Environmental Research ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres

The association between mountaintop mining and birth defects among live births in central Appalachia, 1996–2003

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ARTICLE INFO

Article history:
Received 30 September 2010
Received in revised form
9 May 2011
Accepted 26 May 2011

Keywords:
Mountaintop coal mining
Coal pollutants
Health impacts
Birth defect outcomes
Ecological study
Central Appalachia

ABSTRACT

Birth defects are examined in mountaintop coal mining areas compared to other coal mining areas and non-mining areas of central Appalachia. The study hypothesis is that higher birth-defect rates are present in mountaintop mining areas. National Center for Health Statistics natality files were used to analyze 1996–2003 live births in four Central Appalachian states ($N=1{,}889{,}071$). Poisson regression models that control for covariates compare birth defect prevalence rates associated with maternal residence in county mining type: mountaintop mining areas, other mining areas, or non-mining areas. The prevalence rate ratio (PRR) for any birth defect was significantly higher in mountaintop mining areas compared to non-mining areas (PRR=1.26, 95% CI=1.21, 1.32), after controlling for covariates. Rates were significantly higher in mountaintop mining areas for six of seven types of defects: circulatory/respiratory, central nervous system, musculoskeletal, gastrointestinal, urogenital, and 'other'. There was evidence that mountaintop mining effects became more pronounced in the latter years (2000–2003) versus earlier years (1996–1999.) Spatial correlation between mountaintop mining and birth defects was also present, suggesting effects of mountaintop mining in a focal county on birth defects in neighboring counties. Elevated birth defect rates are partly a function of socioeconomic disadvantage, but remain elevated after controlling for those risks. Both socioeconomic and environmental influences in mountaintop mining areas may be contributing factors.

1. Introduction

Collectively, congenital birth anomalies, or birth defects, occur in about 1 in 33 births in the United States, and are the leading cause of infant mortality in the United States (Centers for Disease Control and Prevention, 2010). Birth anomalies can result from genetic defects (single-gene or chromosomal), non-genetic maternal environmental exposures, or a combination of genetic and non-genetic factors (Jenkins et al., 2007). Genetic diseases occur in about 11% of births (Brent, 2004). Recognized non-genetic risk factors for birth anomalies include: maternal rubella infection (Cochi et al., 1989); pre-pregnancy obesity (Stothard et al., 2009; Watkins et al., 2003); pre-pregnancy diabetes (Correa et al., 2008); some drugs and medications (Holmes et al., 2001; Koren, 1994); lifestyle factors including maternal smoking and alcohol use (Kuehl and Loffredo, 2002); prenatal exposure to environmental contamination (Brent, 2004; Ritz et al., 2002; Gilboa et al., 2005; Marshall et al., 1997); and other maternal factors such as age and stress (Reefhuis and Honein, 2004; Rittler et al., 2007; Carmichael and Shaw, 2000). Regarding environmental contamination, ambient air pollution has been identified in multiple studies (Wigle et al., 2007; Vrijheid et al., 2011), although null findings have also been reported (Strickland et al., 2009.) The majority of birth defects are believed to be multifactorial, with both genetic and environmental contributing causes (Brent, 2004; Weinhold, 2009).

Recent public health studies focusing on quantity of coal mined in a given area irrespective of mining type (surface/underground) have found a significant mining effect on increased risk of low-birth-weight deliveries (Ahern et al., 2010) as well as health effects for adults in coal mining areas of Appalachia (Hendryx, 2009; Hendryx and Ahern, 2008, 2009; Hendryx et al., 2007, 2008; Hendryx and Zullig, 2009). In contrast to other research, the current study focuses on birth defects, and on effects of a type of mining that has particularly serious environmental impacts: mountaintop mining (also known as mountaintop-removal mining).

Mountaintop coal mining conducted in mountainous central Appalachia is a process whereby rock and vegetation above coal seams is removed and deposited in sites adjacent to the mining pits,

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0013-9351/$ - see front matter © 2011 Elsevier Inc. All rights reserved.
doi:10.1016/j.envres.2011.05.019

typically in valleys at heads-of-hollows or headwater streams (Office of Surface Mining Reclamation and Enforcement, 2010). Mountaintop mining is widespread through portions of eastern Kentucky, eastern Tennessee, southern West Virginia, and southwestern Virginia, and has increased from 77,000 to 272,000 acres between 1985 and 2005, a 250% increase (Skytruth, 2009a). As of 2005, 2700 ridges had been impacted by mountaintop mining in the Central Appalachian area (Skytruth, 2009a).

Mountaintop mining creates large-scale impairment of surface water and groundwater and significant disturbances in local air quality (Palmer et al., 2010; Ghose, 2007; McAuley and Kozar, 2006; Hitt and Hendryx, 2010; US Department of Labor, 2010). Surface explosives use significant amounts of ammonium-nitrate and diesel fuel (Ayers et al., 2007), with blasts expelling coal dust and flyrock containing sulfur compounds, fine particulates including metals, and nitrogen dioxide (Ayers et al., 2007; Ghose and Majee, 2007; Lockwood et al., 2009). Area groundwater has elevated levels of sulfate, calcium, magnesium, bicarbonate ions, selenium, and hydrogen sulfide (Palmer et al., 2010; McAuley and Kozar, 2006; Hartman et al., 2005; Lemly, 2002; Lashof et al., 2007). Post-mining, slurry produced from washing coal can leach arsenic, barium, mercury, lead, and chromium into groundwater (Lockwood et al., 2009; Sludge Safety Project, 2004), which may contribute to elevated rates of arsenic in area private wells and elevated levels of iron, manganese, aluminum, lead, and arsenic in groundwater (Palmer et al., 2010; McAuley and Kozar, 2006; Shiber, 2005; Stout and Papillo, 2004). Transporting coal to power plants releases significant quantities of nitrogen oxide and particulate matter (Lashof et al., 2007; Aneja, 2009). Respirable ambient particulate matter, sulfur dioxide, nitrous oxide, benzene, carbon monoxide, and polycyclic aromatic hydrocarbons are elevated in areas proximate to coal extraction, processing, and transportation (Ghose and Majee, 2007).

Some chemicals associated with mountaintop mining processes (including mercury, lead, arsenic, thallium, selenium, cadmium, chromium, ammonium-nitrate, iron, manganese, and polycyclic aromatic hydrocarbons) have been shown in animal and/or human studies to pose adverse developmental or reproductive risks (Agency for Toxic Substances and Disease Registry, 2010). In addition, ambient particulate matter and gaseous air pollutants, also associated with coal production, have been associated with fetal developmental problems (Glinianaia et al., 2004; Maisonet et al., 2004; Dejmek et al., 2000); congenital anomaly risks (Vrijheid et al., 2011; Gilboa et al., 2005; Ritz et al., 2002; Dolk et al., 2010; Bocskay et al., 2005; Smrcka and Leznarova, 1998; Antipenko and Kogut, 1993); heritable gene mutations (Somers et al., 2002, 2004; Samet et al., 2004); and mutations in fetal DNA (Šrám et al., 2005; Perera et al., 1992, 1998, 1999, 2004). An additional source of fetal exposure to air pollution, maternal smoking, has been associated with orofacial clefts, limb reduction defects, gastroschisis (Honein et al., 2007; Torfs et al., 2006; Kallen, 1997), and congenital heart defects (Malik et al., 2008). Biologic pathways for impacts of air pollutants on the placenta and fetus have been identified (Kannan et al., 2006). In Heshun, China, areas within 6 km of a coal mine had high prevalence of neural tube defects in human infants compared with outlying areas (Liao et al., 2009).

Given evidence of greater levels of water and air disturbance resulting from mountaintop mining compared to other surface and underground mining, this study advances previous research concerning health disparities in Appalachian mining areas by identifying geographic areas within four states in central Appalachia where mountaintop mining takes place, and tests the hypothesis that prevalence rates for birth anomalies will be greater in mountaintop mining areas relative to other mining areas and to non-mining areas after control for risk factors.

2. Materials and methods

2.1. Design

We conducted a retrospective, ecological analysis to determine whether mother's residence during pregnancy in one of the three geographic areas (mountaintop mining county, other coal mining county, or non-mining county) was related to the rates of births with a congenital anomaly, before and after statistical control for other risks. The study area contained four central Appalachian states (Kentucky, Tennessee, Virginia, and West Virginia). We used individual-level data from the National Center for Health Statistics natality data files for live births occurring in 1996–2003, and data on mining type for the same period.

2.2. Exposure data

Coal mining data were obtained from the Department of Energy, Energy Information Administration for 1996–2003, and from a map of surface mining areas in central Appalachia derived from satellite imagery (Skytruth, 2009b). The map was overlaid with county-level coal production figures to identify the coal mining counties in central Appalachia where mountaintop mining takes place, and other counties where coal mining takes place but not mountaintop mining. Mountaintop mining was identified from the satellite imagery as a surface mining site that crosses over a ridge or mountain peak, and that either (1) spans at least 320 acres including at least 40 acres of removed ridge top or (2) spans 40–320 acres and contains at least 10–40 acres of removed ridge top (Skytruth, 2009b). A county was classified as a mountaintop mining county regardless of the number or size of sites or whether the site was historical or active over the study period. Surface mining, but not true mountaintop mining, occurs in Appalachia outside of this central Appalachian mountaintop mining zone; also, both underground mining and other mining activities (e.g., coal processing) take place in both types of mining areas. A map of the four Appalachian states showing these mining areas is provided in Fig. 1.

2.3. Outcome and covariate data

The primary dependent variable and covariates were drawn from the National Center for Health Statistics natality data files for the years 1996–2003, with mother's county of residence identified. The file contains information on every live birth in the US; data for the current study are limited to the four central Appalachian states where mountaintop mining takes place.

The presence of 22 types of congenital anomalies is recorded in the natality dataset. Analyses were conducted considering individual types of anomalies, groupings of anomalies by major organ system (central nervous system, circulatory/respiratory, gastrointestinal, urogenital, musculoskeletal, chromosomal, and 'other'), and by the presence or absence of any anomaly.

To account for other potential risk factors, we included individual-level covariates known to be risk factors from the literature on birth defects (Brent, 2004; Correa et al., 2008; DeMarco et al., 2011; Eriksson et al., 2003; Kuehl and Loffredo, 2002; Reefhuis and Honein, 2004; Rittler et al., 2007): mother's age (35 or over versus less than 35); mother's race (African American, Native American, and White as the referent (Asian American populations in central Appalachia are small and were not included separately)); mother's Hispanic origin (yes/no); sex of the infant; mother's years of education (scored 0–17 representing no education to 5 or more years of college); low prenatal care (<9 visits versus 9 or more visits as the referent); alcohol consumption during pregnancy (yes/no); cigarette smoking during pregnancy (yes/no); and diabetes co-morbidity (yes/no). One county-level covariate indicated whether or not the county of mother's residence was located in a metropolitan statistical area. For descriptive purposes we also found the per capita supply of active primary care physicians and obstetricians–gynecologists for each of the three geographic areas based on data from the Area Resource File (2006).

2.4. Analysis

We examined amounts of surface mining over time in the central Appalachian mountaintop mining area and other mining areas. We conducted descriptive analyses of study variables followed by inferential analyses of the prevalence rate ratios (PRRs) of congenital anomalies in the three geographic areas (mountaintop mining, other mining, and non-mining) before and after control for covariates. Non-mining areas were used as the referent in rate calculations. Because specific anomalies are rare, for the primary regression analyses we created a dichotomous measure of the presence or absence of any anomaly; however, we also analyzed by anomalies grouped into major organ systems.

We calculated crude and adjusted estimates using Poisson regression, modeling number of cases and using the natural logarithm of the number of live births as the offset. We exponentiated the beta coefficients from the models to calculate the prevalence rate ratios.

Mountaintop mining activity has increased over time, and evidence indicates that its environmental impacts persist after mining activity at a given site ceases

Please cite this article as: Ahern, M.M., et al., The association between mountaintop mining and birth defects among live births in central Appalachia, 1996–2003. Environ. Res. (2011), doi:10.1016/j.envres.2011.05.019

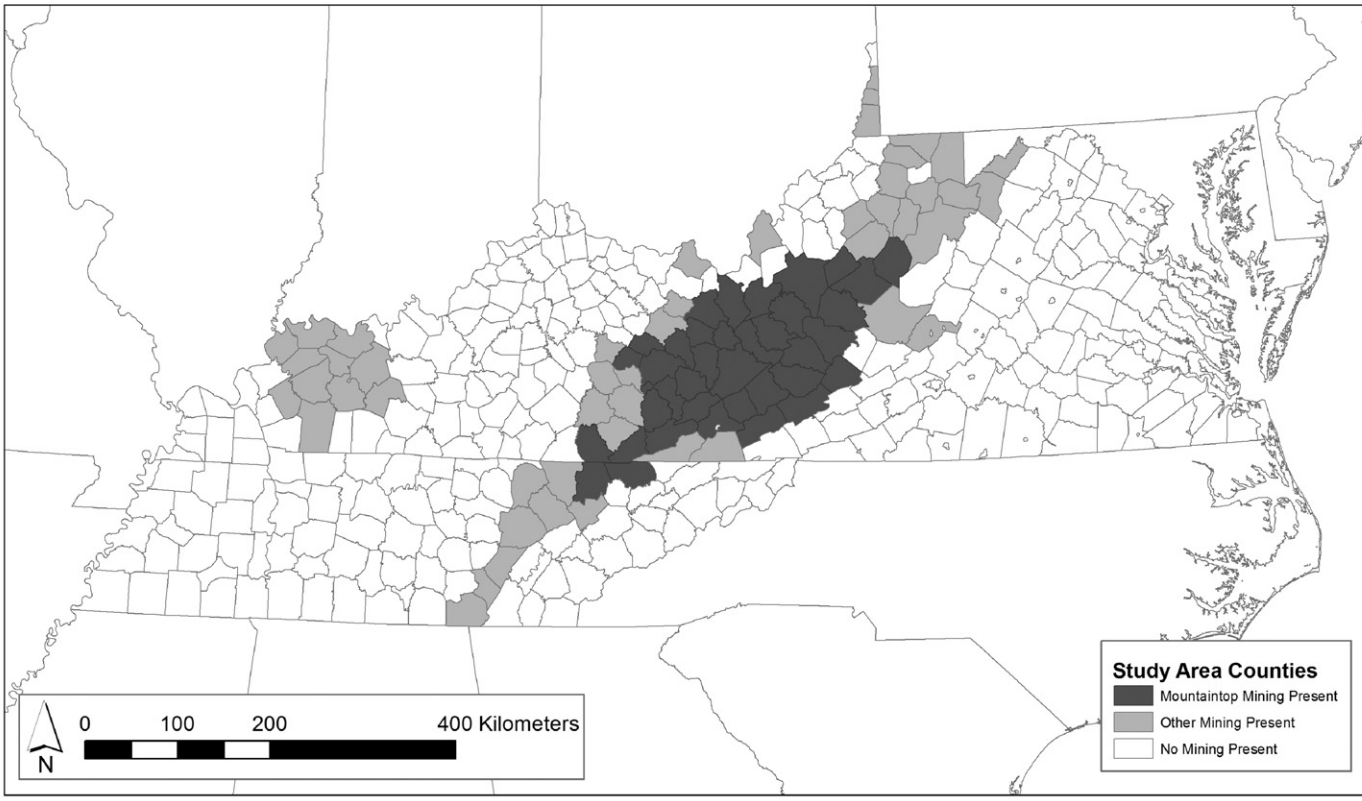

Fig. 1. Map of four central Appalachian states showing type of county mining activity for 1996–2003.

(Palmer et al., 2010), such that environmental damages may accumulate over time. We examined rates for the entire time period 1996–2003, and separately for earlier years (1996–1999) and later years (2000–2003) to investigate whether mountaintop mining effects were greater in the more recent period.

Finally, we conducted a spatial analysis to investigate autocorrelation among mountaintop mining areas, and spatial correlations between birth defect rates and mountaintop mining. Environmental risk factors, especially air and water pollutants, frequently cross-county boundaries (Mennis, 2002; Downey, 2003). The impacts of surface coal mines on air pollution (Chaulya et al., 2002) and water pollution (Rathore and Wright, 1993) are no different. This diffusion of exposure can occur through air pollution and water pollution crossing county boundaries, or through people traveling to neighboring counties and becoming exposed to the pollutants in the areas surrounding their county of residence. Moreover, as Fig. 1 shows, mountaintop mining is clustered in one part of the study region, suggesting that exposure to mountaintop mining in one county is compounded by exposure to mountaintop mining in neighboring counties. We quantified spatial autocorrelation using the software package Geoda (Anselin et al., 2006).

To account for observed spatial autocorrelation, a neighborhood around each county was created consisting of all counties within 52 km of the centroid of the focal county. Then, we calculated a spatial covariate for each county, which is the percent of counties in this neighborhood, including the focal county, where mountaintop mining is present. A map of this covariate is provided in Fig. 2. A 52 km radius (rounded up from 51.032 km) was chosen because that distance allowed for all counties to have at least one neighbor. Using this spatial covariate, we calculated a bivariate Global Moran's I test for the spatial association of mountaintop mining and birth defects. In a final set of Poisson regression models we tested the relative strength of the original mountaintop mining variable and the spatially correlated mountaintop mining variable; the hypothesis is that the spatial measure that allows for cross-county effects will be associated with birth defects more strongly than the original variable that measures only whether or not mountaintop mining activity occurs in the focal county.

3. Results

3.1. Amounts of mining

Amounts of surface mining in the non-mountaintop mining area declined from 15 million tons (20% of total production in those counties) in 1996 to 8 million tons (15% of production) in 2003. During the same period in the mountaintop mining area total surface production was substantially higher: 110 million tons (50% of production) in 1996, and 101 million tons (43% of production) in 2003. Over the entire time period, about 85 million tons of coal were extracted from surface mines in the non-mountaintop mining area, compared to about 882 million tons in the mountaintop mining area.

3.2. Frequency and rates of anomaly types by mining group

The total number of live births with non-missing data on congenital anomalies was 1,889,071. Table 1 lists the frequency and rates per 10,000 live births of anomaly types by mining group. Statistical tests are reserved for analyses reported below, but unadjusted rates in the mountaintop mining group were higher for multiple types of birth defects across all body systems. The more general "other" categories and the final unclassified category were the most commonly recorded anomalies and may reflect inability to record a specific anomaly at birth without confirmatory diagnostic data. Rates for any anomaly were approximately 235 per 10,000 live births in the mountaintop mining area versus 144 per 10,000 live births in the non-mining area.

3.3. Descriptive summary of study variables

A descriptive summary of study variables is provided in Table 2. Mothers in the mountaintop mining area had less education, were more likely to smoke, were less likely to have prenatal care, and were less likely to have consumed alcohol during pregnancy. The per capita supply of active primary care doctors and obstetricians–gynecologists was not significantly different between county groups.

Please cite this article as: Ahern, M.M., et al., The association between mountaintop mining and birth defects among live births in central Appalachia, 1996–2003. Environ. Res. (2011), doi:10.1016/j.envres.2011.05.019

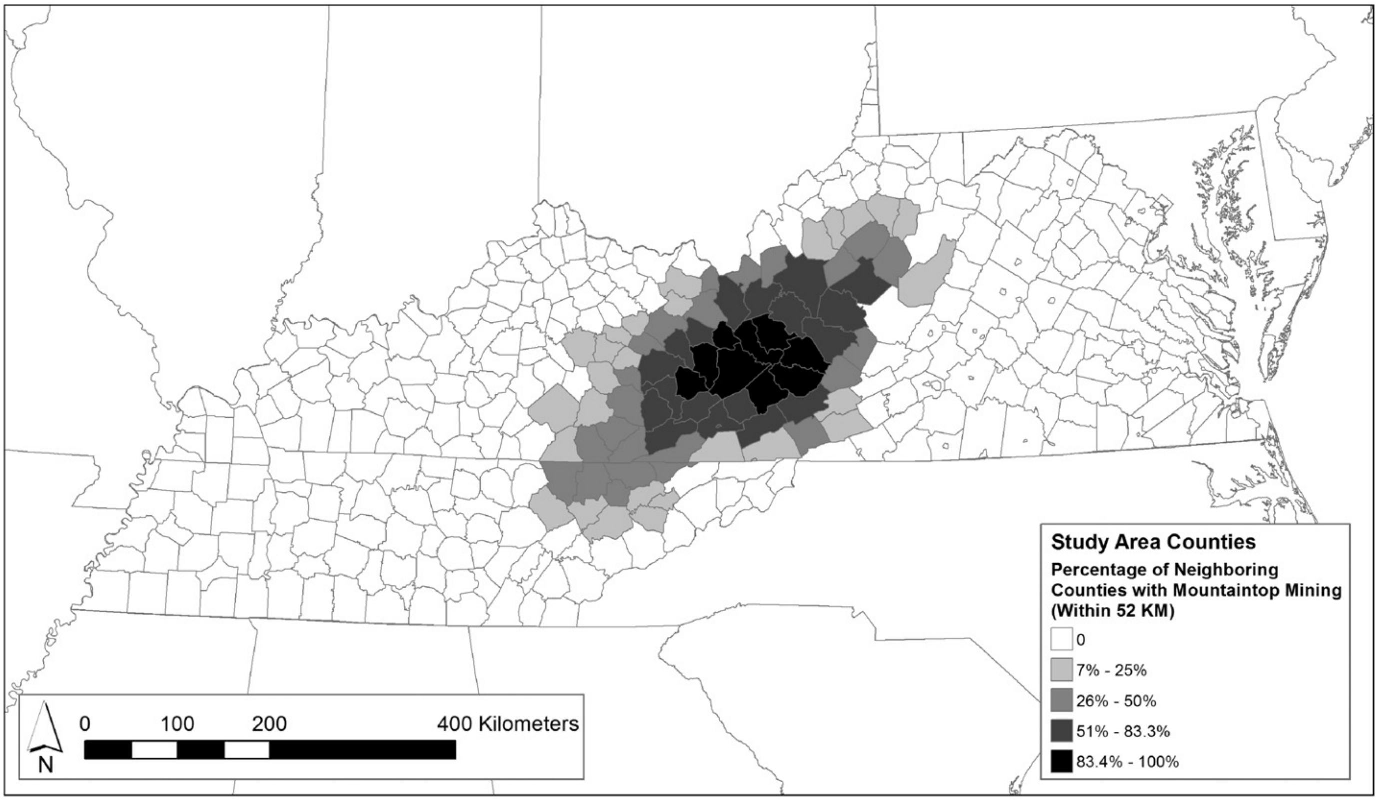

Fig. 2. Percent of neighboring counties that have mountaintop mining within 52 km of county centroid.

Table 1
Number (and prevalence per 10,000 live births) with a congenital anomaly by presence and type of coal mining in Kentucky, Tennessee, Virginia, and West Virginia, 1996–2003.

Type of anomaly	Non-mining (N=1,666,985 live births)	Mining in non-mountaintop mining area (N=112,771 live births)	Mountaintop mining area (N=109,315 live births)
Anencephaly	178 (1.1)	12 (1.1)	16 (1.5)
Meningomyelocele/spina bifida	378 (2.3)	24 (2.1)	43 (3.9)
Hydrocephalus	382 (2.3)	27 (2.4)	40 (3.7)
Microcephalus	82 (0.5)	13 (1.2)	9 (0.8)
Other central nervous system	246 (1.5)	32 (2.8)	53 (4.8)
All central nervous system[a]	1163 (7.0)	102 (9.0)	137 (12.5)
Heart malformations	1603 (9.6)	133 (11.8)	136 (12.4)
Other circulatory/respiratory	1028 (6.2)	104 (9.2)	317 (29.0)
All circulatory/respiratory[a]	2550 (15.3)	226 (20.0)	448 (41.0)
Rectal atresia/stenosis	107 (0.6)	11 (1.0)	20 (1.8)
Tracheo-esophageal fistula	167 (1.0)	16 (1.4)	19 (1.7)
Omphalocele/gastroschisis	494 (3.0)	47 (4.2)	53 (4.8)
Other gastrointestinal	487 (2.9)	40 (3.5)	80 (7.3)
All gastrointestinal[a]	1222 (7.3)	113 (10.0)	168 (15.4)
Malformed genitalia	687 (4.1)	71 (6.3)	66 (6.0)
Renal agenesis	155 (0.9)	17 (1.5)	14 (1.3)
Other urogenital	1808 (10.8)	228 (20.2)	266 (24.3)
All urogenital[a]	2586 (15.5)	308 (27.3)	341 (31.2)
Cleft lip/palate	1496 (9.0)	135 (12.0)	133 (12.2)
Polydactyly/syndactyly/adactyly	1754 (10.5)	92 (8.2)	94 (8.6)
Club foot	1164 (7.0)	101 (9.0)	114 (10.4)
Diaphramatic hernia	226 (1.4)	17 (1.5)	27 (2.5)
Other musculoskeletal	2469 (14.8)	227 (20.1)	402 (36.8)
All musculoskeletal[a]	6816 (40.9)	550 (48.8)	736 (67.3)
Down syndrome	781 (4.7)	52 (4.6)	53 (4.8)
Other chromosomal	578 (3.5)	40 (3.5)	43 (3.9)
All chromosomal[a]	1342 (8.1)	89 (7.9)	96 (8.8)
Other congenital anomaly	10,164 (61.0)	861 (76.4)	931 (85.2)
Any anomaly	24,065 (144.4)	2067 (183.3)	2569 (235.0)

[a] The totals for each system are less than the numbers for specific anomalies due to cases with more than one specific anomaly.

Table 2
Descriptive characteristics of live births 1996–2003 by presence and type of coal mining, Kentucky, Tennessee, Virginia, and West Virginia, (N=1,889,071).

Variable	Non-mining (N=1,666,985)	Mining in non-mountaintop mining area (N=112,771)	Mountaintop mining area (N=109,315)
Number of counties	318	49	37
N (%)			
Mother's age ≥ =35	274,836 (16.5)	15,141 (13.4)	14,457 (13.2)
African American	324,491 (19.4)	5716 (5.1)	3192 (2.9)
Native American	2946 (0.2)	178 (0.2)	71 (0.1)
Hispanic	89,391 (5.4)	1397 (1.2)	324 (0.3)
Female sex of infant	813,889 (48.8)	54,827 (48.6)	53,047 (48.5)
Low or absent prenatal care	234,413 (14.3)	17,208 (15.5)	18,234 (17.0)
Diabetes co-morbidity	54,900 (3.3)	3341 (3.0)	4041 (3.8)
Alcohol consumption	8741 (0.5)	365 (0.3)	221 (0.2)
Smoking	234,652 (14.1)	24,125 (22.3)	30,303 (28.6)
Non-metropolitan area	337,742 (20.3)	59,079 (52.4)	81,409 (74.4)
Mean (standard deviation)			
Mean years of education (0–17)	13.0 (2.5)	12.6 (2.2)	12.3 (2.1)
Active primary care physicians per 10,000 residents	14.8 (19.0)	12.9 (15.9)	12.8 (9.4)
Active obstetricians/gynecologists per 10,000 residents	0.7 (1.1)	0.6 (0.7)	0.5 (0.6)

Table 3
Unadjusted and adjusted prevalence rate ratios (with 95% confidence limits) for central Appalachian mountaintop mining area, and other coal mining areas, relative to non-mining referent areas, for births 1996–2003 with a congenital anomaly in Kentucky, Tennessee, Virginia, and West Virginia.

	Mountaintop mining area	Other coal mining areas
Unadjusted[a]	1.63 (1.54, 1.72)	1.27 (1.20, 1.35)
Adjusted[b]	1.26 (1.21, 1.32)	1.10 (1.05, 1.16)

[a] Covariate includes mother's age ≥ =35.
[b] Covariates include: mother's age ≥ =35, years of education, smoking during pregnancy, drinking during pregnancy, African American race, Native American race, Hispanic ethnicity, infant sex, low prenatal care, diabetes co-morbidity, and residence in a metropolitan area.

3.4. Unadjusted and adjusted prevalence ratios in mining areas

Table 3 shows the prevalence rate ratios (PRRs) and 95% confidence limits for the mining variables in both the unadjusted and adjusted models. The unadjusted models include only mother's age ≥ =35 as a covariate. The dependent variable was the presence or absence of any anomaly. Before adjustment, both mining areas had significantly higher prevalence rates for anomalies, with the mountaintop mining area showing the highest rates. After adjustment using the full set of covariates, the PRRs were reduced but remained significantly higher in both groups relative to the non-mining referent; the PRR for the mountaintop mining area was 1.26 (95% CI=1.21, 1.32). The unadjusted and adjusted confidence intervals for the two mining groups do not overlap, showing that PRRs in mountaintop mining areas are also significantly higher than in the non-mountaintop mining area.

3.5. Results specific to major organ systems

As shown in Table 4, regression models specific to major organ systems resulted in significantly higher adjusted prevalence rate ratios in the mountaintop mining area for five of the six types of anomalies and for the 'other' category: circulatory/respiratory (PRR=1.93, 95% CI=1.73, 2.15); central nervous system (PRR=1.36, 95% CI=1.11, 1.67); gastrointestinal (PRR=1.41, 95% CI=1.17, 1.71); urogenital (PRR=1.35, 95% CI=1.19, 1.54); musculoskeletal (PRR=1.30, 95% CI=1.20, 1.41); and other conditions (PRR=1.13, 95% CI=1.04,1.23). For the other mining areas, the PRRs were significantly elevated relative to the non-mining referent for the urogenital category (PRR=1.32, 95% CI=1.15, 1.51) and for the other category (PRR=1.12, 95% CI=1.03, 1.22). Although rates were significantly elevated for six of seven tests in mountaintop mining areas, elevated rates for circulatory/respiratory conditions are most pronounced.

Table 4
Adjusted[a] prevalence rate ratios for circulatory/respiratory, central nervous system, gastrointestinal, urogenital, musculoskeletal, chromosomal, or other congenital anomaly, births by mining group relative to non-mining referent,1996–2003 in Kentucky, Tennessee, Virginia, and West Virginia.

Anomaly type	Mountaintop mining area	Other coal mining areas
Circulatory/ respiratory	1.93 (1.73, 2.15)	1.08 (0.94, 1.24)
Central nervous system	1.36 (1.11, 1.67)	1.18 (0.95, 1.46)
Gastrointestinal	1.41 (1.17, 1.71)	1.02 (0.82, 1.28)
Urogenital	1.35 (1.19, 1.54)	1.32 (1.15, 1.51)
Musculoskeletal	1.30 (1.20, 1.41)	1.08 (0.99, 1.18)
Chromosomal	0.92 (0.72, 1.18)	0.85 (0.66, 1.09)
Other anomaly	1.13 (1.04, 1.23)	1.12 (1.03, 1.22)

[a] Covariates include: mother's age > =35, years of education, smoking during pregnancy, drinking during pregnancy, African American race, Native American race, Hispanic ethnicity, infant sex, low prenatal care, diabetes co-morbidity, and residence in a metropolitan area.

3.6. Results for early versus late time periods

Table 5 summarizes the adjusted PRRs for the mountaintop mining area relative to the non-mining referent for two periods of time, 1996–1999, and 2000–2003. For three organ systems (gastrointestinal, urogenital, and other), mountaintop mining effects were not significant in the earlier period but were significant in the later period. Rates for circulatory/respiratory defects were significantly higher in mountaintop mining areas in both time periods but the PRR was more than twice as high in the recent period. Musculoskeletal defects were significant at about the same levels in both periods. Central nervous system defects were significant only in the earlier period. Overall, the prevalence rate for any defect was significant in both periods but was higher in the more recent period.

Table 5
Adjusted[a] prevalence rate ratios for earlier (1996–1999) and later (2000–2003) time periods by anomaly type, live births in Kentucky, Tennessee, Virginia, and West Virginia, for the mountaintop mining area compared to the non-mining referent.

Anomaly type	Mountaintop mining 1996–1999	Mountaintop mining 2000–2003
Circulatory/respiratory[b]	1.20 (1.03, 1.41)	2.81 (2.43, 3.25)
Central nervous system	1.42 (1.06, 1.91)	1.30 (0.95, 1.76)
Gastrointestinal[b]	1.30 (0.94, 1.80)	1.53 (1.18, 1.96)
Urogenital [b]	1.16 (0.94, 1.42)	1.62 (1.38, 1.93)
Musculoskeletal [c]	1.31 (1.17, 1.46)	1.30 (1.15, 1.46)
Chromosomal	1.21 (0.89, 1.64)	0.68 (0.46, 1.03)
Other anomaly[b]	0.99 (0.88, 1.12)	1.29 (1.15, 1.45)
Any anomaly[b]	1.13 (1.06, 1.21)	1.42 (1.33, 1.52)

[a] Covariates include: mother's age $\geq =35$, years of education, smoking during pregnancy, drinking during pregnancy, African American race, Native American race, Hispanic ethnicity, infant sex, low prenatal care, diabetes co-morbidity, residence in a metropolitan area, and mining in non-mountaintop mining areas.
[b] Significant increase from earlier to later period.
[c] No increase over time but significant mountaintop mining effect in both periods.

Table 6
Adjusted[a] prevalence rate ratios for circulatory/respiratory, central nervous system, gastrointestinal, urogenital, musculoskeletal, chromosomal, other, and any congenital anomalies, births 2000–2003 in Kentucky, Tennessee, Virginia, and West Virginia, comparison of original mountaintop mining measure and spatial autocorrelation measure.

Anomaly type	Original measure	Spatial measure
Circulatory/respiratory	2.81 (2.43, 3.25)	3.30 (2.69, 4.06)
Central nervous system	1.30 (0.95, 1.76)	1.35 (0.88, 2.05)
Gastrointestinal	1.53 (1.18, 1.96)	1.48 (1.01, 2.20)
Urogenital	1.62 (1.38, 1.93)	1.77 (1.39, 2,21)
Musculoskeletal	1.30 (1.15, 1.46)	1.31 (1.11, 1.54)
Chromosomal	0.68 (0.46, 1.03)	0.57 (0.33, 1.01)
Other anomaly	1.29 (1.15, 1.45)	1.36 (1.18, 1.57)
Any anomaly	1.42 (1.33, 1.52)	1.47 (1.35, 1.61)

[a] Covariates include: mother's age $\geq =35$, years of education, smoking during pregnancy, drinking during pregnancy, African American race, Native American race, Hispanic ethnicity, infant sex, low prenatal care, diabetes co-morbidity, residence in a metropolitan area, and mining in non-mountaintop mining areas.

Although not shown in Table 5, rates in the non-mountaintop mining area did not show the same increase. The rate for the "other" category of defects increased from the earlier to the later period, but no other organ system showed a significant increase over time.

3.7. Results of spatial analyses

Based on the results in Table 5, the spatial analysis used birth defect data for the period 2000–2003. The percentage of birth defects within each county exhibited strong spatial autocorrelation (Moran's $I=0.5116$, $p<0.001$) suggesting that birth defects vary across the study area and exhibit clustering. We used the spatially derived covariate defined as the percent of counties in the focal county's 52 km neighborhood where mountaintop mining is present in a bivariate Global Moran's I calculation and found that the spatial mountaintop mining variable and county birth defect percentage covaried across the study area (Moran's $I=0.1666$, $p<0.001$). This indicates a potentially strong relationship between birth defects of a county and mountaintop mining activity in that county's neighborhood.

Table 6 summarizes the relative strength of the adjusted PRRs when the primary mining variable was the original mountaintop mining measure, compared to the 52 km measure allowing for cross-county autocorrelation. The spatial measure was significantly related to birth anomalies, as was the original measure, and the point estimates of the spatial measure in all significant cases were higher than the original measure except for gastrointestinal anomalies; however, the confidence intervals for the original and spatial measures are overlapping.

4. Discussion and Conclusions

4.1. High birth defect prevalence rates in mountaintop mining areas

Findings show significantly higher prevalence rates for birth defects overall, and for six of the seven types of anomalies examined in mountaintop mining areas versus other mining and non-mining areas, consistent with previous research showing greater surface, air, and water disturbance specific to surface mining areas where mountaintop mining occurs (see Section 1). The PRRs have become significantly worse in mountaintop mining areas in more recent years for four anomaly types and for birth anomalies overall.

The disparity present in the mountaintop mining area is partly accounted for by socioeconomic disadvantage and associated risks. For example, pregnant mothers in the mountaintop mining area are more likely to smoke and to have a lower level of education, reflecting the chronically disadvantaged nature of mining-dependent economies and the associated burden of poor health for Appalachian residents in coal mining areas. Research has shown that coal mining areas have the highest poverty rates, unemployment rates, and age-adjusted death rates in the region (Hendryx and Ahern, 2009). However, after accounting for socioeconomic risks, birth anomaly rates remain elevated in the mountaintop mining area, leaving open the possibility that water or air pollution may be contributing factors. Surface mines affect the quality of groundwater and local surface water, impacting homeowners' water supply sources (McAuley and Kozar, 2006; Hitt and Hendryx, 2010). These environmental impacts are exacerbated when coal blasting and processing are present, and persist after mine reclamation (US Department of Labor, 2010).

The results from the spatial analysis and from Table 6 suggest that the impacts of mountaintop mining extend beyond the immediate site of mining operations. However, the overlapping confidence intervals indicate that the impact a community experiences from mountaintop mining in its own county exceeds the additional impact from nearby counties. This measurement of the spatial impact of coal mines may be muted by the county-level resolution of the data. A finer-scale analysis, such as using zip codes or census tracts, might reveal stronger spatial effects of mountaintop coal mining, which are obscured by the larger size of counties (Baden et al., 2007). However, our dataset only contained the county of residence for the birth mother, preventing a more detailed spatial analysis.

In this exploratory study, we do not have the data to examine biological mechanisms by which mountaintop mining pollution may lead to birth defects. Investigating these potential mechanisms remains an important future research step. Given the multiple forms of mountaintop mining pollution identified in previous research, involving multiple chemicals operating through both water and air transport routes (see Section 1), and the fact that elevated rates of birth defects were present across multiple organ systems, we offer as a working hypothesis for future research that mothers residing in different locations within the region may be exposed to different or combined impacts of the industry.

As examples, in one area the primary influence may be impaired water from coal processing facilities, while another area may be primarily impacted by rock dust and explosive chemicals at an active mountaintop site. Radon released from mining activity and subsequently falling to the ground as radioactive lead and plutonium is another possibility. Some communities are proximate to multiple types of mining activities. In general, the mechanisms by which environmental exposures lead to birth defects are imperfectly understood (Kannan et al., 2006; Wigle et al, 2007). However, we know from previous research on chemical agents contributing to birth defects that impurities present in coal (e.g., lead, mercury) and the chemicals used or created in its extraction, processing, and transportation (e.g., polycyclic aromatic hydrocarbons, particulate matter inhalation leading to oxidative stress) are possible agents in the etiology of birth defects (Kannan et al., 2006; Vinceti et al., 2001; Wigle et al., 2008).

4.2. Limitations of the study

Coal extraction, processing, and transportation activities, including forms of surface mining, occur in both mountaintop and other mining areas, and the environmental consequences of mining activities do not obey county lines; both of these factors will tend to make observed effects conservative. The results of the spatial analysis suggest that cross-county effects do occur, as would be expected. Because there are no direct environmental exposure data available, these analyses relied on an ecologic design using the type of mining in the county of maternal residence as a proxy. Yet county of residence does not equate to individual-level exposure to specific types of air and water pollution, and there may be other unmeasured factors associated with residence in a county with mountaintop mining. Future research should aim to increase geographic specificity and test individual-level exposure-outcome relationships over time.

Self-reported data from the birth certificate on behaviors such as smoking and drinking during pregnancy are likely to contain error. Mothers may be hesitant to report these behaviors if they are aware that they should be avoided during pregnancy (Ernhart et al., 1988). Levels of prenatal care received and mother's education may also contain error, although misclassification of these risk factor data from the birth certificate is likely to be non-differential with respect to residence in a mining or non-mining area. Reported drinking levels among mothers in mountaintop mining areas were lower than in other areas, which seems inconsistent with other risk variables such as smoking or education. However, West Virginia state health surveys indicate that binge drinking levels are lower in mountaintop mining counties compared to state averages (Bureau for Public Health, 2007), a previous study found no differences in alcohol consumption among mothers by mining group in Appalachia (Ahern et al., 2010), and other research has found that drinking levels in general in Appalachia are lower than other parts of the country (Hendryx and Zullig, 2009).

Reporting regarding birth defects is incomplete on birth certificates and is dependent on how easily anomalies are detected after birth and before data are completed for the birth registration (Watkins et al., 1996). The prevalence of birth defects is about 3% of live births, which we did not find overall in the present data, suggesting an under-detection problem. Future research can seek to confirm the relationships identified here using state birth defects surveillance programs or case-control designs. Although rates among live births are certainly underestimated in our study, there is no *a priori* reason to suppose that they are differentially overestimated in mining areas.

The data we have are also limited to birth defects reported for live births. Birth defects detected prenatally increase the probability of elective pregnancy termination, and mothers in certain groups, such as women in poverty or those with poorer access to care, may have less knowledge of prenatal defects (Cragan and Khoury, 2000; Cragan and Gilboa, 2009); mothers in mountaintop mining areas may therefore have been less likely to terminate a pregnancy if poorer socioeconomic status or poorer access to care made them less aware of prenatal defects. We adjusted for this possible bias using mother's education, receipt of early prenatal care, and rural–urban setting as covariates. We also found that the supply of primary care physicians and obstetricians/gynecologists was not significantly lower in mountaintop mining areas, suggesting that access to care was comparable across groups.

4.3. Conclusions, significance of the study, and policy implications

Results extend previous research on low-birth-weight outcomes and on adult morbidity and mortality in mining areas by demonstrating increased rates of birth defects as an additional public health effect related to coal mining in Appalachia. Results also offer one of the first indications that disparities are concentrated specifically in mountaintop mining areas, and have become more pronounced as this type of mining activity has expanded. Existing regulations to protect air and water quality in mountaintop mining areas may be inadequate (Palmer et al., 2010), and enforcement of those regulations has been lax (Ward, 2008; Burns, 2007), although recent efforts by the Environmental Protection Agency (2010) may be moving in the direction of stricter regulations. The findings documented in this study contribute to the growing evidence that mountaintop mining is done at substantial expense to the environment, to local economies (Hendryx and Ahern, 2009; Hendryx, in press) and to human health.

Acknowledgements

The authors gratefully acknowledge the assistance of Suzanne Gilboa, Ph.D., Juhua Luo, Ph.D., and Matthew Armistead in the preparation of this manuscript.

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Please cite this article as: Ahern, M.M., et al., The association between mountaintop mining and birth defects among live births in central Appalachia, 1996–2003. Environ. Res. (2011), doi:10.1016/j.envres.2011.05.019

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Please cite this article as: Ahern, M.M., et al., The association between mountaintop mining and birth defects among live births in central Appalachia, 1996–2003. Environ. Res. (2011), doi:10.1016/j.envres.2011.05.019