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Can mortality displacement mask thresholds in the concentration-response relation between particulate matter air pollution and mortality?

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ABSTRACT

Two critical issues for public health assessment and regulation of exposure to particulate matter air pollution (PM) are whether there is a threshold in the concentration-response relation between PM and mortality and whether there is mortality displacement. In this vein, a number of time-series studies have concluded that a linear relation without a threshold is appropriate for describing the concentration-response relation, and a number of other studies have concluded that the mortality effects of PM exposure cannot be attributed to mortality displacement alone. Using three-state (healthy, frail, dead) population models that incorporate actual time series data from Cook County, Illinois for the period 1987–2000, the author investigates the shape of the concentration-response relation between PM and mortality, as observable from time-series data, in the presence of mortality displacement. It is found that thresholds in the concentration-response relation can be masked, or hidden, by linear concentration-response relations if some of the effect of PM exposure is attributable to mortality displacement. This is an important finding that has implications for studies that have found a linear concentration-response relation appropriate, particularly given the markedly different implications for public health assessment and regulation of a linear versus threshold concentration-response relation.

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1. Introduction

The shape of the concentration-response relation (Daniels et al., 2000; Koop and Tole, 2006; Samoli et al., 2005; Schwartz et al., 2008; Vedal et al., 2003) and mortality displacement (Dominici et al., 2003; Fung et al., 2005a,b; Murray and Nelson, 2000; Roberts and Switzer, 2004; Schwartz, 2000; Smith et al., 1999; Zanobetti et al., 2000; Zeger et al., 1999) are two issues that have received extensive attention in investigations of the mortality effect of exposure to ambient particulate matter air pollution (PM). Knowledge of the shape of the concentration-response relation between ambient PM exposure and mortality is vital for public health assessment and the setting of appropriate regulatory standards for PM (Anderson, 2009; Ren and Tong, 2008; Schwartz et al., 2008). Numerous studies have investigated the shape of the concentration-response relation with many concluding that the relation is approximately linear; that is, that the incremental effect of exposure to PM on mortality is constant (Daniels et al., 2000; Samoli et al., 2005; Schwartz et al., 2008; Schwartz and Zanobetti, 2000). In many studies a hypothesis of particular interest has been whether there is a threshold, that is a PM concentration below which exposure has no impact on mortality, in the concentration-response relation (Daniels et al., 2000; Koop and Tole, 2006; Samoli et al., 2008; Vedal et al., 2003). A threshold in the concentration-response relation has important consequences for regulators as it implies that a tightening of PM standards that results in a standard below the threshold will have zero, or less than anticipated, benefits in terms of reduced mortality. Conversely, a linear concentration-response relation implies that any tightening of PM standards will have resulting benefits in terms of reduced mortality. Mortality displacement, or harvesting, is another issue that is critical for public health assessment of the mortality effect of ambient PM exposure (Roberts, 2011; Roberts and Switzer, 2004; Samet et al., 2000; Schwartz, 2000; Zeger et al., 1999). Mortality displacement describes the scenario where the only effect of PM exposure is to hasten the deaths of a frail subset of the population that have a relatively short expected future lifetime, irrespective of exposure to PM. Public health assessment of PM exposure would differ substantially if it were known that the mortality effect of PM was mortality displacement alone, rather than the deaths of otherwise healthy individuals. A number of studies, utilizing different methodologies, have investigated the issue of mortality displacement (Dominici et al., 2003; Murray and Lipfert, 2010; Murray and Nelson, 2000; Schwartz, 2000; Smith et al., 1999; Zanobetti et al., 2000;

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Zeger et al., 1999). For the most part, these studies have concluded that the mortality effects of PM exposure cannot be attributed to mortality displacement alone. If the effect of PM exposure is not mortality displacement alone this means that PM, apart from killing frail individuals, may be killing otherwise healthy individuals and/or causing otherwise healthy individuals to transition into a frail state.

Studies investigating thresholds in the concentration-response relation have typically proceeded by directly modeling threshold relations and statistically comparing these relations to a linear relation and/or allowing the concentration-response relation to be modeled by a smooth function and visually determining whether a linear or threshold relation appears appropriate (Daniels et al., 2000; Samoli et al., 2008; Schwartz and Zanobetti, 2000; Smith et al., 2000). As noted above, the general consensus from investigations of the shape of concentration-response relation is that a linear relation is appropriate for modeling the mortality effects of PM (Daniels et al., 2000; Samoli et al., 2005; Schwartz et al., 2008; Schwartz and Zanobetti, 2000). However, these results should be tempered somewhat by the findings of Roberts and Martin (2006) who concluded that Akaike's Information Criterion (AIC) was not always successful in detecting nonlinearities in the concentration-response relation between PM and mortality. The shape of the concentration-response relationship is an important issue for other ambient air pollutants including ozone (Bell et al., 2006; Kim et al., 2004).

Mortality displacement in the association between PM and mortality has been investigated using a range of methods in an attempt to obtain estimates of the effect of PM that exclude short-term mortality displacement or to explicitly estimate the size of the frail population and the effects of PM on this frail population (Dominici et al., 2003; Murray and Nelson, 2000; Schwartz, 2000; Smith et al., 1999; Zanobetti et al., 2000; Zeger et al., 1999). As discussed above, these studies have generally concluded that the mortality effects of PM exposure cannot be attributed to mortality displacement alone. A common feature of a number of these studies is the use of a three-state population model (healthy, frail, dead) to motivate mortality displacement (Murray and Nelson, 2000; Smith et al., 1999; Zanobetti et al., 2000; Zeger et al., 1999). Under this model, individuals transition from the healthy population into the frail population and deaths only occur from the frail population; mortality displacement corresponds to the situation where the mean lifetime in the frail population is short and PM only affects transitions from the frail population to death. Previous studies have utilized the three-state model to simulate mortality for exploring the properties of methods used to investigate mortality displacement (Fung et al., 2005a,b; Murray and Nelson, 2000; Roberts and Switzer, 2004; Smith, 2003; Smith et al., 1999; Zeger et al., 1999). Some of these simulation studies have concluded that methods developed for investigating mortality displacement may not always be successful (Fung et al., 2005b; Roberts and Switzer, 2004; Smith, 2003). In a recent study the three-state population model was extended to allow for multiple healthy and frail populations (Roberts, 2011). Mortality displacement is also an important issue for other ambient air pollutants including ozone (Zanobetti and Schwartz, 2008).

To the best of the author's knowledge this paper provides the first joint investigation of the issues of mortality displacement and thresholds in the concentration-response relation. The goal of the investigation is to determine the shape of concentration-response relation between PM and mortality, as observable from time-series data, in the presence of mortality displacement and/or a frail population. In the presence of mortality displacement, a recent study developed a relationship between the sum of the coefficients of a distributed lag model and the size of the frail population (Roberts, 2011). Here our interest is not in the development of such a relationship for concentration-response models, but rather in empirically observing the shape of the concentration-response relation in the presence of mortality displacement. It is illustrated that thresholds in the concentration-response relation can be masked if some of the mortality effect of PM exposure is attributable to mortality displacement. This observation means that in some investigations a finding of a linear concentration-response relation may be an artifact of mortality displacement masking an underlying threshold concentration-response relation. This is an important finding that has implications for studies that have found a linear concentration-response relation appropriate, particularly given the markedly different implications for public health assessment of a linear versus threshold relation.

2. Data

The data for this study were obtained from the National Mortality, Morbidity, and Air Pollution Study (NMMAPS) database. The NMMAPS database is a freely available database that contains daily mortality, weather and air pollution data for selected areas in the United States (US), for the period 1987–2000. The NMMAPS database has been extensively used to investigate the association between air pollution and mortality (Martin and Roberts, 2008; Peng et al., 2005; Ren et al., 2008). Further information on this database and access to this database can be obtained at http://www.ihapss.jhsph.edu/. For this study relevant data for Cook County, Illinois, for the period 1987–2000 was extracted from the database. The daily data extracted were: the number of non-accidental deaths of individuals aged over 65 years; average concentration of ambient particulate matter of less than 10 μm in diameter, measured in units of $\mu g\, m^{-3}$; and average measures of temperature and dew point temperature. The average ambient particulate matter (denoted PM_{10}) concentrations were constructed by adding back a trend to a daily time-series of detrended particulate matter concentrations. Both the trend and detrended time-series are available in the NMMAPS database.

For the purposes of the simulations, missing PM_{10} concentrations (251 days) were imputed as the average of the one-day's previous and one-day's subsequent PM_{10} concentrations. Two outlying PM_{10} concentrations, four negative PM_{10} concentrations and four outlying mortality counts had their values replaced using this scheme. In the investigations that follow the previous day's (lag-1) PM_{10} concentration is used as this has been the focus of most attention in large multi-city studies conducted in the US (Peng et al., 2005; Welty and Zeger, 2005). Hereafter, PM_{10} will represent the lag-1 PM_{10} concentration.

3. Statistical methods

A three-state (healthy, frail, dead) population model is used to generate mortality time-series that incorporate mortality displacement. This model assumes that individuals start in the healthy population and, at some point in time, transfer into the frail population and that deaths occur from the frail population. To generate mortality time-series from the three-state model the author closely followed the specifications used by Roberts (2011), Roberts and Switzer (2004), Smith et al. (2000), and Zeger et al. (1999). Under this specification, on day t, it is assumed that e_t individuals transition from the effectively infinite healthy population into the frail population of size f_t, and that among the now $f_t + e_t$ individuals in the frail population d_t of them die on day t. To complete the model, it is assumed that (1) e_t is Poisson distributed with mean μ_t; (2) d_t is binomially distributed with probability ϕ_t and number of trials $f_t + e_t$; (3) the long-run average number of entrants into the frail population is equal to the long-run average number of deaths ($\bar{d}$); and (4) the number of individuals in the frail

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