a 3.4-μg/m³ increment in 2-day moving average of same-day and previous-day nitrate concentrations was associated with the largest increase of 1.32% (95% confidence interval: 0.73, 1.92) in cardiovascular hospitalizations; elevation in manganese level (0.02 μg/m³) was linked to a 0.91% (95% confidence interval: 0.19, 1.64) increase in respiratory hospitalizations. Upon further adjustment for gaseous copollutants, nitrate, sodium ion, chloride ion, magnesium, and nickel remained significantly associated with cardiovascular hospitalizations, whereas sodium ion, aluminum, and magnesium, components abundantly found in coarser PM10, were associated with respiratory hospitalizations. Most positive links were seen during the cold season. These findings lend support to the growing body of literature concerning the health associations of particulate matter composition and provide important insight into the differential health risks of components found in fine and coarse modes of PM10.

Particulate matter pollution has been the most widespread health threat among the criteria air pollutants. Assessments of most particulate matter–health associations have largely focused on the ambient concentration of total mass (weight) of particulate matter with aerodynamic diameter less than 10 μm (PM10) and particulate matter with aerodynamic diameter less than 2.5 μm (PM2.5). However, significant heterogeneity in risk estimates suggests that the aspect of particulate matter most harmful to health may not be best quantified by mass measurement alone. Particulate matter is a complex mixture of numerous components (i.e., chemical species) (1). The predominant components are sulfate, nitrate, ammonium, sea salt, mineral dust, organic compounds, and black or elemental carbon, each making up about 10%–30% of the overall mass load (2). Because not all particulate matter is the same, the ultimate goal is to identify the components and sources most directly responsible for adverse health effects to allow for more targeted regulations (3, 4).

As large-scale data collection on particulate matter chemical composition began in the past decade, researchers have been able to investigate associations between acute exposure to particulate matter components and death and nonfatal health outcomes. Although early air pollution studies conducted in Western countries identified evidence of adverse health effects of carbonaceous species (i.e., elemental and organic carbon) and nickel (5–10), the overall epidemiologic
findings linking particulate matter components to health risks remain mixed (11). Similarly, no consensus has been found in Asian epidemiologic studies regarding the health effects of specific particulate matter components. Two recent studies conducted in Xi’an, China, reported a positive association between PM$_{2.5}$ components originating from fossil fuel combustion (e.g., elemental carbon) and daily cardiorespiratory mortality risk, especially during cold seasons (12, 13). A Shanghai, China, study linked elevations in the black carbon level to increases in total and cardiovascular mortality risk after adjustment for PM$_{2.5}$ mass, but found no association with respiratory mortality risk (14); Korean researchers found significant associations of total and daily cardiovascular mortality risk with only magnesium and ammonium at the $P < 0.05$ level and not with the other components they examined (15). Particulate matter composition, and thus its toxicity, varies temporally and geographically depending upon the city-specific sources of origin (e.g., local or regional emissions) and interactions between sources, meteorological conditions, and other time-varying factors. Hence, more composition studies under different atmospheres are needed to enhance our understanding of particulate matter–related health effects.

Hong Kong is a coastal urban city on the boundary region of the Asian continent and the Pacific Ocean. Its air pollution levels often exceed the recommended quality guidelines of the World Health Organization (Geneva, Switzerland), posing a serious public health threat. Although 2 decades of active air pollution research have associated particulate matter mass with elevated daily risk of death (16, 17) and emergency hospital admissions in Hong Kong (18–21), individual particulate matter chemical components and sources responsible for adverse health effects have rarely been examined. In Hong Kong, particulate matter components originate from several major emission sources, such as motor vehicles, soil and road dust, and polluted sea salt, as well as industrial and agricultural combustion from the adjacent Pearl River Delta region (22). In this study, we used the PM$_{10}$ composition data that have been measured consecutively for more than a decade to estimate the associations between chemical components and daily cardiorespiratory emergency hospital admissions.

**METHODS**

**Data**

Between January 1, 2001, and December 31, 2007, the Hong Kong Environmental Protection Department collected 24-hour filter samples of PM$_{10}$ at 6 general air quality monitoring stations (Figure 1). These stations cover urban areas with different land uses (e.g., residential, commercial, industrial, and a mix of these), new towns, and rural areas in Hong Kong, and they capture the air quality to which the general population is exposed on a regular basis (23). Twenty-six PM$_{10}$ chemical components were speciated from the samples via various analytical methods as reported elsewhere (22). Upon exclusion of contaminated components and those that had more than 25% of samples below the method’s detection limit or that had more than 25% of missing samples, we included station-specific measurements of 18 PM$_{10}$ components. They were elemental carbon, organic carbon, nitrate, sulfate, ammonium ion, chloride ion, sodium ion, potassium ion, aluminum, arsenic, calcium, cadmium, iron, magnesium, manganese, nickel, lead, and vanadium. Measurements of organic carbon were converted to those of organic matter by multiplying by a factor of 1.6 (24). To adjust for copollutants and meteorological conditions, we calculated daily mean concentrations of nitrogen dioxide and sulfur dioxide, as well as PM$_{10}$ mass and 8-hour mean concentration of ozone from hourly tapered element oscillating microbalance air pollutant data collected at the same monitoring stations; we obtained daily mean temperature and relative humidity data from the Hong Kong Observatory for the same study period.

We acquired from the Hong Kong Hospital Authority daily counts of emergency hospital admissions into publicly funded hospitals between January 1, 2001, and December 31, 2007. These hospitals provide 24-hour accident and emergency services and represent 90% of the hospital beds that serve Hong Kong residents (Figure 1) (19). We considered hospitalizations for all cardiovascular causes (International Classification of Diseases, Ninth Revision, codes 390–459) and respiratory causes (International Classification of Diseases, Ninth Revision, codes 460–519). Hospitalizations due to influenza (International Classification of Diseases, Ninth Revision, code 487) were excluded from the respiratory category and treated as a potential confounder in the data analysis.

**Statistical analysis**

Because each monitoring station collected PM$_{10}$ samples, on average, every sixth day on a distinct sampling schedule, there might have been samples taken simultaneously from multiple stations or only a single station, or there might have been no samples taken from any stations on a particular day. Collectively, 71% of the study days were covered by measurements from at least 1 station. To compute the territory-wide mean concentrations of PM$_{10}$ components, we applied a centering method to remove the station-specific influence on the measurements of each component by 1) calculating the annual mean ($X_i$) for each monitoring station $i$; 2) subtracting the annual mean from the daily mean concentration for station $i$ on each sample day $j$ ($X_{ij}$); 3) adding the annual mean of all stations ($X$) to the resulting centered values ($X_{ij} - X$) for each station and sampling day to produce $X_{ij}^0 = X_{ij} - X_i + X$; and 4) taking the average of $X_{ij}^0$ over all stations (25). The final PM$_{10}$ exposure time series contained nonmissing territory-wide mean concentrations of 18 chemical components for 1,805 days over the 7-year study period (71%), which is equivalent to data for 5 days a week. All pollutant concentrations are expressed in μg/m$^3$ except for elemental carbon and organic matter, which are reported in μg carbon/m$^3$.

We applied generalized additive models with autoregressive terms to estimate associations between PM$_{10}$ chemical components and cause-specific emergency hospital admissions (26). Smoothing splines with 8 degrees of freedom per year for time trend, 6 degrees of freedom for current-day temperature and previous 3-day moving average, and 3 degrees of freedom for current-day relative humidity and previous 3-day moving average were adopted a priori to minimize
problems associated with multiple testing and core model selection strategies (5, 27). We also adjusted for day of week, public holidays, and influenza epidemics (16).

We first used single-pollutant models to examine associations of emergency hospitalization with exposure to individual PM$_{10}$ components on the same day (lag0) and for single-day exposure on the previous 1–3 days (lag$_1$ to lag$_3$) while adjusting for time-varying confounders. Then, we focused mainly on exposure to a 2-day moving average of same-day and previous-day pollutant concentrations (lag$_{01}$) as a priori lag structure based on previous Hong Kong studies (16, 17). To further control for potential confounding effects of gaseous copollutants, we constructed multipollutant models to investigate the independent associations between PM$_{10}$ components and emergency hospitalizations in the presence of nitrogen dioxide, sulfur dioxide, and ozone. We evaluated additional multipollutant models in which we also adjusted for PM$_{10}$ mass. Pearson’s correlations were used to summarize the relationships between air pollutants. Moreover, we conducted separate analyses for warm seasons (May–October) and cold seasons (November–April) with 4 degrees of freedom per year for time trend per season (11). For sensitivity analysis, we reanalyzed the time-series models after either imputing the missing component concentrations for the days without any samples (751 days) by linear interpolation using the na.approx function in the R zoo package (28) or replacing the missing data with nonmissing measurement values from the previous day. Risk estimates were reported as the percent increase [(relative risk – 1) × 100%] in daily emergency hospital admissions for an interquartile-range increment in air pollution concentrations. Where appropriate, 95% confidence intervals and 2-sided $P$ values are reported. We performed time-series analyses using the gam function in the R mgcv package (29).

RESULTS

Over the 7-year study period, we identified 400,011 cardiovascular and 587,422 respiratory emergency hospital admissions in Hong Kong, which are equivalent to 157 (standard deviation, 24) and 230 (standard deviation, 49)
admissions per day, respectively (Table 1). The mean daily average temperature and relative humidity were 23.6°C and 78.3%, respectively. The daily mean concentration for PM$_{10}$ was 55.9 μg/m$^3$, with organic matter, sulfate, nitrate, elemental carbon, and ammonium ion accounting for 23.8%, 20.6%, 6.6%, 6.5%, and 5.9% of the overall particulate matter mass, respectively. These major components were moderately to highly correlated with nitrogen dioxide ($r = 0.61$–0.80) and nil to mildly correlated with sulfur dioxide and ozone (Web Table 1 available at http://aje.oxfordjournals.org/). Moderate to strong correlations were also seen between many components (e.g., $r = 0.76$ for nickel and vanadium; $r = 0.93$ for sulfate and ammonium ion). The majority of PM$_{10}$ components had consistently higher concentrations during the cold season (data not shown).

The single-pollutant models of single-day exposure lags exhibited similar patterns of associations as those from previous studies in which the risk estimates of PM$_{10}$ components varied by lag structures and health outcomes (Figure 2). We observed the largest significant associations of PM$_{10}$ mass (per 44.3 μg/m$^3$) with emergency hospitalizations for cardiovascular causes at lag0 (1.53%, 95% confidence interval (CI): 0.68, 2.38; Figure 2A) and with hospitalizations for respiratory causes at lag1 (0.95%, 95% CI: 0.22, 1.68; Figure 2B). Elemental carbon, organic matter, nitrate, potassium ion, iron, manganese, nickel, lead, and vanadium demonstrated significant links with cardiovascular hospitalizations in more than half of the lags examined, whereas only magnesium and manganese were significantly associated with respiratory hospitalizations at 2 lags (i.e., lag0 and lag1).

### Table 1. Summary Statistics of Emergency Hospital Admissions, Meteorological Measurements, and Concentrations of PM$_{10}$ and Its Components in Hong Kong, China, 2001–2007

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daily Mean (SD)</th>
<th>Minimum</th>
<th>Maximum</th>
<th>IQR</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of emergency hospital admissions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiovascular</td>
<td>157 (24)</td>
<td>66</td>
<td>243</td>
<td>30</td>
</tr>
<tr>
<td>Respiratory</td>
<td>220 (49)</td>
<td>89</td>
<td>518</td>
<td>61</td>
</tr>
<tr>
<td>Meteorological conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>23.6 (4.9)</td>
<td>8.2</td>
<td>31.8</td>
<td>8.1</td>
</tr>
<tr>
<td>Relative humidity, %</td>
<td>78.3 (9.9)</td>
<td>31.3</td>
<td>98.1</td>
<td>11.4</td>
</tr>
<tr>
<td>Pollutant concentration, μg/m$^3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen dioxide</td>
<td>59.4 (22.3)</td>
<td>14.3</td>
<td>171.3</td>
<td>29.2</td>
</tr>
<tr>
<td>Sulfur dioxide</td>
<td>21.7 (15.1)</td>
<td>2.8</td>
<td>138.5</td>
<td>13.3</td>
</tr>
<tr>
<td>Ozone</td>
<td>42.9 (28.6)</td>
<td>2.9</td>
<td>206.5</td>
<td>36.2</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>55.9 (32.5)</td>
<td>3.5</td>
<td>296.3</td>
<td>44.3</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.3 (0.3)</td>
<td>−0.1</td>
<td>2.9</td>
<td>0.3</td>
</tr>
<tr>
<td>Ammonium</td>
<td>3.3 (2.8)</td>
<td>−0.5</td>
<td>22.8</td>
<td>3.6</td>
</tr>
<tr>
<td>Arsenic</td>
<td>0.006 (0.007)</td>
<td>0.0</td>
<td>0.07</td>
<td>0.01</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.002 (0.003)</td>
<td>0.0</td>
<td>0.08</td>
<td>0.002</td>
</tr>
<tr>
<td>Calcium</td>
<td>0.8 (0.6)</td>
<td>−0.1</td>
<td>6.2</td>
<td>0.6</td>
</tr>
<tr>
<td>Chloride ion</td>
<td>0.9 (1.1)</td>
<td>−0.4</td>
<td>11.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Elemental carbon</td>
<td>3.7 (1.6)</td>
<td>0.6</td>
<td>21.6</td>
<td>1.8</td>
</tr>
<tr>
<td>Iron</td>
<td>0.6 (0.4)</td>
<td>0.0</td>
<td>3.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Lead</td>
<td>0.07 (0.07)</td>
<td>0.0</td>
<td>1.0</td>
<td>0.09</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.3 (0.2)</td>
<td>0.0</td>
<td>1.9</td>
<td>0.2</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.02 (0.02)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.007 (0.006)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.005</td>
</tr>
<tr>
<td>Nitrate</td>
<td>3.7 (3.3)</td>
<td>−0.4</td>
<td>36.8</td>
<td>3.4</td>
</tr>
<tr>
<td>Organic matter</td>
<td>13.3 (8.8)</td>
<td>0.5</td>
<td>69.2</td>
<td>11.1</td>
</tr>
<tr>
<td>Potassium ion</td>
<td>0.6 (0.6)</td>
<td>0.0</td>
<td>5.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Sodium ion</td>
<td>1.5 (1.0)</td>
<td>−0.1</td>
<td>8.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Sulfate</td>
<td>11.5 (7.5)</td>
<td>0.8</td>
<td>63.6</td>
<td>9.8</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.01 (0.01)</td>
<td>0.0</td>
<td>0.1</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Abbreviations: IQR, interquartile range; PM$_{10}$, particles with aerodynamic diameter less than 10 μm; SD, standard deviation.

* Over the 7-year study period, there were 2,556 (100%) days of complete emergency hospitalization, meteorological, and gaseous pollutant data and 1,805 (71%) days of nonmissing data for PM$_{10}$ mass and its 18 chemical components.
Figures 3A and 3B show the cause-specific risk estimates at lag01 exposure based on single-pollutant models. A 3.4-μg/m³ increment in nitrate concentration was associated with the largest significant increase of 1.32% (95% CI: 0.73, 1.92) in cardiovascular hospitalizations at lag01, followed by interquartile range–increment in organic matter level (1.09%, 95% CI: 0.39, 1.81; Figure 3A). Positive associations were also observed for elemental carbon, nickel, lead, iron, manganese, and most ions (sodium ion, potassium ion, and chloride ion), which corresponded to 0.41%–0.90% increases in cardiovascular hospitalizations. In contrast, fewer significant associations with respiratory hospitalizations were found (Figure 3B). Elevation in manganese level (per 0.02 μg/m³) was associated with a 0.91% (95% CI: 0.19, 1.64) increase in respiratory hospitalizations, followed by interquartile range–increment in sodium ion, magnesium, aluminum, and sulfate levels (0.63%–0.77% increases in hospitalizations). No risk estimates were sensitive to alternative regression models in which we imputed missing data (data not shown).

Figures 3C and 3D show that most of the positive associations, which were statistically significant based on single-pollutant models, diminished in multipollutant models in which we simultaneously controlled for nitrogen dioxide, sulfur dioxide, and ozone, in addition to adjusting for time-varying (e.g., seasonal) confounders. The cardiovascular admission risks of nitrate (1.03%, 95% CI: 0.38, 1.67) and nickel (0.49%, 95% CI: 0.001, 0.97) were slightly attenuated in the presence of gaseous copollutants, whereas the associations of sodium ion (1.09%, 95% CI: 0.46, 1.73), chloride...
ion (0.58%, 95% CI: 0.24, 0.92), and magnesium (0.6%, 95% CI: 0.1, 1.09) were stronger based on the multipollutant models compared with the single-pollutant models (Figure 3C). In addition, only sodium ion (0.65%, 95% CI: 0.11, 1.19), aluminum (0.56%, 95% CI: 0.02, 1.1), and magnesium (0.63%, 95% CI: 0.21, 1.04) remained significantly associated with respiratory hospitalizations after adjustment for gaseous copollutants (Figure 3D). Further adjustment for PM$_{10}$ mass in the multipollutant models did not substantially change the regression results (data not shown). Table 2 shows that sodium ion and chloride ion were associated with cardiorespiratory hospitalizations in the cold season. In the cold season, nickel was significantly associated with cardiovascular hospitalizations, and aluminum and magnesium were significantly associated with respiratory hospitalizations. For nitrate, a significant association with cardiovascular hospitalizations was seen in the warm season.

**DISCUSSION**

The majority of recent epidemiologic studies of particulate matter pollution and health have been based on PM$_{2.5}$ mass and its composition because PM$_{2.5}$ is often presumed to be more relevant as an exposure indicator than larger particles (i.e., PM$_{10}$). However, because of the complex physicochemical properties of particulate matter at different size fractions, the physiopathological mechanism underlying adverse health effects has yet to be fully understood (30). Thus, the contribution of larger particles to poor health should be further investigated. Our study is one of the few that has focused on exposure to PM$_{10}$ components. In contrast to a previous London, United Kingdom, study that also examined the link between health and various PM$_{10}$ components but found evidence of an association of only nitrate and sulfate with respiratory admissions (31), we observed positive associations between multiple PM$_{10}$ components and emergency hospitalizations for cardiorespiratory causes in Hong Kong at the various lags examined.

We found that combustion-related particles (i.e., elemental carbon, organic matter, nitrate, potassium ion, iron, manganese, nickel, and lead) were associated with elevated cardiovascular hospitalizations, and sulfate was associated with respiratory hospitalizations based on single-pollutant models. These components reflect the major combustion sources in Hong Kong, which are local gasoline and diesel vehicle exhausts, residual oils from marine vessels, and regional industrial and agricultural combustion (22). Our findings are in accord with those of studies previously reporting evidence of adverse effects of PM$_{2.5}$ components from combustion of coal and heavy oil on mortality risk and hospital admissions (5, 6, 8, 32–34). We took a step further to adjust for gaseous copollutants and found that most of the significant associations diminished, suggesting possible confounding effects. This is consistent with previous Hong Kong studies showing that the addition of nitrogen dioxide and sulfur dioxide reduced the magnitude and statistical significance of PM$_{10}$ associations (16, 25). Burnett et al. (35) also reported the diminishment of particle mass and sulfate associations with cardiorespiratory hospitalizations in Toronto, Canada, after simultaneously adjusting for gaseous pollutants. Conversely, Cao et al. (12) showed that the inclusion of nitrogen dioxide and sulfur dioxide did not mask the positive association between combustion-related particles and mortality risk in Xi’an, China. Because most existing studies have relied on single-pollutant models, the potential confounding effect of gaseous pollutants on associations between particulate matter components and health should be investigated further.

Our analysis showed that the associations of nitrate and nickel with cardiovascular hospitalizations remained significant after controlling for gaseous copollutants. Current epidemiologic evidence on the health risks of nitrate has been conflicting. Most studies that have examined the associations of nitrate have found no link with cardiovascular hospitalizations (27, 31, 32) and death (13, 15, 36), whereas 2 studies conducted in London, United Kingdom, and California suggested nitrate to be more important for respiratory than for cardiovascular hospitalizations (31, 33). Nitrate is acidic in nature. Although there has been no convincing animal toxicologic evidence of nitrate effects at ambient levels, it is hypothesized that acidic aerosols may lower the pH within the airways by depositing hydrogen ions, thereby triggering adverse reactions (37, 38). Nitrate can be found in both fine and coarse particles (Web Figure 1). In Hong Kong, nitrogen oxides emitted from power plants, industry, and motor vehicles both locally and from the adjacent Pearl River Delta region generate most of the finer-mode nitrate through oxidation (39). When maritime and polluted urban air masses mix together, coarse-mode nitrate can also be formed through the reaction of nitric acid with sodium chloride (40, 41). In contrast, nickel is found almost exclusively in the fine mode of PM$_{10}$ (i.e., PM$_{2.5}$), and it serves as an index of heavy oil combustion from marine vessels in coastal cities like Hong Kong. Our observed nickel association is in agreement with another recent Hong Kong study that showed better nickel correspondence than vanadium correspondence to cardiovascular hospitalization (42), as well as with other PM$_{2.5}$ composition studies reported in Xi’an, China, and the United States (5–7, 12).

Sodium ion and chloride ion are considered signature elements for sea salt particles in coastal areas, and magnesium is related to sea salt, as well (22). In Hong Kong, 16% of PM$_{10}$ mass originated from sea salts, which is much higher than the 9% reported in studies conducted in Barcelona, Spain, and Copenhagen, Denmark (22, 43, 44). Mar et al. (45) reported that sea salt was consistently linked to increased cardiovascular and total mortality risk in Atlanta, Georgia, whereas Andersen et al. (44) did not associate sea salt with hospital admissions among children or the elderly in Copenhagen. These components are most abundantly found in the coarser mode of PM$_{10}$. In our study, sodium ion, chloride ion, and magnesium remained significantly associated with cardiovascular hospitalizations after adjustment for gaseous copollutants; risk estimates of sodium ion and magnesium were also robust for respiratory hospitalizations. Most studies did not link sodium to adverse health (8, 11, 12, 15, 27) except for 2 studies conducted in New York, New York, and 26 US communities (6, 7). Epidemiologic evidence of the impact of chloride has been highly mixed (8, 12, 13, 15, 34, 36, 46), and evidence on magnesium has been more scarce. Only 1 Korean study has associated magnesium in PM$_{2.5}$ with respiratory death (15). The heterogeneity in findings may arise

Am J Epidemiol. 2014;179(9):1086–1095
from the use of PM$_{2.5}$ composition instead of PM$_{10}$ composition, which also comprises larger crustal materials. Besides originating from sea salt, sodium and chloride can be generated from combustion emissions from coal, vehicles, and smelters, and magnesium can be generated from soil and/or road dust (1, 15, 47).

We observed a significant association of aluminum with respiratory hospitalizations after controlling for gaseous copollutants. Aluminum is found most abundantly in the coarser mode of PM$_{10}$. It is classified as crustal material derived from exposed soil, unpaved roads, and construction activities and is moderately correlated with magnesium (22). Several studies showed significant links between soil and/or road dust and adverse health outcomes (8, 43, 44, 48–50), whereas some did not (45, 51–54). Overall, epidemiologic studies on aluminum are limited.

Our findings add to those previously reported in several ways. First, this is one of the few studies that has focused on exposure to PM$_{10}$ components, whereas the majority of epidemiologic studies have been based on PM$_{2.5}$ components. Unlike cities where PM$_{2.5}$ composition data are measured in consecutive years, PM$_{2.5}$ chemical components in Hong Kong were measured only every sixth day for 3 nonconsecutive years. Hence, the data are sparse, and time-series analyses have limited statistical power to assess the associations between PM$_{2.5}$ components and health outcomes. The application of PM$_{10}$ composition data allowed us to detect adverse health associations of not only components that are in the fine mode, but also those that have substantial fractions in the coarser mode of PM$_{10}$. Second, we conducted the first Asian study to investigate the links between particulate matter components and emergency hospital admissions with adjustment for gaseous copollutants, whereas all other Asian studies of this sort focused on mortality risk. Emergency hospital admissions were unplanned and unscheduled admissions, which could be more sensitive to environmental effects than overall hospitalizations and mortality risk (20). Third, with nearly 1 million emergency hospitalizations over 7 years, our study was well powered to detect statistically significant associations.

We acknowledge the limitations of the study, including the every-sixth-day sampling scheme for the PM$_{10}$ composition analysis. Exposure misclassification error might exist, though the risk estimates were insensitive to alternative interpolation methods. Our findings of the associations of PM$_{10}$ components with hospitalizations should be interpreted with caution for several reasons. First, measurement error cannot be eliminated from our study. Components with very low ambient concentrations (e.g., cadmium) might be subject to more instrument or laboratory errors. Likewise, components from local sources (e.g., elemental carbon from traffic) might be subject to more error than those regionally transported, given their higher spatial heterogeneity (55). Components with large measurement errors may have smaller regression estimates and lower

Figure 3 continues
Table 2. Percent Change in Emergency Hospital Admissions per Interquartile Range Increment in PM$_{10}$ and Chemical Components at lag01 by Season$^a$, Adjusted for Meteorological Factors, Seasonal and Temporal Trend, Day of Week, Influenza Epidemic, and Gaseous Copollutants$^b$, Hong Kong, China, 2001–2007

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Cardiovascular Admissions</th>
<th>Respiratory Admissions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Warm Season</td>
<td>95% CI</td>
</tr>
<tr>
<td>PM$_{10}$</td>
<td>0.91</td>
<td>-0.69, 2.54</td>
</tr>
<tr>
<td>Nitrate</td>
<td>0.78</td>
<td>0.13, 1.43</td>
</tr>
<tr>
<td>Sodium ion</td>
<td>0.25</td>
<td>0.13, 1.43</td>
</tr>
<tr>
<td>Chloride ion</td>
<td>0.19</td>
<td>-0.18, 0.55</td>
</tr>
<tr>
<td>Aluminum</td>
<td>0.35</td>
<td>-0.78, 1.50</td>
</tr>
<tr>
<td>Magnesium</td>
<td>0.43</td>
<td>-0.4, 1.26</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.19</td>
<td>-0.37, 0.75</td>
</tr>
</tbody>
</table>

Abbreviations: CI, confidence interval; PM$_{10}$, particles with aerodynamic diameter less than 10 μm.

$^a$ Warm season, May–October; cold season, November–April.

$^b$ Gaseous pollutants include nitrogen dioxide, sulfur dioxide, and ozone.

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statistical significance (56). The issue of representativeness associated with particulate matter components may hinder the interpretations of the relative strength of the observed associations in monitor-based studies of ambient particulate matter composition. Second, we did not adjust for exposure to multiple components in the regression models because of the moderate to strong correlations among PM\textsubscript{10} components. It is possible that the chosen PM\textsubscript{10} component is responsible for the observed risk estimates, or the association could be due to the component’s correlation with another component that is the true toxic agent, or multiple components could be jointly responsible. Finally, we did not directly measure coarse particulate matter (i.e., PM\textsubscript{2.5–10}) composition, nor did we have a long enough period of PM\textsubscript{2.5} composition data to subtract coarse particulate matter from PM\textsubscript{10} composition measurements. Thus, we cannot assess the health effects of chemical components in coarse particulate matter.

In summary, we found evidence that combustion-related particles (i.e., nitrate and nickel), sea salt-related particles (i.e., sodium ion, chloride ion, and magnesium), and particles related to soil/road dust (i.e., aluminum) were significantly associated with cause-specific emergency hospital admissions in Hong Kong in the presence of gaseous copollutants, particularly during the cold season. This study lends support to the growing body of literature concerning the adverse effects of chemical components in coarse particulate matter.

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This work was supported by the Environmental Conservation Fund (project ECF 35/2010) and the Health and Medical Research Fund (grant 11120311).

We thank the Environmental Protection Department of the Hong Kong Special Administrative Region for supplying the air monitoring data; the Hospital Authority for the hospital admission data; and the Hong Kong Observatory for the weather data for this study.

Conflict of interest: none declared.

References