Particulate matter from re-suspended mineral dust and emergency cause-specific respiratory hospitalizations in Hong Kong

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ABSTRACT

While contribution from non-exhaust particulate matter (PM) emissions towards traffic-related emissions is increasing, few epidemiologic evidence of their health impact is available. We examined the association of short-term exposure to PM_{10} apportioned to re-suspended mineral dust with emergency hospitalizations for three major respiratory causes in Hong Kong between 2000 and 2008. Time-series regression model was constructed to examine association of PM_{10} from re-suspended mineral dust with emergency hospitalizations for upper respiratory infection (URI), chronic obstructive pulmonary disease (COPD) and asthma at exposure lag 0 to 5 days, adjusting for time trends, seasonality, temperature and relative humidity. An interquartile range (6.8 $\mu g/m^3$) increment in re-suspended mineral dust on previous day was associated with 0.66% (95% CI: 0.12, 0.98) increase in total respiratory hospitalizations, and 1.01% (95% CI: 0.14, 1.88) increase in URI hospitalizations. A significant 0.66%−0.80% increases in risk of COPD hospitalizations were found after exposure to re-suspended mineral dust at lag 3 or later. Exposure to mineral dust at lag 4 was linked to 1.71% increase (95% CI: 0.14, 2.22) in asthma hospitalizations. Associations from single-pollutant models remained significant in multi-pollutant models, which additionally adjusted for PM_{10} contributing from vehicle exhaust, regional combustion, residual oil, re-suspended mineral dust, fresh sea salt, aged sea salt, secondary nitrate and secondary sulfate, or gaseous pollutants (i.e., nitrogen dioxide, sulfur dioxide, or ozone), respectively. Our findings provide insight into the biological mechanism by which non-exhaust pollution may be associated with risk of adverse respiratory outcomes, and also stress the needs for strategies to reduce emission and re-suspension of mineral dust. More research is warranted to assess the health effects of different non-exhaust PM emissions under various roadway conditions and vehicle fleets.

Keywords: re-suspended mineral dust, respiratory hospitalization, upper respiratory, COPD, asthma, time-series analysis

1. INTRODUCTION

Road traffic emissions are a major source of urban air pollution (Charron et al., 2007). They contribute to particulate matter (PM) pollution via two ways: primary exhaust emissions from the tailpipe of motor vehicles, and non-exhaust emissions from brake/tyre wear, road surface abrasion (road wear), or re-suspension of deposited material (e.g., mineral dust), which may be generated from a wide variety of sources (e.g., construction) near the roadside, due to traffic-induced turbulence (Grigoratos and Martini, 2014; HEI, 2010; Pant and Harrison, 2013; Thorpe and Harrison, 2008). Non-exhaust emission of PM becomes increasingly important, particularly in developed countries in recent decades. It is because contribution from primary exhaust emissions to total traffic PM pollution have reduced considerably, due to the introduction of stringent standards for exhaust emission from diesel and gasoline vehicles, technological upgrades of engine and exhaust systems, and cleaner fuels (HEI, 2010; Pant and Harrison, 2013; Thorpe and Harrison, 2008). Thus, it is estimated that 80−90% of the total traffic PM emissions will come from non-exhaust emission by the end of the decade (Rexeis and Hausberger, 2009).

As the contribution from non-exhaust PM emissions increases, so should our understanding of the potential toxicity and health impact of non-exhaust-related particles. A few toxicological studies reported possible link between brake wear particles and pro-inflammatory responses in lung cells *in vitro* (Gasser et al., 2009; Mazzarella et al., 2007), and that studded tyre wear particles may have associated with considerable pro-inflammatory potential and profound effects on macrophages *in vitro* and animal models (Gustafsson et al., 2008; Karlsson et al., 2011; Lindbom et al., 2006). Yet, no epidemiologic studies have directly linked brake/tyre wear PM with adverse health effects on humans. In contrast, several epidemiologic studies have investigated the potential association between fine particles ($PM_{2.5}$) from crustal soil or re-suspended mineral dust and human health using source apportionment modeling (Andersen et al., 2007; Bell et al., 2014; Halonen et al., 2009; Lall et al., 2011; Sarnat et al., 2008; Schreuder et al., 2006). Though these studies show suggestive association of re-suspended mineral dust with adverse respiratory outcomes, heterogeneity in the findings remains. This may be explained by the application of $PM_{2.5}$ rather than coarse particles ($PM_{2.5–10}$) that are predominantly released by much of the non-exhaust processes (e.g., mechanical abrasion and corrosion). Other possible reasons include variation in the chemical composition depending on factors including brake and tire manufacturers, vehicle type and movement, street maintenance, season and meteorological parameters (Pant and Harrison, 2013; Stanek et al., 2011), as well as difference in the underlying study populations.

In a recent study conducted by our research group, we found positive association between risks of emergency hospitalizations for total respiratory causes and several PM_{10} apportioned factors in Hong Kong (Pun et al., 2015). Among the observations, the statistically significant association with PM_{10} factor whose chemical profile was most reflective of that of re-suspended mineral dust was intriguing, given that this was the first Asian study to report such association, and the only other study that examined such relationship reported no significant association in Copenhagen (Andersen et al., 2007). The current study built upon this observation by assessing the association of PM_{10} apportioned to re-suspended mineral dust with emergency hospitalization for three major respiratory causes respectively. Parallel epidemiologic evaluation was also performed for aluminum, calcium and iron, the chemical tracers that were largely apportioned to the re-suspended mineral dust factor, as well as evaluation for other PM_{10} sources for comparison. Findings from this study may provide a useful perspective on and further understanding of non-exhaust particles and their associated health impact, especially in Asia where studies of such kind is scarce.

2. METHODS

2.1. Hospitalization Data

We have previously compiled daily count data of emergency hospitalization into twenty-six publicly funded, regulated by the Hong Kong Hospital Authority, hospitals across the territory for the period of 2001 to 2008 (Figure S1; Pun et al., 2015, 2014a). In this study, we used the 9th revision of the International Classification of Diseases (ICD-9) code to extract hospitalizations for three major respiratory causes: chronic obstructive pulmonary disease (COPD; ICD-9: 491,492 and 496), asthma (ICD-9: 493). ICD-9 classification for acute upper respiratory infection (URI, ICD-9: 464−466) was only available from 2001 to 2007; thus analysis for URI was restricted to 2001-2007, whereas analyses for all other respiratory causes focused on 2001−2008. Since prior work has shown influenza outbreaks to be a confounder of the association between PM and respiratory hospital admissions (Ren et al., 2006), influenza hospitalizations (ICD-9: 487) were excluded from the total count of respiratory hospitalizations, and were subsequently adjusted in the regression analysis.

2.2. Exposure Assessment

We employed the positive matrix factorization (PMF) 5.0 with the inclusion of nineteen PM_{10} chemical species, characterized from filter samples collected from six monitoring stations between 1 January 2001 and 31 December 2008, to identify physically realistic sources. Detailed analytical methods and profiles for source-apportioned PM_{10} have been published elsewhere (Pun et al., 2014b, 2015; Z. B. Yuan et al., 2013), and a summary can be found in the eAppendix (Supplementary). Briefly, eight apportioned factors, reflective of chemical profiles for vehicle exhaust, regional combustion, residual oil, re-suspended mineral dust, fresh sea salt, aged sea salt, secondary nitrate and secondary sulfate, were obtained (Figure S2). Some factors have distinctive chemical profile corresponding to a specific emission source, such as vehicle exhaust emission that explained 80% of the variation in elemental carbon. Two factors are identified as composite of two or more sources that cannot be reasonably separated in the PMF model due to similarity in the source profile. Regional combustion emission was associated with large variation for a mixture of combustible constituents, arising from wood/biomass burning (e.g., potassium ion) and coal combustion (e.g., arsenic, cadmium, lead and zinc) in power plants and industrial facilities in the adjacent Pearl River Delta region (Z. Yuan et al., 2013). In this study, we primarily focused on PM_{10} from re-suspended mineral dust, a composite characterized by high loadings of aluminum, calcium and iron. This factor refers to material that is derived from a combination of exposed soil and dust from traffic, unpaved roads and construction activities from within Hong Kong and nearby Pearl River Delta region (Yuan et al., 2006). It might also take into account, to some degree, the particles emitted directly from brake/tyre/road wear and abrasion and then re-suspended, as evident by the present of aluminum and iron that appear to be ubiquitous in brake linings, tyres and car paint. However, further separation of brake/tire wear emission, road surface wear emission and re-suspension emissions was not attainable in the PMF model.

Daily mean temperature and relative humidity were also obtained from the Hong Kong Observatory for the same study period. Daily mean concentrations of nitrogen dioxide (NO_2) and sulfur dioxide (SO_2), as well as 8-hour mean (10:00 AM–6:00 PM) concentration of ozone (O_3) were also calculated from hourly air pollutant data.

2.3. Statistical analysis

Given fairly high temporal correlations of PM_{10} constituents and sources across the six monitoring stations ($r >$ 0.70), we used *a priori* method of centering and averaging to remove the station-specific influence on the resulting

PMF-resolved PM_{10} source contributions (Pun et al., 2014a, 2014b; Tian et al., 2013). The resultant time series contained nonmissing territory-wide mean source-apportioned PM_{10} for five consecutive days a week over the entire study period. No notable difference was observed between days with nonmissing sampling data and those with missing data in terms of cause-specific respiratory hospitalizations, apportioned sources and meteorological factors; thus missing data were not imputed. Previous analyses have shown that risk estimates of PM_{10} constituents and sources were insensitive to either regression models in which no data imputation was used or models in which imputation of missing sampling days was applied (Pun et al., 2014a, 2014b).

We used generalized additive model with log link, Poisson-distributed errors and autoregressive terms to estimate the associations of PM_{10} from re-suspended mineral dust and hospital admissions for total respiratory causes, COPD, URI and asthma, respectively (Hastie and Tibshirani, 1990). Each model adjusted for time-varying confounders, with smoothing splines with 8 degrees of freedom (df) per year for time trends and seasonality, 6 df for current day temperature and previous 3-day moving average, and 3 df for current day relative humidity and previous 3-day moving average selected *a priori* to minimize problems associated with multiple testing and core model selection strategies (Bell et al., 2009). Dummy variables for day of week, public holidays and influenza epidemics were also controlled for. We estimated hospitalization risks associated with levels of pollution on the same day (lag_0) and up to 5 days (lag_5) prior to hospitalization, while controlling for time trend, seasonality, meteorological conditions, calendar effects and influenza epidemic. Parallel epidemiological evaluation for aluminum, calcium and iron, the chemical tracers of re-suspended mineral dust, was also conducted. We further tested the robustness of the association in multi-pollutant models, where we adjusted for all eight PM_{10} sources simultaneously. Although not the primary focus of the study, the associations of cause-specific respiratory hospitalizations with the remaining PM_{10} sources were also explored in the multi-pollutant models to provide comparison with that of re-suspended mineral dust. In addition, we constructed two-pollutant models adjusting for NO_2, SO_2 or O_3 respectively. In an exploratory analysis, the average $PM_{2.5}$-to-PM_{10} ratios for calcium and iron were calculated using the available daily constituent concentrations in $PM_{2.5}$ and PM_{10} measured in Tsuen Wan air monitoring station, which is located close to the geographic center of Hong Kong and is likely to be more representative of Hong Kong's air quality in general, between November 2004 and November 2005. Ratio for aluminum was not computed due to unstable $PM_{2.5}$ aluminum measurements. All estimates were reported as the percent increase [(relative risk−1)×100%] in daily

cause-specific emergency hospital admissions for an interquartile range (IQR) increment in pollutant concentrations. The analyses were performed in the statistical environment R Software, version 3.1.2 (R Development Core Team, Vienna).

3. RESULTS

Between 2001 and 2008, there were 659,963 emergency respiratory hospitalizations (~226 admissions per day) in Hong Kong (Table 1). COPD hospitalizations accounted for 23.9% of total respiratory causes, followed by URI (18.6%) and asthma (7.5%). The daily mean temperature and relative humidity were 23.5ºC and 78.1% respectively. The average daily PM_{10} concentration was 55.9 $\mu g/m^3$, of which 13% was from re-suspended mineral dust that was almost comparable to the contribution from vehicle exhaust (15%; see Table S1 for descriptive statistics of all apportioned PM_{10} sources). The annual average contribution of mineral dust was relatively constant (p-trend = 0.053), compared to the rapid decreasing contribution of vehicle exhaust over the study period (p-trend = 0.015; Figure S3 in the Supplementary). Refer to Table S1 in the Supplementary for Pearson's correlations between source-apportioned PM_{10} and meteorological factors.

PM_{10} from re-suspended mineral dust and its chemical tracers was positively associated with hospitalizations for total respiratory, COPD, URI and asthma at various lag exposures, respectively (Figure 1). An IQR of 6.8 $\mu g/m^3$ increment in PM_{10} contribution from mineral dust on previous day (lag 1) was statistically significantly associated with 0.66% (95% CI: 0.12, 0.98) increase in total respiratory hospitalizations, and 1.01% (95% CI: 0.14, 1.88) increase in URI hospitalizations. Re-suspended mineral dust was also positively linked to increased risk of COPD hospitalizations at all lags examined, and the associations were statistically significant at 3 or more days prior to hospitalization (lag 3), corresponding to 0.66%−0.80% increases in risk. Risks of asthma hospitalizations were significantly increased (1.71%; 95% CI: 0.14, 2.22) with exposure to mineral dust at lag 4.

Results from multi-pollutant models that further adjusted for potential confounding of other PM_{10} sources were similar to those from single-pollutant models (Table 2). The increased hospitalization risks of total respiratory causes (0.63%; 95% CI: 0.22, 1.04), URI (0.93%; 95% CI: 0.01, 1.85) and COPD (0.77%; 95% CI: 0.17, 1.36) were slightly attenuated relative to single-pollutant model estimates; the risks of asthma hospitalizations was strengthened

185 at lag 4 based on the multipollutant model (1.44%; 95% CI: 0.34, 2.55) compared with the single-pollutant model. In
186 contrast to re-suspended mineral dust that exhibited differential temporal lag pattern of associations by cause-
187 specific respiratory causes, increment in PM_{10} apportioned to vehicle exhaust, secondary nitrate, secondary sulfate at
188 earlier days prior to hospitalization (e.g., lag 3-5) were generally and positively associated with respiratory
189 hospitalizations regardless of causes, after adjusting for all other sources (Figure S4). Level of PM_{10} from aged sea
190 salt was consistently linked to cause-specific respiratory hospitalizations at shorter lag (e.g., lag 0). However, no
191 discernible lag pattern was found for PM_{10} apportioned to regional combustion, residual oil and fresh sea salt.
192 Additional sensitivity analysis showed that the patterns of associations were similar in two-pollutant models
193 adjusting for O_3, NO_2, or SO_2 (Figure S5 in the Supplementary). Figure 2 shows that tracer species of mineral dust
194 were most abundantly found in the coarser mode of PM_{10}, with average $PM_{2.5}$-to-PM_{10} ratio ≤ 0.38.
195

196 **4. DISCUSSION**

197 Particles arising from re-suspension of mineral dust are primarily coarse particles generated by mechanical grinding
198 of tyre and brakes, and agricultural activities, in contrast to their combustion counterparts that are mostly fine
199 particles (Peng et al., 2008). Currently, no study has examined the adverse health associated with $PM_{2.5–10}$ from non-
200 exhaust traffic sources, because quantitative measurements of composition or sources of coarse PM are lacking.
201 Instead, most epidemiologic studies used $PM_{2.5}$ composition to identify non-exhaust traffic PM. While studies from
202 Connecticut and Massachusetts USA, Finland and Chile have reported that $PM_{2.5}$ from soil and/or road dust are
203 predictors of respiratory emergency department visits/hospitalizations (Bell et al., 2014; Cakmak et al., 2009a;
204 Halonen et al., 2009), research from New York City, Atlanta, and Washington State USA and Korea found no
205 evidence of association (Heo et al., 2014; Lall et al., 2011; Sarnat et al., 2008; Schreuder et al., 2006). Such
206 conflicting findings might attest to the limitation that $PM_{2.5}$ does not capture majority of the particles emitted by
207 non-exhaust traffic sources, and thus may not capture their true health impacts.
208

209 This study is one of the two existing research that apportioned PM_{10} composition to re-suspended mineral dust,
210 along with other sources, and is the first to examine the dust association with cause-specific respiratory
211 hospitalizations. The resultant exposure indicator, with an average $PM_{2.5}$-to-PM_{10} ratio ≤ 0.38, enabled us to capture
212 a wider spectrum of health effects associated with particles in either fine or coarse fraction of PM_{10}, compared to the

use of $PM_{2.5}$ composition alone. We associated an IQR increment in PM_{10} from re-suspended mineral dust on the previous day with an increased risk of total respiratory hospitalization, after adjusting for covariates; this increase in risk was mainly seen for URI hospitalizations. Statistically significantly positive associations were also observed for COPD and asthma hospitalizations, though with pollutant exposure at 3 or more days prior to hospitalizations. The patterns of associations were similar in models considering tracer species, multi-pollutant models adjusting for all PM_{10} sources, and two-pollutant models adjusting for gaseous pollutants. Our observed positive association between respiratory hospitalization and PM_{10} mineral dust is in contrast to findings reported by Andersen et al. (2007), which showed no significant association of PM_{10} crustal materials (comprised of road concrete, tire wear, igneous rock and limestone) with respiratory and asthma hospital admissions among elderly and children in Copenhagen. The heterogeneous findings may due to the difference in PM_{10} composition and source profiles between cities, which vary considerably depending on factors including brake and tire manufacturers, vehicle movement, street maintenance, season and meteorological parameters. Other factors, such as longer study period, larger sample size in our study, as well as population susceptibility between cities, may also explain the difference.

Precise biological mechanisms of how PM influence pathogenesis of respiratory illnesses remain unknown; however, several key factors (e.g., size fraction, chemical composition, surface area) must be taken into account in order to better understand the toxicity and potential adverse health effects of PM. In this study, we found PM_{10} mineral dust or its tracer species, which were generally $PM_{2.5-10}$, to be associated with URI hospitalizations at shorter day exposure lag, whereas association of hospitalizations for lower respiratory tract illnesses (i.e., COPD and asthma) was at longer lag (e.g., lag 3). Such observed differential temporal lag patterns of associations may be explained by the different triggering mechanisms in the lung by the fine and coarse fraction of PM_{10} soil/road dust (Centers for Disease Control and Prevention et al., 2010). The differential temporal lag pattern of associations of respiratory hospitalization by PM_{10} from vehicle exhaust and those from age sea salt may be also explained by particle size, which has been shown to be important factor affecting particles deposition in the respiratory tract (Samet and Dominici, 2000). Coarse particles, carrying more biological agents (e.g., endotoxins) than finer particles, deposit primarily in the upper airway by impaction, thereby causing irritation and epithelial disruptions, inducing and/or exacerbating upper respiratory illnesses with shorter delay (Ferguson et al., 2013; Schulz et al., 2000). On the other hand, finer particles (e.g., $PM_{2.5}$) tend to travel deeper in airways and alveoli of the lung by impaction, sedimentation

or diffusion, causing inflammation in the lower respiratory tract and lung tissues in a more delayed observable fashion (Donaldson and Stone, 2003; Kreyling et al., 2006). Animal models have shown coarse particles, on a mass basis, to have higher hydroxyl radical generating capacity, greater cytokine production of macrophages and bacterial endotoxin content, and produce significantly more pulmonary inflammatory responses compared to fine particles (Shi et al., 2003; Tong et al., 2010); whereas smaller particles may be more potent if taking into consideration of particle number or surface area. Our findings of PM_{10} mineral dust provide support for the importance of PM size-mediated impacts on upper and lower respiratory tract illnesses.

In addition, the heterogeneous associations across cause-specific respiratory illnesses or PM_{10} sources reported in this study may reflect effects of different generation processes, and of the combination of chemical constituents emitted from these sources (Kim et al., 2012). Toxicological studies have suggested that carbonaceous constituents, tracer for vehicle exhaust, may elevate levels of biomarkers for systemic inflammation and platelet activation (Delfino et al., 2009), and exposure to Pb, present in coal combustion as well as construction material, enhanced the production of oxidative stress, leading to inflammatory reactions (Saxena and Flora, 2004). Aluminum and iron, tracers for re-suspended mineral dust, may contribute to the formation of free radicals, induce oxidative processes and up-regulate pro-inflammatory mediators *in vitro*, thereby resulting in pulmonary inflammation and respiratory diseases (Garçon et al., 2000; Risom et al., 2005). There is also suggestive evidence that patterns of temporal lag structure of association varied by PM chemical constituents, as Kim et al. (2012) reported that delayed patterns of increased relative risks for asthma hospitalizations began at later lags for sulfate and nitrate than for elemental and organic carbon. Further work is needed to examine the biological mechanism in which PM constituents may affect human health.

As the relative non-exhaust contribution towards any traffic related emissions is becoming greatly significant and posing challenges for authority, findings from the current study stress the needs for strategies and measures for abatement of particle emission and re-suspension. While road/street sweeper alone may not significantly reduce PM_{10} concentration (Amato et al., 2010; Keuken et al., 2010), other measures such as cleaning road and pavement with water, or applying dust suppressants/dust binders (e.g., aqueous solutions of magnesium/calcium chloride and calcium magnesium acetate) to maintain wet road surface have shown to be effective in certain conditions (Aldrin et

al., 2008; Norman and Johansson, 2006). Amato et al. (Amato et al., 2014) concluded in a recent review that a combination of strategies aiming at minimizing the emission sources (e.g., improve wear properties of materials and traffic, better maintenance of road) and minimizing re-suspension (e.g., road cleaning, reduce traffic) would likely provide optimal abatement of PM non-exhaust emissions from road traffic.

Findings from our study should be interpreted with caution, as we cannot eliminate exposure measurement error. Particles from re-suspended mineral dust tend to be more spatially heterogeneous, which might be subject to more error and bias the estimates towards the null (Kioumourtzoglou et al., 2014b). Quantitative measurement of composition or sources of coarse PM, or measurements of both $PM_{2.5}$ and PM_{10} composition for the calculation of $PM_{2.5–10}$ composition for source apportionment are needed to determine clear differences in source contribution by size fraction and validate our findings. Finally, we did not account for the uncertainty of the estimated source contributions directly in the health model. Any underestimation of the resulting inferences, however, is expected to be small given the consistency in source identification across monitors and in effects obtained, and the agreement of our findings with previous studies (Kioumourtzoglou et al., 2014a).

5. CONCLUSION

In summary, we found evidence of significantly positive association of total respiratory hospitalizations with exposure PM_{10} from re-suspended mineral dust, adjusting for covariates (e.g., vehicle exhaust). Exposure at early lag day was linked to URI hospitalization, whereas exposure at later lags was associated with COPD and asthma hospitalizations. These findings help prioritize research on the biologic mechanisms of PM effect on specific pulmonary conditions, and stress the needs for strategies to reduce emission and re-suspension of mineral dust.

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