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Using spatio-temporal modeling for exposure assessment in an investigation of fine particulate air pollution and cardiovascular mortality

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ABSTRACT

Background: U.S. urban air quality has improved dramatically over the past decades. We evaluated acute effects of fine particulate matter ($PM_{2.5}$) on cardiovascular (CVD) mortality among residents of Allegheny County in SW Pennsylvania (1999–2011) using spatio-temporal modeling of air pollutants (AP) to reduce misclassification error in exposure assessment.

Methods: Spatio-temporal kriging of daily $PM_{2.5}$ and ozone (O_3) was used to produce daily exposure estimates at the residence ZIP code. Time-stratified case-crossover analysis was conducted to examine short-term effects of $PM_{2.5}$ on CVD mortality, adjusting for O_3 and apparent mean temperature. We studied both single and distributed lags for days 0–5. All CVD mortality and subcategories of ischemic heart disease (IHD), acute myocardial infarction, cerebrovascular disease, peripheral vascular disease (PVD), heart failure and cardiac arrhythmia were examined.

Results: A total of 62,135 deaths were identified. We found significant associations of $PM_{2.5}$ with IHD and PVD mortality at lag day 5: (2.1% (95% CI, 0.2–4.1%) and (7.6%, 95% CI, 0.05–15.7%) per 10 $\mu g/m^3$ increase of $PM_{2.5}$ in single lag models and for IHD in distributed lag models. There were no statistically significant associations with $PM_{2.5}$ for any of the other outcomes.

Conclusions: The application of finer scale geographically resolved AP exposures made it possible to study acute effects of $PM_{2.5}$ on CVD mortality in a large metropolitan area. Our study results demonstrated the continued presence of a dose response relationship of increased risk of CVD mortality within this lower range of $PM_{2.5}$ exposure.

1. Introduction and background

Brook et al. (2010), as part of a scientific statement from the American Heart Association (AHA), extensively reviewed the available evidence to study the relationship of PM air pollution and CVD. They summarized that there is a small, yet consistent association between increased cardiovascular disease mortality and short term elevations in PM_{10} and $PM_{2.5}$. Studies show that for every 10 $\mu g/m^3$ elevation in $PM_{2.5}$ during the preceding 1–5 days, there is increase of 0.4–1.0% in daily cardiovascular mortality. Hospital admissions due to CVD were also elevated in response to daily changes in PM levels. The AHA statement also concluded that there is strong evidence of short term effects of $PM_{2.5}$ on ischemic heart disease morbidity and mortality, moderate (yet growing) evidence for heart failure and ischemic stroke, and modest or mixed evidence for peripheral vascular and cardiac arrhythmia/arrest (Brook et al., 2010).

Since the AHA statement, several additional studies have been conducted in the United States and other parts of the world which have examined the relationship of short-term $PM_{2.5}$ exposure with CVD mortality. In a study conducted in New York, Ito et al. found that $PM_{2.5}$ was associated with CVD mortality in the warm season at lag day 0 (% Excess Risk (ER)=2.0%; 95% confidence interval (CI),

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0.7–3.3 per 10 μg/m^3); and at lag day 1 (1.9%; 95% CI, 0.8–3.1 per 10 μg/m^3) and in the cold season at lag day 1 (1.0%; 95% CI, −0.1 to 2.2 per 10 μg/m^3) (Ito et al., 2011). Zhou et al. found a significant positive association for cumulative effect from lag day 0–2 for $PM_{2.5}$ for all-cause and cardiovascular mortality during the warm season in Detroit, suggesting a role of secondary pollutants; in contrast, Seattle showed positive associations in the winter (Zhou et al., 2011).

Shang et al. conducted a meta-analysis of time series studies from China during 1990–2012 and found that each 10 μg/m^3 increase in $PM_{2.5}$ was associated with a 0.44% (95% CI: 0.33–0.54) increase in CVD mortality (Shang et al., 2013). The associations for PM_{10} were similarly strong. In 2013, Shah et al. conducted a meta-analysis of global studies conducted during 1984–2012 that examined the relationship of daily levels of particulate matter and gaseous pollutants with heart failure hospitalizations and death (Shah et al., 2013). They found that increases in particulate matter concentration were associated with heart failure hospitalization or death ($PM_{2.5}$, 2.12% per 10 μg/m^3, 95% CI: 1.42–2.82; PM_{10}, 1.63% per 10 μg/m^3, 95% CI: 1.20–2.07). Strongest associations were seen on the day of exposure, with more persistent effects for $PM_{2.5}$. Samoli et al. conducted meta-regression of time series in 10 European Mediterranean metropolitan areas (Samoli et al., 2014). They found a statistically significant increase in cardiac deaths of 1.33% (95% CI: 0.27–2.40%) for a 10 μg/m^3 increase in six days' $PM_{2.5}$ exposure.

Five studies to date have examined the relationship between daily $PM_{2.5}$ and mortality in the greater Pittsburgh (Allegheny County, PA area). Chock et al. conducted a time series from 1989 to 1991 and found statistically significant results for PM_{10} with daily non-accidental mortality for age <75 in 0-lag model (Chock et al., 2000). However, due to small signal to noise ratio, they could not credibly ascertain the relative association of $PM_{2.5}$ and mortality. Franklin et al. in a multicity analysis, found a statistically significant association between lag day 1 $PM_{2.5}$ and all-cause mortality in Pittsburgh (Franklin et al., 2007). In another multicity analysis, Franklin et al. found an overall statistically significant association of $PM_{2.5}$ and non-accidental deaths and CVD mortality but Pittsburgh specific results were not available (Franklin et al., 2008).

Two investigations focused on cardiovascular and respiratory morbidity and mortality in the Pittsburgh region (Mazumdar and Sussman, 1983; Arena et al., 2006). The first used coefficient of haze, an early marker of total suspended particulates, SO_2 and weather variables at three separate monitor locations (1972–77) to study the relationship of cardiovascular and respiratory mortality in Allegheny County residents. Results indicated a possible association between heart disease and same day particulate levels. Arena et al. (2006) considered daily cardiopulmonary hospitalizations in people 65 years and older in Allegheny County for the period 1995–2000 and countywide average PM_{10} measures. Using generalized additive models (GAM), a Poisson regression model was fit to the number of daily admissions using predictor variables: 0–5 lag days of PM_{10}, daily temperature and humidity, day of the week, and time. There were eight monitoring locations, and average values were computed for PM_{10} using all eight for a daily average. Their findings suggest that there was a positive association of PM_{10} with hospital admissions, and the effect was related to current-day of the hospitalization. This translates into an increase of 0.0609% (95% CI 0.0263–0.0955) in cardio- pulmonary hospital admissions above that which is predicted by seasonal trend, daily temperature and relative humidity, and day of the week per 1 microgram increase in PM_{10}/m^3 (.6% per 10 μg/m^3).

In summary, a number of studies have been conducted in the Pittsburgh (Allegheny County) area over the past several decades to examine the short term effects of particulate matter on morbidity and mortality. None to date, however, has published results of the short term association of $PM_{2.5}$ and cardiovascular disease mortality specifically. Also, none have examined subgroups of cardiovascular mortality (e.g., ischemic heart disease, cerebrovascular disease).

One of the most common limitations cited by authors of each of these investigations is the availability of only a few monitors for exposure assessment over a large area and thus likely creating increased exposure error with distance from the monitoring site.

Allegheny County which is located in SW PA has unique characteristics for studying the effects of environmental exposures. The area has long been a seat of heavy industry in the northeastern corridor of the United States. The Pittsburgh area ranks as the fourth highest in air pollution levels in the country and is the home to the country's largest coke oven operation, a significant emitter of particulates and metals. The county is characterized by complex terrain, periods of heavy traffic, large industrial sources, and frequent inversion events. This combination of topography, meteorology, and emission sources results in significant spatial variability in many pollutant concentrations, including fine particulate matter ($PM_{2.5}$) and black carbon (BC). Tunno et al. in Pittsburgh, designed a 2-year monitoring campaign to capture spatial variation in $PM_{2.5}$ and BC. Inversion-focused integrated monitoring (0600–1100 h) was performed during year 1 (2011–2012) and compared with 1-week 24-h integrated results from year 2 (2012–2013) (Tunno et al., 2016). They found stronger spatial contrasts in $PM_{2.5}$ and BC using inversion-focused sampling, suggesting greater differences in peak exposures across urban areas than is captured by most integrated saturation campaigns. Temporal variability, commercial and industrial land use, $PM_{2.5}$ emissions, and elevation were significant predictors as well as peak hours suggesting that regional levels of $PM_{2.5}$ are not always as sensitive or predictive.

The primary goal of the present study was to examine the acute effects of fine particulate matter ($PM_{2.5}$) on cardiovascular (CVD) mortality among residents of Allegheny County in SW Pennsylvania (1999–2011) using spatio-temporal modeling of air pollutants (AP) to reduce misclassification error in exposure assessment. We employed spatio-temporal kriging on a fine grid over the county to estimate exposure daily levels of $PM_{2.5}$ and ozone for each of the 126 ZIP code tabulation areas (ZCTAs) in Allegheny County, Pennsylvania from 1999 to 2011. These daily exposure levels were used in a time-stratified case-crossover study design to examine the short-term association of ambient $PM_{2.5}$ with the risk of death due to CVD, adjusting for ozone (O_3) and apparent mean temperature. We also sought to identify vulnerable population subgroups defined by sociodemographic characteristics, location at the time of death and time of year (season) of death who may be more sensitive to the short-term effects of $PM_{2.5}$.

2. Materials and methods

As of 2010 Census (2010), the population of Allegheny County was 1.2 million of whom 305,000 reside in the city of Pittsburgh. The racial distribution for Allegheny County is primarily white (81.0%) and African American (13.4%).

2.1. Mortality data

Mortality data for Allegheny County residents for the period January 1, 1999–December 31, 2011 were obtained from the Pennsylvania Department of Health Vital Statistics Division. These data were collected from death certificate information and included for each death, the date and cause of death (International Classification of Diseases (ICD)-10), sex, age, race, education, location at the time of death, ZIP code of residence, county and state