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Ambient air pollution and term birth weight in Texas from 1998 to 2004

Laura A. Geer^{1,*}, Jeremy Weedon², and Michelle L. Bell³

¹Department of Environmental and Occupational Health Sciences, State University of New York, Downstate School of Public Health, Brooklyn, New York, USA

²Department of Epidemiology and Biostatistics, State University of New York, Downstate School of Public Health, Brooklyn, New York, USA

³Yale School of Forestry and Environmental Studies, Environmental Engineering and Epidemiology/Public Health, Yale University, New Haven, Connecticut, USA

Abstract

Previous studies have explored the association between air pollution levels and adverse birth outcomes such as lower birth weight. Existing literature suggests an association, although results across studies are not consistent. Additional research is needed to confirm the effect, investigate the exposure window of importance, and distinguish which pollutants cause harm.

We assessed the association between ambient pollutant concentrations and term birth weight for 1,548,904 births in TX from 1998 to 2004. Assignment of prenatal exposure to air pollutants was based on maternal county of residence at the time of delivery. Pollutants examined included particulate matter with aerodynamic diameter 10 and 2.5 μm (PM_{10} and $\text{PM}_{2.5}$), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), carbon monoxide (CO), and ozone (O_3). We applied a linear model with birth weight as a continuous variable. The model was adjusted for known risk factors and region. We assessed pollutant effects by trimester to identify biological exposure window of concern, and explored interaction due to race/ethnicity.

An interquartile increase in ambient pollutant concentrations of SO_2 and O_3 was associated with a 4.99-g (95% confidence interval [CI], 1.87–8.11) and 2.72-g (95% CI, 1.11–4.33) decrease in birth weight, respectively. Lower birth weight was associated with exposure to O_3 in the first and second trimester, whereas results were not significant for other pollutants by trimester. A positive association was exhibited for $\text{PM}_{2.5}$ in the first trimester. Effects estimates for PM_{10} and $\text{PM}_{2.5}$ were inconsistent across race/ethnic groups.

Current ambient air pollution levels may be increasing the risk of lower birth weight for some pollutants. These risks may be increased for certain racial/ethnic groups. Additional research including consideration of improved methodology is needed to investigate these findings. Future studies should examine the influence of residual confounding.

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*Please address correspondence to: Laura A. Geer, Assistant Professor, Department of Environmental and Occupational Health Sciences, State University of New York, Downstate School of Public Health, 450 Clarkson Ave., Box 43, Brooklyn, NY 11203-2098, USA; laura.geer@downstate.edu.

Supplemental Materials: Supplementary information relating to characteristics of excluded births, distribution of air pollutant monitors by pollutant, and correlation coefficients of the air pollutants is available in the publisher's online edition of the *Journal of the Air & Waste Management Association*.

Introduction

Previous research suggests an association between maternal exposure to air pollution and adverse birth outcomes, including low birth weight (LBW), preterm birth, intrauterine growth restriction, and post-neonatal infant mortality (Glinianaia et al., 2004; Lacasana et al., 2005; Maisonet et al., 2004; Sapkota et al., 2010; Woodruff et al., 2008; Wu et al., 2009). Infant birth weight is an important predictor of infant survival (Hogue et al., 1987). In addition to more acute infant health effects associated with reduced birth weight including respiratory distress, variable heart rate, cerebral palsy, and deafness, restriction of fetal growth has been associated with delays in motor and social development in children (Jedrychowski et al., 2004; Miranda et al., 2009). Reduced birth weight has also been associated with adulthood disorders such as cardiovascular disease, diabetes, and obesity (Ashdown-Lambert, 2005; Miranda et al., 2009; Vos et al., 2006).

Results of studies on the association between air pollution and birth weight are not always consistent, with differing pollutants and exposure periods identified by study. For instance, higher levels of carbon monoxide (CO) and particulate matter (PM) with an aerodynamic diameter $10\text{ }\mu\text{m}$ (PM_{10}) were associated with reduced birth weight in some studies (Bell et al., 2007b; Dejmek et al., 1999; Gouveia et al., 2004; Ha et al., 2001; Maisonet et al., 2001; Mannes et al., 2005; Ritz et al., 2000; Salam et al., 2005; Wilhelm and Ritz, 2003; Wilhelm and Ritz, 2005; Xu et al., 2001; Yang et al., 2003), whereas no association was identified in other studies (Bobak, 2000; Chen et al., 2002; Lin et al., 2004; Maisonet et al., 2001; Parker et al., 2005). Parker and Woodruff (2008) divided the United States into seven different regions for spatial comparison of pollutant associations with birth weight. Their results suggest that regional differences in pollutant composition may account for varied results for PM with an aerodynamic diameter $2.5\text{ }\mu\text{m}$ ($\text{PM}_{2.5}$) and PM_{10} across studies (Parker and Woodruff, 2008). For example, associations were found with coarse particles but not with fine particles in some regions. They partially attribute differences in effects estimates across study regions to differences in pollutant composition. Inconsistency across studies is also likely due to methodological differences such as exposure assignment, pollutants included for comparison, and variation in adjustment for confounders (Woodruff et al., 2010).

Finding from these previous studies are varied and warrant further consideration. To address some of these inconsistencies, we performed a study of ambient air pollutant concentrations and term birth weight in Texas, while adjusting for relevant confounders such as maternal characteristics and region. To the best of our knowledge, this is the largest study examining pregnancy outcomes and criteria air pollutants in Texas. This state is comprised of multiple metropolitan regions with a myriad of industrial/petrochemical and mobile sources contributing substantially to air pollution emissions, presenting challenging regulatory concerns. In this research we examined the effects of air pollution on term birth weight over a 6-year period for sulfur dioxide (SO_2), nitrogen dioxide (NO_2), CO, ozone (O_3), PM_{10} , and $\text{PM}_{2.5}$, and explored effects by gestational and trimester exposure. We also explored whether effects differed by race/ethnicity to investigate whether some segments of the population are disproportionately affected by air pollution.

Methods

Birth data

We accessed birth certificate records from the Texas Department of State Health Services, Vital Statistics Unit, for all births beginning January 1, 1998, to December 31, 2004 ($n = 2,550,957$). Data collected from birth records included maternal county of residence at time of birth; last menstrual period (LMP); month prenatal care began; mother's characteristics (age, race/ethnicity, marital status, education, and alcohol and tobacco use during

pregnancy); gestational age in weeks; birth order; parity; type of birth; type of delivery; sex of child; and birth weight. Excluded births included those births with missing data for weight (0.1%), births with weight <1,000 g or >5,500 g (0.7%), births missing gestational age (7.5%), births with gestational period >44 weeks or <37 weeks (5.0%), unspecified county location for maternal residence (0.1%), multiple pregnancy (2.8%), and births with impossible gestational age and birth weight combinations and codes for missing data (e.g., birth weight as 9999) (9.4%) (Alexander et al., 1996). These restrictions were applied in earlier work (Bell et al., 2007b). Births were omitted if LMP data were missing (9.3%). Multiple exclusion criteria might apply to a single observation. Using the estimated date of conception (14 days from LMP), we calculated trimester divisions for the first trimester (first 91 days), second trimester (second 91 days), and third trimester (remaining days of pregnancy); similar definitions have been applied elsewhere (Bell et al., 2007b; Parker et al., 2005; Rich et al., 2009). Births were not included in the analysis of a particular pollutant if the county of residence did not have a monitor for that pollutant. Characteristics of excluded births are summarized in supplemental Table S1. The distributions of excluded mothers' age, ethnicity, and education level were similar to the sample analyzed. After excluding 38.2% of births, 1,548,904 births remained.

Pollution data

Daily average concentrations were estimated for the pollutants O₃, PM₁₀, PM_{2.5}, SO₂, NO₂, and CO for each county for the years 1997–2004. Data were obtained from the U.S. Environmental Protection Agency Air Quality System (2008). Most monitors collected hourly levels for gaseous pollutants and 24-hr averages for particles. Not all pollutants had data for every day. The number of monitors varied by county, and averages were obtained from a single monitor or an average of multiple monitors within the county. The frequency of monitor type per county is summarized in supplemental Table S2.

Assignment of prenatal exposure to air pollutants was based on maternal county of residence. For each pregnancy, we first generated weekly averages for each pollutant using an average of measured levels by monitors within the county of the mother's residence at time of delivery. Then we combined each pregnancy's weekly averages to estimate each mother's air pollution exposure over the gestational period and for each trimester of pregnancy. This approach avoids biasing exposure estimates based on differences in measurement frequency, such as more measurements in one portion of the pregnancy than another. The method to generate exposure estimates has been applied in previous work (Bell et al., 2007b). Not all monitors or counties collected data over the entire study period. To prevent inaccurate exposure estimates due to data gaps or seasonal measurements, we excluded births if the mother's county of residence had no pollution monitors (22% of births), or if air pollutant data were not available for 75% of the weeks in each trimester for that pollutant. Characteristics of excluded births due to missing pollution data are summarized in supplemental Table S3.

Data from 40 of 254 Texas counties were included in the analysis: Bexar, Bowie, Brazoria, Brewster, Caldwell, Cameron, Cass, Collin, Dallas, Denton, Ector, Ellis, El Paso, Galveston, Gregg, Harris, Harrison, Hays, Hidalgo, Hood, Hunt, Jeff Davis, Jefferson, Johnson, Kaufman, Kleberg, Lubbock, McLennan, Marion, Montgomery, Nueces, Orange, Parker, Potter, Rockwall, Smith, Tarrant, Travis, Victoria, and Webb. Approximately 78% of all births occurred in these 40 counties. The county with the largest land area is Brewster with 6,097 mi², a population density of 1 persons/mi², and 6 monitors, and the smallest county is Rockwall with 148 mi², 173 persons/mi², and 1 monitor.

Meteorologic data

Meteorologic factors associated with temperature discomfort, including county-level temperature and dew-point temperature, were incorporated into our analysis (Kalkstein and Valimont, 1986). Wind speed was included in the analysis because it factors into the calculation of apparent temperature at higher temperatures (Kalkstein and Valimont, 1986). Seasonal variability in birth weight has been associated with temperature in previous studies (Lawlor et al., 2005; Murray et al., 2000). Daily measurements of temperature variables were obtained from the National Climatic Data Center (2006), and averages of each were generated based on the same procedure described for air pollutants.

Modeling design

We assessed the association between nonpollutant variables and term birth weight in a linear model (Basu et al., 2004; Bell et al., 2007b; Parker and Woodruff, 2005; Woodruff et al., 2003). Term birth weight was included as a continuous variable. Resultant, statistically significant variables were included as potential confounders in multipollutant linear models to examine gestational pollutant exposure.

We adjusted all models for previously identified risk factors for lower birth weight, including: mother's age (Khoshnood et al., 2005; Valero de Bernabe et al., 2004), prenatal care (Shi et al., 2004; Valero de Bernabe et al., 2004), maternal smoking and educational status (Kleinman and Madans, 1985; Valero de Bernabe et al., 2004), race/ethnicity (Alexander et al., 2003; Valero de Bernabe et al., 2004), and socioeconomic factors (Valero de Bernabe et al., 2004). Ritz and Wilhelm (2008) found that adjusting for covariates found on birth certificates, as a routine source of data for pregnancy studies, is sufficient to remove most confounding due to behavioral factors. Models were adjusted for factors that might influence exposure and birth weight, including mother's marital status (married/unmarried), tobacco use during pregnancy (yes/no), alcohol use during pregnancy (yes/no), and education (<12 years, 12 years, 13–15 years, >15 years, unknown). To incorporate the nonlinear relationship between mother's age and birth weight (Khoshnood et al., 2005), models contained categorical variables of mother's age (<20, 20–24, 25–29, 30–34, 35–39, > 39 years). Mother's race/ethnicity was defined as non-Hispanic white, non-Hispanic black, Hispanic, and non-Hispanic other. The “other” category incorporates race/ethnicities for which separate analysis was prohibited by sample size (e.g., includes North American Indian, South or Central American Indian, Chinese, Asian Indian, Japanese, Korean, Hawaiian, Samoan, Filipino, Vietnamese, Other Asian, and Guamanian).

For all models, we adjusted for possible regional differences in pollutant concentrations and covariates by adding indicator variables for 10 of the 11 Texas Health Service Regions into the model, which reflect local and regional public health coverage (Texas Department of State Health Services, 2010). State-participating local health departments and public health districts in Texas are sponsored by the Department of Health Services. This state agency is responsible for bringing comprehensive public health services to the citizens. Texas Public Health Region 2 was omitted due to limited air monitoring data for that region. Such an adjustment can potentially address residual confounding by capturing differences in social and physical contextual factors across regions, including urban/rural, population density, racial distribution, community-level socioeconomic status, access to health services, and even climatological differences and differences in pollutant source. For example, Zeka et al. (2008) found that greater open space land in the census tract had a protective effect for birth weight. We applied pollutant/race/ethnicity exposure interaction terms into the model to investigate whether air pollution's effects on term birth weight differed by race/ethnicity.

Additional covariates included meteorologic variables such as temperature, humidity, and wind speed, and indicator variables for neonate's gender, type of delivery (primary cesarean section, repeat cesarean section, vaginal birth), the time frame in which prenatal care began (first, second, or third trimester; no care), first in birth order (yes/no), gestational duration (37–38, 39–40, 41–42, 43–44 weeks), and year of birth.

To examine potential confounding associated with gestational co-pollutant exposure, we implemented two pollutant linear models, including pollutants that were statistically significant in single pollutant models. We excluded pollutant pairs that were highly correlated or exhibited known links in formation pathways.

To assess gestational pollutant exposure by trimester, we used a linear model and assigned exposure averages for each trimester. We addressed potential covariance among variables representing trimester exposures using a sensitivity analysis with a model that used trimester exposures as: (a) $P_{a,j}^i$ = exposure to pollutant j over trimester a for birth i ; (b) residuals of $E[P_{b,j}^i] = \beta_1 + \beta_2 P_{a,j}^i$, representing exposure to pollutant j over trimester b for birth i , adjusted for exposure over trimester a ; and (c) residuals of the model $E[P_{c,j}^i] = \beta_3 + \beta_4 P_{a,j}^i + \beta_5 P_{b,j}^i$, representing exposure to pollutant j over the trimester c for birth i , adjusted for exposure over trimesters a and b . The β values are regression coefficients, in which β_1 and β_3 represent intercepts, β_2 represents the association between exposure in trimesters a and b (i.e., change in exposure in trimester b associated with a unit increase in exposure in trimester a), β_4 represents the association between exposure in trimesters a and c adjusted for exposure in trimester b , and β_5 represents the association between exposure in trimesters b and c adjusted for exposure in trimester a . This analysis was repeated with each trimester used as the initial reference trimester (i.e., trimester a). This approach was applied to earlier research on air pollution and pregnancy outcomes to address pollutant concentration correlation by trimester (Bell et al., 2007b).

Results

Of the 1,548,904 births considered in the analysis, 43,369 (2.8%) were characterized as LBW (<2,500 g), with 789,941 (51%) male and 758,962 (49%) female. Mothers were predominantly married, 1,068,743 (69%), and Hispanic, 789,941 (51%), with a mean age of 26.5 years. Descriptive statistics of the study population and variables including weather and pollutant exposure data are provided in Table 1.

Air pollution concentrations during the gestational period were correlated for some pollutants, with the strongest relationships for CO and SO₂ ($r = 0.60$), and NO₂ and CO ($r = 0.50$). Correlations are supplied in Table S4 of the supplemental material.

Findings of the linear model exploring the associations between nonpollution variables and term birth weight are presented in Table 2. Decreases in term birth weight were associated with female infants; shorter gestational periods; maternal tobacco and alcohol use; less maternal education; prenatal care beginning later in pregnancy; unmarried; older or younger mothers; non-white race/ethnicity for the mother; being first in birth order; and with some Texas Public Health Service Regions.

Model results of the association between single-pollutant gestational exposure and term birth weight are presented in Table 3. Higher exposure to SO₂ and O₃ were associated with reduced birth weight in the model. A positive and statistically significant association of higher birth weight with higher exposure was seen for PM₁₀ and PM_{2.5}. No association was identified between term birth weight and NO₂ or CO concentrations.

Results from two-pollutant linear models, comparing pollutants with and without co-pollutant adjustment, are presented in Figure 1. Results for all pollutants considered in the multivariate analysis were robust to co-pollutant adjustment.

Because trimester exposures are often correlated for any given pollutant, we calculated trimester correlations: 0.42, 0.71, and 0.69 for CO; 0.73, 0.49, and 0.74 for NO₂; 0.52, 0.54, and 0.30 for PM₁₀; 0.52, 0.52, and 0.31 for PM_{2.5}; 0.75, 0.76, and 0.60 for SO₂; and 0.09, 0.13, and -0.16 for O₃. We performed an analysis including all trimesters of exposure in the linear model to examine associations with term birth weight, and an analysis of adjusted trimester exposures as described in the Materials and Methods section. Results that were consistent across all trimester models are provided in Table 4. Reduced birth weight was associated with exposure in the first and second trimester for O₃, and in the first trimester for PM_{2.5}, although particle results exhibited a positive association.

We examined the potential effects of race/ethnicity on the association between gestational air pollution exposure and term birth weight using an interaction term for race/ethnicity and gestational exposure in the model (Table 5). Reductions in birth weight were associated with an increase in gestational exposure to the air pollutants SO₂ for Hispanic mothers, to O₃ for non-Hispanic black and non-Hispanic white mothers, and to PM₁₀ for non-Hispanic white mothers compared with mothers of other race/ethnic groups. Higher birth weight was associated with an increase in gestational exposure to the air pollutants PM₁₀ and PM_{2.5} in Hispanic mothers, and to PM₁₀ in non-Hispanic black mothers, compared with mothers of the other race/ethnic groups.

Discussion

Our study explored the association between gestational air pollution exposure to SO₂, NO₂, CO, O₃, PM₁₀, and PM_{2.5} and reduced birth weight. In additional analyses, we explored impacts of pollutant exposure by trimester, and the potential effect modification of race/ethnicity on these associations. Our results suggest an association between reduced birth weight and gestational exposure to SO₂ and O₃, and independent effects during the first and second trimesters for O₃. Positive associations found for particles need to be further explored.

Comparison of results with other studies

Our findings for SO₂ and O₃ are consistent with several studies exhibiting effects for these pollutants (Bobak, 2000; Ha et al., 2001; Liu et al., 2003; Maisonet et al., 2001; Morello-Frosch et al., 2010; Ritz et al., 2000; Rogers et al., 2000; Salam et al., 2005). Ozone was also associated independently with observed effects in the first and second trimesters. This is in comparison with effects observed for the second and third trimesters by Salam et al. (2005). In our study SO₂ was associated with decreased birth weight over the entire gestational period, in contrast to observed first-trimester (Bell et al., 2007b; Liu et al., 2003) and second-trimester (Maisonet et al., 2001) effects identified in previous studies.

Similar to our findings, some studies did not find an association between CO and infant birth weight (Maisonet et al., 2001; Parker et al., 2005; Ritz and Yu, 1999). In contrast to our study results, in previous studies low-birth-weight effects were associated with both CO (Bell et al., 2007b; Maisonet et al., 2001; Ritz and Yu, 1999; Salam et al., 2005; Wilhelm and Ritz, 2005), and NO₂ (Brauer et al., 2008).

The pollutants PM₁₀ (Chen et al., 2002; Dejmek et al., 1999; Gouveia et al., 2004; Ha et al., 2001; Rogers and Dunlop, 2006; Salam et al., 2005; Wilhelm and Ritz, 2005; Xu et al., 2011; Yang et al., 2003) and PM_{2.5} (Bell et al., 2007b; Jedrychowski et al., 2004; Ritz et al.,

2007; Slama et al., 2007) have also been associated with low birth weight in earlier work. In our study, however, we observed higher birth weight with higher PM. Similar results were found in a nationwide study by Parker and Woodruff (2008), where PM_{2.5} concentrations were positively associated with birth weight in some regions. An earlier study found no association for both PM_{2.5} and PM₁₀ in southwestern Texas, and a decrease in birth weight in southeastern Texas was associated with PM₁₀, but not PM_{2.5} (Parker and Woodruff, 2008). The results for PM and birth weight have varied by study, with a range of null, negative, and positive results across studies. Inconsistent results across studies could be caused by differences in populations, collinearity of pollutants, and variations in the exposure assessment. Additional studies suggest that spatial and temporal heterogeneity in PM composition may partially explain the differing effects estimates from studies of PM and risk of hospital admissions (Bell et al., 2009; Peng et al., 2005). In a Connecticut and Massachusetts-based study, Bell et al. (2010a) found variations in effects estimates for birth weight for different particulate constituents of PM_{2.5}. Differences in the composition and source of PM may contribute to variation of results across studies and regions (Bell et al., 2007a, 2010b). For example, differences in birth weight by Texas Public Service Region may be partially attributed to differences in air pollution mixtures, particularly with respect to differing chemical structure of particles (e.g., constituents of PM_{2.5}). As PM_{2.5} chemical components exhibit different spatial heterogeneity (Bell et al., 2010b), studies' results may be affected by the method to assess exposure. Considering recent findings from the literature (Sapkota et al., 2010), it is plausible that particulate pollutant exposure is a stronger risk factor for preterm birth than for term LBW. This would potentially confound associations with term LBW by increasing the number of small-for-gestational-age (SGA) infants born prematurely.

Effect modification by race/ethnicity

Some populations may have disproportionate burdens from air pollution caused by increased susceptibility to effects of pollutants due to psychosocial stressors (Zeka et al., 2008), lower baseline health status and access to health and social resources during pregnancy, and behaviors that lead to increased susceptibility (e.g., increased use of drugs and alcohol, and inadequate weight gain during pregnancy) (Ponce et al., 2005).

In Texas, Hispanics are more likely than other race/ethnic groups to live in poverty, with approximately 25% considered poor in 1999 (Federal Reserve Bank of Dallas, 2010). Much of the disparity in income can be attributed to immigrant status resulting in less education and lower wages (Federal Reserve Bank of Dallas, 2010). Non-Hispanic blacks have the second highest percentage in poverty and the lowest median income level. Historically, non-Hispanic black women have experienced worse birth outcomes than non-Hispanic white women (Bell et al., 2007b; Maisonet et al., 2001; Miranda et al., 2009) and Hispanic women (Miranda et al., 2009).

In previous findings, non-Hispanic blacks have been identified as a group at high risk for reduced birth weight in association with pollutant effects (Bell et al., 2007b; Maisonet et al., 2001); however, in our study race/ethnicity findings were inconsistent. We found that for some pollutants, Hispanic and non-Hispanic blacks had higher effect estimates relating pollutants to birth weight than did other race/ethnicities. Though little data are available to provide evidence, possible explanations for these findings include:

1. Particulate pollutants in our study occurred in locations where Hispanics/non-Hispanic blacks were at lower risk of exposure to air pollution (e.g., due to improved housing, greater distance from roadways, etc.).
2. Source and composition of PM were less toxic in areas where Hispanics/non-Hispanic blacks resided in the study.

3. A scenario of competing risks whereby a possible stronger association with preterm birth results in a paradoxically increased birth weight for those born at term.

Differences in effects estimates by race/ethnicity could be due to differences in other baseline risk factors; however this issue needs to be further explored. Additional data suggest that risk levels for birth outcomes can vary within Latino/Hispanic ethnic communities; for example, Puerto Ricans in urban areas in the United States have a higher risk of infant mortality compared with Mexicans and Cubans (Sims et al., 2007). Similarly, differences in birth weight by Texas Public Service Region may be attributed to race/ethnicity and socioeconomic factors such as Hispanic ethnicity and percent below the poverty line. Timing and access to care and behaviors that lead to increased susceptibility may differ by region and influence birth weight. The extent to which pollutant levels and race/ethnicity correlate by region is also an area for future exploration.

Trimesters

It has been hypothesized that air pollution exposures in the first and third trimesters have the most effect due to susceptibility during periods of rapid fetal growth, although the biological mechanisms of effect are not fully understood (Wilhelm and Ritz, 2005). Data from recent studies support this theory (Bell et al., 2007b; Ritz et al., 2007). For example, trimester effects associated with PM₁₀ exposure were stronger for first- and third-trimester exposures (Parker and Woodruff, 2008), and with PM_{2.5} exposure for the first month and last 2 weeks of pregnancy (Huynh et al., 2006). Our results are consistent with increased effects estimates in the first trimester for O₃. However, we also observed effects for O₃ in the second trimester, as seen in Salam et al. (2005), and a positive association in the first trimester for PM_{2.5}. Additionally, it has been suggested that exposure assignment based on maternal residence at birth will increase exposure misclassification of first- and second-trimester exposure estimates, resulting in nondifferential bias of effects estimates toward the null (Sapkota et al., 2010). As a result, it is still unknown whether observed effects reflect increased susceptibility during specific windows of exposure. One strength of our study is an analytical method that addresses correlations among trimester exposures, which has not been incorporated in much of the earlier work. Greater understanding of mechanisms of toxicity will allow for more targeted assessment of exposure during the time period of highest concern.

Exposure estimation

Our approach for estimating exposure generates county-level estimates based on ambient monitoring data. Such estimates are based on the number of monitors and their locations in a county, the spatial distribution of the population in relation to monitors, and placement of monitors in relation to sources (e.g., monitors sited away from roadways and other areas with high-concentrations). Various studies suggest that county-level measurements depend on the geographical size of a county and could lead to varying levels of precision in exposure assignments (Parker and Woodruff, 2008). The use of ambient monitoring data may also introduce exposure misclassification due to time-activity patterns including commuting, time spent indoors (with exposures from environmental tobacco smoke [ETS], cooking and heating fuels, attached garages), occupational exposures, and local pollutant-specific heterogeneity due to such factors as proximity to traffic (Bell et al., 2010b; Slama et al., 2008; De Medeiros et al., 2009). More heterogeneity was found in pollution at a subcounty scale compared to between counties in California (Basu et al., 2004), and effects estimates were increased for within- versus between-city gradients for PM_{2.5} (Jerrett et al., 2005). Effects estimates for CO in models relying on stationary monitors are likely attenuated due to spatial heterogeneity from variations in indoor and outdoor sources (Ritz

and Yu, 1999). In Wilhelm and Ritz (2005), limiting their analysis to exposure estimates within 1 mile of monitors resulted in increased effects estimates for PM₁₀ and CO.

Alternative exposure methods have been developed to estimate residential exposures. Nearest and inverse-distance weighting for ambient monitoring values, land use regression models, and road proximity have been used to characterize impacts of vehicular traffic (Brauer et al., 2008; Genereux et al., 2008; Slama et al., 2007). Statistical methods have been developed to help address spatial heterogeneity of pollutants (Peng and Bell, 2010). Future work could explore the use of these exposure approaches; however, these methods often require data that may not be available for all studies (e.g., land-use characteristics, individual residential locations), and each has its own limitations.

Residential mobility

Our study bases exposure over pregnancy on the residence location at time of birth, although some mothers may have moved during pregnancy. Previous studies found that residential mobility rates during pregnancy range from 9% to 35% (Bell and Belanger, 2012; Brauer et al., 2008; Canfield et al., 2006; Fell et al., 2004; Khoury et al., 1988; Shaw and Malcoe, 1992). Moving alone does not indicate that exposure misclassification has occurred. In a Canadian study, longitudinal residential histories revealed that 62% of pregnant women who moved stayed within the same municipality, and 69% moving stayed within the same county (Fell et al., 2004). Various studies have found that the majority of moves are local and occur over short distances, and therefore do not have an effect on estimates of air pollution exposures (Chen et al., 2010; Kalkstein and Valimont, 1986; Lupo et al., 2010). Third-trimester exposures may have less misclassification than first-trimester exposures as women are closer to the date from which residence is obtained (i.e., date of delivery) (Bell et al., 2007b; Sapkota et al., 2010) and because in later pregnancy women may spend more time closer to home (Slama et al., 2008). In a Texas study, predictors of higher mobility during pregnancy included younger age, lower household income, white ethnicity, and nulliparity (Canfield et al., 2006). Madsen et al. (2010) found that multiparous mothers had less residential mobility. Thus, residential mobility may differ by study population, resulting in varying levels of exposure misclassification.

Physiological mechanisms

Studies have focused on ambient pollutant concentrations and outcomes such as risk for term birth weight <3,000 grams (Slama et al., 2007), SGA, very small for gestational age, and preterm birth (Parker et al., 2005; Ritz et al., 2007; Sims et al., 2007). Various studies have explored the biological mechanisms through which air pollutants could affect birth outcomes. Potential toxicological effects of air pollutants on birth outcomes include effects from oxidative stress and inflammation, heart-rate variability leading to alteration in cardiac function, and changes in blood coagulation, endothelial function, and hemodynamic responses (Ritz and Wilhelm, 2008). Several theories of action have been proposed, including compromised health of the mother through pulmonary inflammation leading to systemic effects, and direct action on the fetus such as through oxidative stress (Glinianaia et al., 2004). Some studies suggest evidence for the effects of O₃ on decreased birth weight (Salam et al., 2005). The proposed mechanism, through respiratory inflammatory processes, is possibly heightened in pregnant women, who may exhibit higher ventilation rates. Inflammation products released include lipid peroxidation products and inflammatory cytokines, which could adversely affect fetal growth (Salam et al., 2005). The biologic mechanisms for reproductive effects have been thought to be similar to the effects of tobacco smoke exposure, including fetal hypoxia due to increased levels of fetal carboxyhemoglobin and placental vasoconstriction (Salamsi et al., 2010). Future studies should explore the toxic mechanisms of air pollutants, such as PAH components of PM, and

other traffic-related pollutants (Kalkstein and Valimont, 1986). Identification of pollutant effects on reduced birth weight and other birth outcomes such as preterm birth has important implications for pollution exposure prevention in women of childbearing age.

Regulatory compliance

Most of the study area meets U.S. EPA's health-based National Ambient Air Quality Standards (NAAQS). A few exceptions include (1) carbon monoxide and PM₁₀ in El Paso and (2) 8-hr ground-level O₃ in Houston–Galveston–Brazoria, Dallas–Fort Worth, and Beaumont–Port Arthur (Texas Commission on Environmental Quality [TCEQ], 2010). Half of the counties included in the study area have been recommended for a “non-attainment” designation for the 8-hr O₃ standard of 0.075 ppm (U.S. EPA 2006). It is anticipated that several counties will be in noncompliance as new NAAQS are released, for example, for SO₂ and for PM_{2.5} (TCEQ 2010). This study suggests that associations between air pollution and low birth weight can occur even in areas with air pollution levels below regulatory standards.

Limitations and areas of future research

Limitations of this study include the lack of complete data on risk factors for reduced birth weight such as prepregnancy weight or weight gain, and detailed information on drinking and smoking, or lack of reporting thereof (Gouveia et al., 2004). Additional research could investigate issues of effect modification, such as whether smoking status modifies the relationship between air pollution and birth outcomes. Our data had a binary variable on smoking (yes/no) for whether the mother smoked during pregnancy (as self-reported on the day of delivery). More detailed data could include information on smoking history such as smoking prior to the pregnancy, smoking patterns during pregnancy (e.g., whether smoking was stopped during the pregnancy), and number of cigarettes per day. Maternal nutrition and underlying health status, as well as history of adverse pregnancy outcome, can also influence birth weight, but these measures are difficult to characterize and are not routinely available. Future studies should incorporate details on maternal health during pregnancy and expand the scope of perinatal outcomes.

Improved methods for assessment of exposure to spatially heterogeneous pollutants should also be implemented to address exposure misclassification. It is possible that pollutants in this study could be acting as proxies for other pollutants of similar sources, and that these proxies differ by region. More data are needed to determine whether these pollutants themselves are responsible for toxic effects or merely serve as proxies for other harmful components of mobile-source pollution.

Future studies should also carefully assess differential pollutant exposure as well as effect estimates by race/ethnicity with individual- and community-level social factors in order to enhance our understanding of how physical, social, and host factors influence birth outcomes.

Conclusions

Our findings confirm results found previously for adverse effects of the air pollutants SO₂ and O₃ on reduced birth weight, although results did not confirm associations previously reported for particles, which may reflect regional differences in pollutant composition and source and possible residual confounding. It is also possible that particulate pollutant exposure is a stronger risk factor for preterm birth than for decreased birth weight at term; however, this needs to be further explored.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Biography

Laura A. Geer is Assistant Professor of Environmental and Occupational Health Sciences.

Jeremy Weedon is Assistant Professor of Epidemiology and Biostatistics.

Michelle L. Bell is Professor of Environmental Health.

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Implications

This is one of the most comprehensive studies examining criteria air pollutants and lower birth weight in Texas. Our findings confirm results found previously for adverse effects of the air pollutant SO₂ on lower birth weight. Results from our study suggest that adverse pregnancy outcomes such as lower birth weight can occur even while maintaining air pollution levels below regulatory standards. Future studies should incorporate the assessment of differential pollutant exposure as well as effect estimates by race/ethnicity with individual and community-level social factors in order to enhance our understanding of how physical, social, and host factors influence birth outcomes.

Figure 1. Change in birth weight per IQR increase in gestational exposure to pollutant, for single- (indicated as none or no adjustment by another pollutant) and two-pollutant linear models (adjusted for Texas Health Service Regions 1–11). The point reflects the central estimate; the vertical line represents the 95% confidence interval.

Table 1Descriptive statistics of the study population and exposures ($n = 1,548,904$)

Variables relating to birth and mother	Value
Birth weight (g)	3 382.8 $\pm$ 467.2
Low birth weight [$< 2\,500$ g (%)]	2.8
Neonate's gender (%)	
Male	50.9
Female	49.1
Type of birth (%)	
Primary cesarean section	14.4
Repeat cesarean section	11.3
Vaginal birth	72.8
Vaginal birth after cesarean	1.4
Unknown	0.1
First child (%)	
Yes	59.8
No	38.7
Unknown	1.5
Month prenatal care began (%)	
No care	1.6
First 3 months of pregnancy	79.4
4th–6th month of pregnancy	14.5
7th month of pregnancy or later	3.1
Unknown	1.4
Gestational length (weeks)	39.6 $\pm$ 1.52
37–38(%)	24.9
39–40 (%)	50.7
41–42 (%)	20.2
43–44 (%)	4.2
Alcohol use by mother (%)	
Yes	0.9
No	98.4
Unknown	0.7
Tobacco use by mother (%)	
Yes	4.9
No	94.5
Unknown	0.6
Mother's education (%)	
< 12 years	32.6
12 years	29.2
13–15 years	16.6
>15 years	20.2

Variables relating to birth and mother	Value
Unknown	1.4
Mother's race/ethnicity (%)	
Non-Hispanic white	34.7
Non-Hispanic black	10.6
Hispanic	50.7
Other ^a	4.0
Mother's marital status (%)	
Married	68.6
Unmarried	31.3
Other	0.1
Mother's age (years)	26.5 ± 6.1
<20 (%)	13.7
20–24 (%)	27.4
25–29 (%)	27.4
30–34 (%)	20.8
35–39(%)	8.9
>39 (%)	1.7
	0.0
County level weather data Temperature (°F)	69.5 ± 5.4
Dew point temperature (°F)	56.6 ± 8.0
Wind speed (miles per hour)	8.7 ± 1.6
Year of birth (%)	
1998	13.0
1999	13.4
2000	14.0
2001	14.2
2002	15.1
2003	15.3
2004	15.1
Gestational pollution exposures	(mean ± SD)
NO ₂ (IQR 2.4 ppb)	15.0 ± 1.9 ppb
CO (IQR 98 ppb)	451 ± 91 ppb
SO ₂ (IQR 1.6 ppb)	2.3 ± 0.8 ppb
O ₃ (IQR 5.9 ppb)	25.4 ± 4.9 ppb
PM ₁₀ (IQR 2.7 µg/m ³)	27.4 ± 4.1 µg/m ³
PM _{2.5} (IQR 1.0 µg/m ³)	12.6 ± 1.0 µg/m ³
Public Health Service Regions (%)	
1	2.0
3	31.8
4	2.0
5	1.5

Variables relating to birth and mother	Value
6	26.0
7	6.2
8	8.8
9	0.6
10	4.4
11	12.6

Notes: Values are percentages or mean $\pm$ SD.

^aIncludes North American Indian, South or Central American Indian, Chinese, Asian, Indian, Japanese, Korean, Hawaiian, Samoan, Filipino, Vietnamese, Other Asian, and Guamanian.

Table 2

Difference in birth weight associated with selected nonpollution variables (95% confidence interval) from a model without air pollution variables

Variable	Difference in birth weight (g)
Child's sex	
Female (reference)	
Male	122.5 (123.9 to 121.1)
Mother's education (years)	
12 (reference)	
<12	-4.7 (-6.6 to -2.7)
13-15	19.6 (17.3 to 21.8)
>15	20.3 (18.0 to 22.6)
Unknown	-0.2 (-6.5 to 6.1)
Tobacco use by mother	
No (reference)	
Yes	-170.5 (-173.9 to -167)
Alcohol use by mother	
No (reference)	
Yes	-14 (-21.5 to -6.4)
Mother's marital status	
Married (reference)	
Unmarried	-32.2 (-33.9 to -30.4)
Mother's race/ethnicity	
Non-Hispanic white (reference)	
Hispanic	-64.1 (-66.0 to -62.3)
Non-Hispanic black	-168.1 (-170.7 to -165.5)
Other	-202.9 (-206.7 to -199.1)
Month prenatal care began	
Month 1-3 (reference)	
Month 4-6	-10.1 (-12.1 to -8.0)
Month 7	-27.4 (-31.5 to -23.4)
No care	-67.5 (-73.1 to -62.0)
Mother's age (years)	
30-34 (reference)	
<20	-92.1 (-95.0 to -89.1)
20-24	-59.7 (-62.0 to -57.5)
25-29	-21.5 (-23.6 to -19.5)
35-39	7.9 (5.1 to 10.7)
>39	-8.8 (-14.4 to -3.3)
Birth order	
Firstborn (reference)	
Not firstborn	75.4 (72.8 to 76.1)

Variable	Difference in birth weight (g)
Gestational length (weeks)	
39–40 (reference)	
37–38	–208.1 (–209.8 to –206.3)
41–42	102.3 (100.4 to 104.2)
43–44	43.5 (39.9 to 47.1)
Public Health Service Regions	
1	–81.7 (–86.7 to 76.7)
3 (reference)	
4	3.7(–0.93 to 8.3)
5	–10.8 (–16.6 to –4.9)
6	–9.7 (–11.5 to –7.9)
7	0.6 (–2.5 to 3.6)
8	–40.3 (–43 to –37.6)
9	–76.6 (–85.8 to –67.4)
10	–88.4 (–92.0 to –84.8)
11	–34.8 (–37.3 to –32.4)

Note: Significant at $p < 0.001$ for all associations except for mother's education category "Unknown" and Public Health Service Regions 4 and 7.

Table 3

Single pollutant model for change in birth weight per IQR increase in pollution for the gestational period (95% confidence interval)

Pollutant	<i>n</i>	Difference in birth weight (g)/IQR
NO ₂	930 296	1.4 (−2.43, 5.24)
CO	953 735	1.85 (−0.15, 3.84)
SO ₂	630 162	−4.99 (−8.11, −1.87) ^a
O ₃	1 081 804	−2.72 (−4.33, −1.11) ^a
PM _{2.5}	759 465	2.49 (0.58, 4.41) ^a
PM ₁₀	1 014 645	1.30 (0.14, 2.46) ^a

Note: Model was adjusted for covariates listed in Table 2, as well as for year of birth and weather data.

^aSignificant at $p < 0.001$.

Table 4

Single-pollutant model for change in birth weight per IQR increase in pollutant for trimester exposure

Pollutant	Trimester	Range among the trimester models for change in birth weight (g) per IQR increase in pollutant
O ₃	1st	−1.45 to −1.31
	2nd	−1.23 to −1.00
PM _{2.5}	1st	1.96 to 2.19

Note: For comparability, the IQR for gestational exposure was used. Model was adjusted for covariates listed in Table 2, as well as year of birth and weather data.

Table 5

Change in birth weight per IQR increase in pollutant for gestational period, by race/ethnicity (95% confidence interval)

Pollutant	Difference in birth weight (g) per IQR of pollutant		
	Non-Hispanic black mother	Hispanic mother	Non-Hispanic white mother
O ₃	-3.89 (-6.6 to -1.17)	-1.87 (-3.95 to 0.21)	-2.97 (-5.15 to -0.78)
SO ₂ ^a	-1.81 (-7.54 to 3.93)	-6.39 (-9.62 to -3.16)	0.34 (-4.22 to 4.9)
PM _{2.5} ^a	1.93 (-3.95 to 7.82)	3.35 (1.37 to 5.33)	-3.44 (-7.01 to 0.12)
PM ₁₀ ^a	9.62 (6.28 to 12.96)	1.59 (0.35 to 2.83)	-2.3 (-4.19 to -0.41)

Notes: Model was adjusted for covariates listed in Table 2, as well as year of birth and weather data.

^aSignificant at $p < 0.05$ for comparison of results from infants with non-Hispanic black mothers to infants of non-Hispanic white or Hispanic mothers.