Adverse birth outcomes, such as low birth weight (LBW), increase risk of mortality and morbidity, including cardiovascular-related events, during childhood (Kannan et al. 2006). In the last decade, numerous studies have reported associations between levels of ambient air pollutants and adverse birth outcomes, although results are not consistent regarding the relevance of specific pollutants or the trimester of exposure. Associations between particulate matter (PM) and pregnancy outcomes differ by study, although many findings do suggest an association. Exposure to PM ≤ 10 μm (PM10) and 2.5 μm (PM2.5) in aerodynamic diameter during gestation has been associated with LBW in some studies (Huynh et al. 2006; Morello-Frosch et al. 2010; Seo et al. 2010), but not others (Madsen et al. 2010; Seo et al. 2010). More studies have been conducted for gaseous pollutants, although results have also been inconsistent, such as for nitrogen dioxide (NO2) (Maroziene and Gruzuleviciene 2002; Morello-Frosch et al. 2010), sulfur dioxide (SO2) (Bobak and Leon 1999; Lin et al. 2004), carbon monoxide (CO) (Liu et al. 2003; Ritz and Yu 1999), and ozone (O3) (Morello-Frosch et al. 2010; Salam et al. 2005).

Several literature reviews of pollutant effects on adverse birth outcomes have noted that results are heterogeneous across studies, but have nonetheless concluded that associations between air pollution and adverse pregnancy outcomes are likely causal (Maisonet et al. 2004; Sapkota et al. 2010; Shah and Balkhair 2011). Shah and Balkhair (2011) concluded that exposure to PM2.5 is likely associated with LBW, preterm birth, and small-for-gestational-age births. These reviews noted that further studies are necessary to clarify which pollutants are most harmful and to identify during which periods of pregnancy infants are most vulnerable. Inconsistencies among previous studies might result from differences in study populations or in study design, such as control for confounders, exposure assessment, statistical methods, and sample size. Other possible explanations are variation in the exposure period and collinearity among pollutants (Maisonet et al. 2004). However, a key reason studies on PM and pregnancy outcomes differ is that the chemical composition of particles varies by location (Bell et al. 2007a). Previous works demonstrated regional variation in the chemical structure of PM2.5 (Bell et al. 2007a) and in PM2.5-associated risk for mortality (Zhou et al. 2011). Several studies have used data on components or sources to investigate whether associations between PM and adverse outcomes are related to chemical composition. In the United States, relative risks of cardiovascular hospitalizations in association with PM2.5 total mass are higher in areas with higher PM2.5 content of bromine, chromium, nickel, and sodium (Zanobetti et al. 2009). In California, long-term exposures to fossil fuel–related PM2.5 (e.g., sulfate) and crustal-related PM2.5 (e.g., silicon) are associated with increased mortality (Ostro et al. 2010). In New York City, the effect of coal combustion–related components (e.g., selenium) on cardiovascular-related mortality is higher in summer than in winter, whereas its effect on cardiovascular-related hospital admission is higher in summer than in winter (Ito et al. 2011).

Most studies of PM2.5 sources or components have focused on adult hospital admissions or mortality, with only a limited number of studies investigating associations between PM2.5 chemical components and birth outcomes. A study conducted in Atlanta, Georgia, reported that PM2.5 elemental carbon and water-soluble PM2.5 metals, such as copper, were associated with lower birth weight (Darrow et al. 2011). Our previous studies of four counties in Connecticut and Massachusetts found associations between PM2.5 components of aluminum, elemental carbon, nickel, silicon, vanadium, and zinc and risk of LBW (Bell et al. 2010).

Given the spatially heterogeneous distribution of PM2.5 components (Bell et al. 2007a), there is value in investigating effects of components over a larger spatial area and associations with components such as organic carbon matter (OCM) that have not been considered previously. In the present study, we investigated associations between exposure to PM10, PM2.5 total mass, PM2.5 chemical components, CO, NO2, O3, and SO2 during pregnancy and birth weight for the Northeastern and Mid-Atlantic regions of the United States. Previous studies have noted that results are heterogeneous across studies, which might contribute to discrepancies across PM2.5 studies.

OBJECTIVES: We explored whether birth weight at term is affected by PM2.5, PM10 (PM ≤ 10 μm), and gaseous pollutants.

METHODS: We calculated exposures during gestation and each trimester for PM2.5 chemical components. PM10, PM2.5, carbon monoxide, nitrogen dioxide, ozone, and sulfur dioxide for births in 2000–2007 for states in the northeastern and mid-Atlantic United States. Associations between exposures and risk of low birth weight (LBW) were adjusted by family and individual characteristics and region. Interaction terms were used to investigate whether risk differs by race or sex.

RESULTS: Several PM2.5 chemical components were associated with LBW. Risk increased 4.9% (95% CI: 3.4, 6.5%), 4.7% (3.2, 6.2%), 5.7% (2.7, 8.8%), and 5.0% (3.1, 7.0%) per interquartile range increase of PM2.5 aluminum, elemental carbon, nickel, and titanium, respectively. Other PM2.5 chemical components and gaseous pollutants showed associations, but were not statistically significant in multipollutant models. The trimester associated with the highest relative risk differed among pollutants. Effect estimates for PM2.5 elemental carbon and nickel were higher for infants of white mothers than for those of African-American mothers, and for males than females.

CONCLUSIONS: Most exposure levels in our study area were in compliance with U.S. Environmental Protection Agency air pollution standards; however, we identified associations between PM2.5 components and LBW. Findings suggest that some PM2.5 components may be more harmful than others, and that some groups may be particularly susceptible.

KEY WORDS: air pollution, environmental health, epidemiology, low birth weight. Environt Health Perspect 120:1746–1752 (2012). http://dx.doi.org/10.1289/ehp.1104763 [Online 20 September 2012]
United States. In previous work, we investigated associations between ambient air pollution and pregnancy outcomes in Connecticut and Massachusetts, but did not consider some key PM$_{2.5}$ chemical components such as OCM (Bell et al. 2010) or did not consider any PM$_{2.5}$ chemical components at all (Bell et al. 2007b). Compared with our previous studies, the present study covers a much larger study area and a population that is 16 times larger, expands the components considered, and evaluates research questions not considered previously, such as potential confounding by gaseous pollutants. To the best of our knowledge, this is the largest study to date of the effects of PM$_{2.5}$ chemical components on birth weight.

The National Research Council Committee and the Health Effects Institute identified as a critical research need studies on which characteristics of particles are most harmful (Health Effects Institute 2002; National Research Council 2004). Scientific evidence on the health impacts of PM$_{2.5}$ components will inform understanding of which sources are most harmful and will benefit policy making efforts to protect public health from airborne PM$_{2.5}$.

**Methods**

**Birth data.** Birth certificate data for Connecticut, Delaware, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, Virginia, Washington, DC, and West Virginia (USA), from 1 January 2000 through 31 December 2007 were obtained from the National Center for Health Statistics (Atlanta, GA). Data that were provided include county of residence, county of birth, birth order, trimester of first prenatal care, date of last menstrual period (LMP), gestational age, infant’s sex and birth weight, as well as maternal and paternal ages and races, and maternal education, marital status, alcohol consumption, and smoking during pregnancy. Further description of these data is available elsewhere (Bell et al. 2007b).

Births with unspecified county of residence or birth, plural deliveries (e.g., twins), gestational period < 44 weeks, gestational period < 37 weeks (nonterm births), birth weight < 1,000 g or > 5,500 g, different counties of residence and delivery, or impossible gestational age and birth weight combinations were excluded from analysis (Alexander et al. 1996). Births also were excluded if LMP was missing or the estimated birth based on LMP and gestational length was > 30 days from the midday of the birth month reported on the birth certificate.

**Air pollution and weather data.** PM$_{2.5}$ chemical components data were obtained from the U.S. Environmental Protection Agency (EPA) Air Explorer (U.S. EPA 2010a). PM$_{10}$ and PM$_{2.5}$ total mass, CO, NO$_2$, O$_3$, and SO$_2$ data were obtained from the U.S. EPA Air Quality System for 1999–2007 (U.S. EPA 2010b). We included only counties with PM$_{2.5}$ chemical component data because these exposures are our primary focus. PM$_{10}$, PM$_{2.5}$, and PM$_{2.5}$ chemical components were measured every 3–6 days. Gaseous pollutants were measured daily, although O$_3$ was measured mainly during the warm season. Some monitors began or ceased observation during the study period. We investigated PM$_{2.5}$ chemical components identified by previous research and literature review to have potential links to health and/or contribute substantially to PM$_{2.5}$ total mass: aluminum, ammonium ion, arsenic, cadmium, calcium, chlorine, elemental carbon, lead, mercury, nickel, nitrate, organic carbon matter, silicon, sodium ion, sulfur, titanium, vanadium, and zinc (Bell et al. 2007a; Franklin et al. 2008; Haynes et al. 2011; Ostro et al. 2007; Zanobetti et al. 2009).

We calculated apparent temperature (AT), a measure that reflects overall temperature discomfort (Kalkstein and Valimont 1986), based on daily temperature and dew point temperature data obtained from the National Climatic Data Center (2010). If weather data were unavailable for a given county, we assigned the AT value for the closest county with weather data.

**Exposure estimation.** For each birth we calculated the average level of each pollutant during gestation and each trimester, and average AT during each trimester. Delivery date was estimated based on self-reported LMP and gestational length, assuming conception 2 weeks after LMP. We defined trimesters as 1–13 weeks, 14–26 weeks, and week 27 to delivery, as in previous studies (Bell et al. 2007b).

Exposures were estimated based on county of residence. Not all counties had data for all pollutants. Measurements from multiple monitors in the same county on the same day were averaged to generate daily pollutant levels. To avoid biases due to changes in measurement frequency, daily pollutant levels and AT values were combined to estimate weekly exposures, which were then averaged to estimate gestational or trimester exposure. Births for which exposure estimates were unavailable for > 25% of the weeks in any trimester for a given pollutant were excluded from analyses of that pollutant.

**Statistical analysis.** Each birth was categorized as low or normal birth weight using clinically defined LBW (< 2,500 g). Logistic regression was used to estimate associations between LBW and gestational exposure to each pollutant with adjustment for maternal race (African American, Caucasian, other), marital status (married, unmarried), tobacco consumption during pregnancy (yes, no, unknown), alcohol consumption during pregnancy (yes, no, unknown), highest education (< 12 years, 12 years, 13–15 years, > 15 years, unknown), age (19, 20–24, 25–29, 30–34, 35–39, ≥ 40 years), infant sex (male, female), gestational length (37–38, 39–40, 41–42, 43–44 weeks), the trimester prenatal care began (1st, 2nd, 3rd, no care, unknown), first in birth order (yes, no, unknown), delivery method (vaginal, cesarean section, unknown), average AT for each trimester, season of birth, and year of birth. In addition we included regional indicators to adjust for local factors such as area-level socioeconomic conditions (Table 1). We conducted sensitivity analyses restricted to first births to assess the influence of multiple births by the same mother on associations (Zhu et al. 1999).

For pollutants showing statistically significant associations with LBW in single-pollutant models, we conducted two-pollutant models that included pairs of pollutants that were not highly correlated (correlation < 0.5). Significant associations with LBW in single-pollutant model, we assessed effects by trimester using a model with trimesters’ exposures included simultaneously. Because trimester exposures could be correlated, we performed sensitivity analysis with trimester exposures adjusted to be orthogonal using a method we published previously (Bell et al. 2007b). In brief, we predicted exposures of two trimesters using exposure level of a given trimester (reference trimester), calculated their residuals, and put them into models besides exposure of reference trimester. This approach can avoid covariance among trimester exposures. This procedure was repeated using each trimester as the reference trimester, and we have four models for trimester analysis in total (main model and three models as sensitivity analyses). Further description of this approach is available elsewhere (Bell et al. 2007b).

Additional analyses were conducted for pollutants that showed statistically robust results in two-pollutant models. We included interaction terms between gestational pollutant exposures and sex or race to investigate whether some populations are particularly susceptible, because previous analysis found higher relative risks associated with ambient air pollution in some populations than in others (Bell et al. 2007b). Statistical significance was determined at an alpha level of 0.05 for the entire analyses.

**Results**

There were 7,098,417 births in 419 counties in the study area during the study time period (2000–2007). Among them, 2,476,383 (34.9%) infants lived in the 50 counties with monitors for PM$_{2.5}$ chemical components, and 1,385,466 (19.5%) infants in 49 counties
had exposure estimates for all pollutants during ≥ 75% of the gestational weeks in all three trimesters. After exclusions (e.g., for preterm birth, plural deliveries), our study population consisted of 1,207,800 infants from 49 counties. This corresponds to 17% of the original data, and some births may have been excluded based on more than one criterion. Many of the counties had only one monitor, but some urban counties had multiple monitors. The average number of monitors per county was 1.08 (range, 1–2) for PM$_{2.5}$ chemical components, and 1.57 (range, 1–9) for PM$_{10}$, PM$_{2.5}$, and gaseous pollutants. The mean (± SD) area of the 49 counties is 540.5 ± 395.3 mi$^2$ (median = 528.6 mi$^2$), and average population was 511,146 ± 453,846 (median = 433,501). About three-quarters of the monitors were in operation during that time. Births that were excluded because of a lack of monitors but were otherwise eligible were similar to births included in the analysis (see Supplemental Material, Table S1 (http://dx.doi.org/10.1289/ehp.1104763)), but included a higher fraction of white mothers (77.5% vs. 65.4%), a lower fraction of African-American mothers (16.2% vs. 25.3%), and a higher fraction of married mothers (68.1% vs. 59.6%). Births excluded for reasons other than a lack of monitors differed with regard to exclusion criteria (e.g., gestational week, birth weight), but were similar to study births with respect to mother’s race, age, marital status, and education.

Table 1. Characteristics of study births (n = 1,207,800).

| Characteristic                      | Mean ± SD or n(%) |
|------------------------------------|-------------------|
| Birth weight (g)                   | 3385.9 ± 472.8    |
| Low birth weight (< 2,500 g)       | 34,038 (2.8)      |
| Sex                                |                   |
| Male                               | 614,923 (50.9)    |
| Female                             | 592,877 (49.1)    |
| Race                               |                   |
| White                              | 789,682 (65.4)    |
| African American                   | 305,798 (25.3)    |
| Other                              | 112,320 (9.3)     |
| Maternal age (years)               |                   |
| < 20                               | 99,017 (8.2)      |
| 20 to 24                           | 249,077 (20.6)    |
| 25 to 29                           | 323,322 (26.8)    |
| 30 to 34                           | 324,221 (26.8)    |
| 35 to 39                           | 173,093 (14.3)    |
| ≥ 40                               | 39,070 (3.2)      |
| Maternal marital status            |                   |
| Married                            | 720,088 (58.6)    |
| Single                             | 487,712 (40.4)    |
| Maternal education                 |                   |
| Less than high school              | 214,063 (17.7)    |
| High school                        | 327,399 (27.1)    |
| Some college                       | 261,206 (21.6)    |
| College                            | 394,363 (32.7)    |
| Unknown                            | 10,769 (0.9)      |
| Maternal alcohol consumption during pregnancy | 3,785 (0.3) |
| Yes                                | 688,991 (57.1)    |
| No                                 | 515,024 (42.6)    |
| Maternal tobacco consumption during pregnancy | 94,559 (7.8) |
| Yes                                | 1,108,456 (91.6)  |
| No                                 | 6,765 (0.6)       |
| Length of gestation (weeks)        |                   |
| 37 to 38                           | 341,094 (28.2)    |
| 39 to 40                           | 639,772 (53.0)    |
| 41 to 42                           | 193,700 (16.0)    |
| 43 to 44                           | 33,234 (2.8)      |

Average male birth weight was 3446.9 ± 478.2 g, with 2.3% LBW. Female birth weight was 3322.7 ± 458.5 g, with 3.4% LBW. About two-thirds of mothers were Caucasian and one-quarter were African American (Table 1). More than 80% of mothers had high school or higher education. From those born in 2000 and 2001, we had fewer study subjects compared with other years because fewer PM$_{2.5}$ chemical component monitors were in operation during that time.

Associations between confounder variables and LBW, which exclude pollutant exposures, were generally consistent with previous research indicating higher risks of LBW for LBW, which exclude pollutant exposures, were generally consistent with previous research indicating higher risks of LBW for

Table 2. Summary statistics of gestational pollutant exposures.

| Pollutant                          | Mean ± SD or IQR |
|------------------------------------|-------------------|
| PM$_{2.5}$ total mass (μg/m$^3$)    | 22.34 ± 4.31      |
| PM$_{10}$ total mass (μg/m$^3$)     | 13.41 ± 2.05      |
| PM$_{2.5}$ chemical components (μg/m$^3$) | 0.019 ± 0.010 |
| Aluminum (Al)                      | 0.019 ± 0.010     |
| Cadmium (Cd)                       | 0.0159 ± 0.00086  |
| Calcium (Ca)                       | 0.046 ± 0.023     |
| Chlorine (Cl)                      | 0.037 ± 0.031     |
| Elemental carbon (EC)              | 0.801 ± 0.324     |
| Lead (Pb)                          | 0.005 ± 0.003     |
| Mercury (Hg)                       | 0.001 ± 0.001     |
| Nickel (Ni)                        | 0.006 ± 0.006     |
| Nitrate (NO$_3^-$)                 | 1.836 ± 0.705     |
| OCM                                | 3.593 ± 0.964     |
| Silicon (Si)                       | 0.07474 ± 0.03037 |
| Sodium ion (Na$^+$)                | 0.154 ± 0.095     |
| Sulfate (SO$_{4}^{2-}$)            | 1.486 ± 0.895     |
| Titanium (Ti)                      | 0.00417 ± 0.00175 |
| Vanadium (V)                       | 0.0023 ± 0.00057  |
| Zinc (Zn)                          | 0.019 ± 0.010     |
| Gaseous pollutants (ppm)           |                   |
| CO                                 | 0.529 ± 0.194     |
| ND$_{2}$                           | 0.021 ± 0.007     |
| SO$_{2}$                           | 6.08 ± 2.52      |
instance, relative risk is higher in urban areas (e.g., Manhattan, New York), than rural areas (e.g., New Hampshire).

Interquartile range (IQR) increases in PM\textsubscript{2.5} chemical components of aluminum, calcium, elemental carbon, nickel, silicon, titanium, and zinc were significantly associated with LBW (Table 4). IQR increases in PM\textsubscript{10}, CO, NO\textsubscript{2}, and SO\textsubscript{2} also were positively associated with LBW, whereas O\textsubscript{3} showed a statistically significant negative association with LBW. When evaluated among first births only, the significant associations with chemical components remained except for silicon (\(\rho = 0.0504\)). Associations were no longer significant for PM\textsubscript{10} and the gaseous pollutants, although the directions of the associations were unchanged (Table 4).

We estimated effects by trimester for all pollutants that were significantly associated with LBW in single-pollutant models and report ranges of trimester-specific associations that were consistent across the main model and three sensitivity models (Table 5). Statistically significant associations were found for aluminum (all trimesters), calcium, nickel, silicon and zinc (third trimester), elemental carbon and titanium (first trimester), and protective effect for O\textsubscript{3} (first trimester). No consistent trimester results were found for other chemical components or gaseous pollutants (data not shown).

Only associations between LBW and aluminum, elemental carbon, nickel, and titanium were robust to adjustment for all co-pollutants with correlation < 0.5 (Figure 1). Results for other pollutants (calcium, silicon, zinc, CO, NO\textsubscript{2}, O\textsubscript{3}, SO\textsubscript{2}, PM\textsubscript{10}) were generally robust, but were not statistically significant after adjustment for at least one co-pollutant [see Supplemental Material, Figure S1 (http://dx.doi.org/10.1289/ehp.1104763)].

For pollutants with consistent associations with LBW in two-pollutant models (PM\textsubscript{2.5} aluminum elemental carbon, nickel, and titanium), we investigated whether associations differed by race or sex. The relative risk of LBW associated with an IQR increase in PM\textsubscript{2.5} elemental carbon was 7.3% (95% CI: 4.9; 9.6%) lower among infants of African-American mothers compared with white mothers, and 3.2% (95% CI: 0.8; 5.6%) lower for females compared with males. The relative odds of LBW with an IQR increase in PM\textsubscript{2.5} nickel were 10.2% (95% CI: 7.9; 12.4%) lower among infants of African-American mothers than for white mothers,
and 4.6% (95% CI: 2.2, 7.1%) lower for females than for males. Associations between aluminum and titanium and LBW did not exhibit statistically significant differences by race or sex (data not shown).

Discussion

To the best of our knowledge, this is the largest study to explore the association between PM$_{2.5}$ chemical composition and pregnancy outcomes. Chemical components of aluminum, calcium, elemental carbon, nickel, silicon, titanium, and zinc were identified as potentially harmful, whereas statistically significant positive associations were not observed for ammonium ion, arsenic, cadmium, chlorine, lead, mercury, nitrate, organic carbon matter, sodium ion, sulfate, or vanadium. Of the components, results for aluminum, elemental carbon, nickel, and titanium were robust to co-pollutant adjustment. These chemical components likely result from different sources. Although all components have multiple sources, traffic emissions are the major source of PM$_{2.5}$ elemental carbon, oil combustion is the major source of PM$_{2.5}$ nickel, road dust is the major source of PM$_{2.5}$ aluminum, and crustal material is a primary source of PM$_{2.5}$ titanium (Bell et al. 2007a; Hains et al. 2007). Our results are consistent with our previous study conducted in Connecticut and Massachusetts, where PM$_{2.5}$ aluminum, elemental carbon, and nickel were associated with LBW (Bell et al. 2010).

Previous studies have reported associations between chemical component exposures and a range of health outcomes. For example, PM$_{2.5}$ elemental carbon was associated with hospitalization for childhood respiratory-related disease, and PM$_{2.5}$ nickel was associated with cardiovascular-related hospitalization (Ito et al. 2011; Ostro et al. 2009). We identified associations between birth outcomes and multiple PM$_{2.5}$ chemical components. As potential future work, researchers may apply source appointment or other methods to identify the origin of harmful pollutants (Lall et al. 2011), but source misclassification would be a potential concern given the size of our study region and heterogeneous distribution of PM$_{2.5}$ chemical components and sources (Bell et al. 2011). Location-specific source apportionment analysis may be necessary for large study areas or when the distribution of PM$_{2.5}$ sources varies within a study area.

For gaseous pollutants, LBW was associated with exposure to CO, NO$_2$, and SO$_2$. Our results also indicated a negative association between O$_3$ and LBW. Some of these results (i.e., CO, NO$_2$, SO$_2$) are similar to those from previous studies (Darrow et al. 2011; Wu et al. 2011). However, none of the gaseous pollutants were significantly associated with LBW in first-birth-only analyses or based on two-pollutant models. This may indicate that previous pregnancy history is not fully taken into account in our model, or that gaseous pollutants are acting as surrogates for other pollutants. Other statistical approaches are needed to clarify potential effects of these exposures, such as longitudinal models or more sophisticated multipollutant models.

Associations between LBW and individual pollutants differed by trimester. Higher exposure of specific pollutants in the first trimester may relate to placenta development, whereas exposure in later stages may affect

Table 5. Percent change in risk of LBW per IQR increment in pollutant for trimester exposure.

| Pollutant       | Trimester | Lowest effect to highest effect across multiple models |
|-----------------|-----------|------------------------------------------------------|
| PM$_{2.5}$ total mass | 3rd       | 2.8 to 3.0                                           |
| Aluminum        | 1st       | 1.5 to 2.6                                           |
| Calcium         | 2nd       | 1.7 to 3.0                                           |
| Elemental carbon| 3rd       | 2.5 to 2.8                                           |
| Nickel          | 1st       | 2.1 to 3.5                                           |
| Silicon         | 3rd       | 3.4 to 5.0                                           |
| Titanium        | 3rd       | 1.3 to 1.4                                           |
| Zinc            | 3rd       | 2.1 to 3.0                                           |
| O$_3$           | 1st       | -5.0 to -4.7                                         |

Results are presented for pollutants and trimesters with consistent significant associations across the trimester models referenced in the methods section. Numbers are the range of effect in the alternative trimester models. No consistent trimester associations were observed for CO, NO$_2$, and SO$_2$. Each model was adjusted by maternal race, marital status, tobacco and alcohol consumption during pregnancy, highest education, and age; infant sex; gestational length; the trimester prenatal care began; first in birth order; delivery method; averaged AT for each trimester; season of birth; year of birth; and regional indicators.

Figure 1. Percent change in relative risk of LBW per IQR increment in selected pollutants for gestational exposure with single (labeled as “None”) and two-pollutant (including the pollutant listed to the left of the estimate plus the pollutant indicated next to each estimate) logistic regression models. The point represents the central estimate and the horizontal line represents the 95% CI. See Table 4 for abbreviations.
maternal vascular alteration, which causes the fetal growth retardation (Lin and Santolaya-Forgas 1999; Mannes et al. 2005). We found statistically significant associations with LBW for exposure during the first trimester to PM$_{2.5}$ aluminum, elemental carbon, and tita-
nium; for exposure in the second trimester for PM$_{2.5}$ aluminum; and for exposure dur-
during the third trimester to PM$_{10}$ and PM$_{2.5}$ aluminum, calcium, nickel, silicon, and zinc. Some of these trimester results are consistent with our previous research in Connecticut and Massachusetts (Bell et al. 2010); how-
ever, other studies have reported associations with exposures during different trimesters. For instance, a study in California found that exposures to PM$_{10}$ and PM$_{2.5}$ in the first tri-
ster were associated with LBW (Morello-Frosch et al. 2010), and in Spain exposure to
NO$_2$ in the first trimester was associated with LBW (Ballester et al. 2010). These inconsis-
tencies might relate to differences in the study area or study design. Another potential reason
is misclassification of the gestational exposure, because many studies, including the present study, determine gestational exposure based on the LMP and gestational length reported by
birth certificate. LMP is likely reported as an approximate date rather than the actual
LMP, resulting in a less accurate delivery date (Bell et al. 2007b). This approximation could
lead to exposure misclassification that would have a larger effect on trimester-specific expo-
sures than on average gestational exposures. Further studies are needed using actual birth
date along with gestational week. Additional study is needed to better understand effects
by trimester, which may inform understand-
ing of high risk periods by exposing ambient
air pollutants.

We observed that associations of LBW with PM$_{2.5}$ elemental carbon and nickel were
stronger among male infants than female infants and among infants of white mothers
than infants of African-American mothers. These findings differ from a previous study that
reported stronger associations between LBW and PM$_{2.5}$ total mass among infants of
African-American mothers than among those of white mothers (Bell et al. 2007b). This
issue warrants further study to better under-
stand susceptibilities.

The biological mechanisms that may contribute to effects of air pollution on birth
outcomes are uncertain, and various hypoth-
eses exist. For instance, NO$_2$ exposure during pregnancy may limit placental vascular func-
tion and disturb fetal growth (Clifton et al. 2001). CO may react with oxygen on hemo-
globin-binding sites, reducing oxygen delivery (Maisonet et al. 2004). Fetal growth may be
retarded by direct toxic effects of air pollu-
tion, similar to effects of smoking (Ritz and
Yu 1999). The mechanism of PM effects on
birth outcomes could be related to the trans-
fer of toxic components to the fetus from PM
that has accumulated in the mother’s lungs
(Ritz et al. 2007). PM has a complex chemi-
cal composition, and its chemical compo-
nants may affect outcomes through different
biological pathways. One possible explanation
is that exposure to PM$_{2.5}$ metal-related com-
ponents, including aluminum and titanium,
increases oxidative stress burdens leading to
adverse health outcomes (Wei et al. 2009).

There is a need for further studies to under-
stand how individual PM$_{2.5}$ chemical compo-
nents and combinations of components affect
the fetus.

Limitations of this study include the reli-
ance on birth certificate data. Some previous
works have described shortcomings regarding
birth certificate variables, especially for
tobacco and alcohol use, prenatal care, preg-
nancy complications, and labor (Dobie
et al. 1998; Northam and Knapp 2006). In fact,
our results showed unknown smoking
status as a risk factor for LBW [see
Supplemental Material, Table S4 (http://
 dx.doi.org/10.1289/ehp.1104763)], suggest-
ing that those with unknown smoking status
were more likely to have been smokers
than nonsmokers, because maternal tobacco
consumption affects LBW (Darrow et al.
2006; DiFranza et al. 2004; Horta et al. 1997;
Parker and Woodruff 2008). On the other
hand, several researchers investigated the reli-
ability and validity of birth certificate data,
and concluded that the data are adequate for
adjustment purposes, though they warranted
cautions (Honein et al. 2001; Roohan et al.
2003). The reliability and validity of birth cer-
dificate data are not fully known; however,
the key variables of interest for our study (i.e.,
birth weight, residence) are likely to be reli-
able and have some of the highest validity of
any birth certificate variables (Northam and
Knapp 2006; Shaw and Malcoe 1992). A fur-
ther challenge is that levels of some chemical
components, such as arsenic, might be below
the minimum detection limit, which could
lead to exposure misclassification. In our data,
> 25% of arsenic measurements were zero,
which may be attributable to levels that were
below the detection limit. Another limitation
is that we estimated exposures by residential
county at birth, and were not able to incorpo-
rate actual address or prior residences if moth-
ers moved during pregnancy. In addition, this
approach does not address spatial heterogene-
ity of pollutants within a county, which may
be particularly important for larger counties
(Peng and Bell 2010). Exposure misclassifica-
tion may occur for residents living far from
monitors. In our data, the maximum distance
from a monitor to the border of a county
was 75.6 km (Essex County, NY). A recent
study showed that correlations between levels
of some PM$_{2.5}$ chemical components were
low for paired monitors that were < 10 km
away (Bell et al. 2011). Our analysis omitted
many births because many counties do not
have PM$_{2.5}$ chemical component monitors
[see Supplemental Material, Table S1 (http://
dx.doi.org/10.1289/ehp.1104763)]. Further,
ambient monitors are warranted at more loca-
tions and with more frequent observations.
Monitors in suburban and rural counties are
particularly needed because monitors tend to
be in urban counties, which may hinder study
of the full range of population characteristics
(Bravo and Bell 2011; Miranda et al. 2011).
A larger study could also address potential
differences in effects across types of locations,
such as urban versus rural, because most of the
counties in our data set were urban. In terms
of residential mobility during pregnancy, our
approach may not introduce substantial mis-
classification because recent studies found
that most moving takes place within a short dis-
tance, though this is worthy of future studies
(Bell and Belanger 2012; Madsen et al. 2010).
Further limitations are that birth certificate
data do not contain parental weight or genetic
information. Several studies have reported that
these factors are also linked to LBW (Freathy
et al. 2010; Frederick et al. 2008).

Conclusions

We found evidence of links between air pol-
lation—including PM$_{2.5}$ chemical compo-
nents and gaseous pollutants—and LBW. We
observed these associations even though most
of our study region, except for a few large city
areas, was in compliance with the National
Ambient Air Quality Standards for PM$_{2.5}$
and PM$_{10}$, and all of the study region was in
compliance with regulatory standards for CO,
SO$_2$, and NO$_2$ (U.S. EPA 2009). Our results
suggest that prenatal exposures to some PM$_{2.5}$
chemical components may be more harmful
than others, but current regulations are based
exclusively on particle size and mass concen-
tration. Our findings also suggest that even if
two regions had identical levels of PM$_{2.5}$
total mass, one might have levels of PM$_{2.5}$
chemical components that result in higher risks
of LBW. This is likely true for other health out-
comes; our previous studies found that some
specific chemical components are associated
with hospital admission (Bell et al. 2009).
Further scientific evidence on which compo-
nents and sources of PM$_{2.5}$ are most harm-
ful would aid decision makers in developing
policies intended to protect public health.
Additional studies covering different regions,
using more detailed birth data, and investigat-
 ing other birth outcomes (such as preterm
birth and small for gestational age) are needed
in early pregnancy to estimate the differential toxicity of various
kinds of pollutants, including PM$_{2.5}$
chemical components, on birth outcomes.
