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Exposure to airborne metals and particulate matter and risk for youth adjudicated for criminal activity

Erin N. Haynes[a,*], **Aimin Chen**[a], **Patrick Ryan**[a], **Paul Succop**[a], **John Wright**[b], and **Kim N. Dietrich**[a]

Erin N. Haynes: Erin.Haynes@uc.edu; Aimin Chen: Aimin.Chen@uc.edu; Patrick Ryan: Patrick.Ryan@uc.edu; Paul Succop: Paul.Succop@uc.edu; John Wright: John.Wright@uc.edu; Kim N. Dietrich: Kim.Dietrich@uc.edu

[a]College of Medicine, Department of Environmental Health, University of Cincinnati, Cincinnati, OH 45267, USA

[b]College of Education, Criminal Justice, and Human Services, University of Cincinnati, Cincinnati, OH 45221, USA

Abstract

Antisocial behavior is a product of multiple interacting sociohereditary variables, yet there is increasing evidence that metal exposure, particularly, manganese and lead, play a role in its epigenesis. Other metals, such as arsenic, cadmium, chromium, and mercury, and exposure to traffic-related air pollution, such as fine particulate matter (≤2.5 μm) have been associated with neurological deficits, yet largely unexplored with respect to their relationship with delinquent behavior. The purpose of this study is to evaluate the ecological relationship between county-wide reported airborne emissions of air metals, particulate matter, and youth adjudicated for criminal activity.

Metal exposure data were collected from the Environmental Protection Agency AirData. Population statistics were obtained from the United States Census 2000 and adjudication data was obtained from the Courts of Common Pleases from each Ohio County.

Simple correlations were calculated with the percentage of adjudications, all covariates, and estimated metal air emissions. Separate negative binomial regression models for each pollutant were used to provide an estimated risk ratio of pollutant emissions on the risk of adjudication for all Ohio counties adjusting for urban–rural residence, percentage of African Americans, median family income, percentage of family below poverty, percentage of high school graduation in 25 years and older populations, and population density.

Metal emissions and PM in 1999 were all correlated with adjudication rate (2003–2005 average). Metal emissions were associated with slightly higher risk of adjudication, with about 3–4% increased risk per natural log unit of metal emission except chromium. The associations achieved statistical significance for manganese and mercury. The particulate matter ≤2.5 and ≤10 μm emissions had a higher risk estimate, with 12% and 19% increase per natural log unit emission, respectively, and also achieved statistical significance.

In summary, airborne exposure to manganese, mercury, and particulate matter are associated with increased risk of adjudication. Causality cannot be proven in observational studies such as this one, but the association warrants further examination in other research studies. Comprehensive

*Correspondence to: 3223 Eden Ave Cincinnati, Cincinnati, OH 45267, USA. Fax: +1 513 558 4838.

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epidemiologic investigations of metal exposure in pediatric populations should include social health outcomes, including measures of delinquent or criminal activity. Furthermore, the influence of metals on the neurotoxic pathway leading to delinquent activity should be further explored.

Keywords

Manganese; Lead; Particulate matter; Mercury; Air pollution; Ecological study

1. Introduction

Antisocial behavior is a product of multiple interacting socio-hereditary variables (Moffitt, 1997); however, there is increasing evidence that metal exposure, particularly, manganese and lead, play a role in its epigenesis. Manganese and lead are both associated with numerous industrial processes, ubiquitous in the atmosphere, and well-established neurotoxicants. Other metals associated with neurological deficits, yet largely unexplored with respect to their relationship with delinquent behavior, include arsenic, cadmium, chromium, and mercury.

The association between lead exposure and aggressive and delinquent adolescent behavior has been previously documented (Braun et al., 2008; Dietrich et al., 2001; Needleman et al., 2002; Nevin, 2000; Pihl and Ervin, 1990). In 1943, Randolph Byers and Elizabeth Lord noted that children referred to them for evaluation of violent, antisocial tendencies were former patients who had been treated for lead poisoning (Byers and Lord, 1943). In the Cincinnati Lead Study, both prenatal and postnatal blood lead exposure were associated with a higher frequency of self- and parent-reported delinquent behaviors at 16 years of age (Dietrich et al., 2001). Early studies of high levels of airborne manganese exposure in miners found symptoms of “locura manganica” or manganese madness including anxiety, hostility, irritability, aggression, violent behavior, and impulsive–compulsive behaviors (Mena et al., 1967; Penalver, 1955a, 1955b). Penalver (1955a, 1955b) described a prodromal sign of manganese madness as victims committing “stupid” crimes. Gottschalk et al. (1991) reported finding significantly higher levels of manganese in the hair of violent prisoners than in community controls. As for the other metals, arsenic in drinking water had an inverse relationship with cognitive function in 10-year children (Wasserman et al., 2004, 2007). Cadmium has been associated with neurodevelopmental deficits (cognition, behavior, and motor skills) (Pihl and Parkes, 1977; Thatcher et al., 1982), but these endpoints may also be explained by lead exposure that was not always accounted for in these earlier studies. Recently, a study has suggested that higher cadmium exposure may cause deficits in cognition (Tian et al., 2009), but the association was not found at the US background exposure level (Cao et al., 2009). The neurodevelopmental effect of chromium has not been well characterized except for a single animal study showing reduced motor activity (Az-Mayans et al., 1986). Mercury exposure at high levels is neurotoxic to the developing fetus, but the effect of lower exposure to methylmercury or elemental mercury remains to be determined in epidemiologic studies (Debes et al., 2006; Myers et al., 2009; Bellinger et al., 2006; DeRouen et al., 2006).

In addition to these selected metals, exposure to traffic-related air pollution and its constituents, including polycyclic aromatic hydrocarbons, has also been shown to be associated with neuroinflammation (Block and Calderon-Garciduenas, 2009; Calderon-Garciduenas et al., 2009). Recent studies of prenatal exposure to airborne polyaromatic hydrocarbons found that high exposure was associated with cognitive developmental delay (Perera et al., 2006, 2009). Exposure to black carbon, a marker of traffic-related air pollution, has also been associated with decreased cognition (Suglia et al., 2008). Though the constituents of fine particulate matter ($PM_{2.5}$—particles with an aerodynamic diameter less than 2.5 μm) vary according to their source, combustion of gasoline and diesel fuel is a significant contributor to PM2.5 mass. The purpose of this study is to evaluate the ecological relationship between county-wide reported airborne emissions of air metals, particulate matter, and youth adjudicated for criminal activity.

2. Materials and methods

Metal exposure data were collected from the Environmental Protection Agency (EPA) AirData (2007). AirData provides annual summaries of air pollution data from the EPA air pollution databases, including data from the National Emission Inventory and the Air Quality Stem database. The National Emission Inventory database provides estimates of annual emissions, in pounds per year, of criteria and hazardous pollutants from point, nonpoint and mobile sources; Air Quality Stem hosts the EPA monitoring data from over 4000 monitoring stations. We located the total air emissions for metals known to have neurodevelopmental sequelae (Grandjean and Landrigan, 2006): lead, manganese, cadmium, arsenic, and mercury in all 88 Ohio counties in 1999. Data for these time periods provides a crude estimate of exposure to air emissions during young life as the antisocial/criminal behavior was recorded at age 10–19 years.

Population statistics obtained from the United States Census 2000 included: total county population, county size (area), the number and percent of individuals ages 10–19, the percent of families living below the poverty level, median family income, number and percent of African Americans, number and percent of individuals 25 years or older who have not graduated from high school, and population density. These potential confounding factors have been hypothesized to be related to lead exposure and criminal behavior (Needleman et al., 1996; Wright et al., 2008).

The number of youth adjudicated for felonies in each Ohio County was based on reports from the Courts of Common Pleas from each Ohio County in 2003–2005. An adjudicated youth is a minor found guilty of criminal activity by a judge in an Ohio court. Most juvenile offenders do not face a judge and those who do and who are adjudicated (found guilty) are usually those with extensive criminal records or those who have committed serious criminal acts. Thus, reported adjudications underestimate the actual volume of crime committed by youth.

To investigate the association between estimated air metal and particulate matter concentrations and the occurrence of adjudications, we first calculated simple correlations with the percentage of adjudications, all covariates, and estimated air emissions. Second, we evaluated the correlation among county covariates and metal emissions and among the air metals. Finally, we used separate negative binomial regression models for each pollutant to provide an estimated risk ratio of pollutant emissions on the risk of adjudication for all Ohio counties (Stretesky and Lynch, 2001). These models were adjusted for urban–rural residence, percentage of African Americans, median family income, percentage of family below poverty, percentage of high school graduation in 25 years and older populations, and population density. The number of average adjudications between 2003 and 2005 was the dependent variable. The natural logarithm of population age 10–19 years was entered as offset terms. The natural logarithm of pollutant emissions was the independent variable. In a subanalysis, we excluded data from the 6 largest counties in Ohio as these large metro areas may have more confounding factors that were not considered in the covariate adjustment. We also analyzed the combined effect of all airborne metals. We report relative risk and 95% confidence interval for each pollutant.

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3. Results

Demographic, geographic, and socioeconomic status of 88 Ohio counties and their correlation with adjudication rate is shown in Table 1. The variables significantly associated (p<0.05) with the rate of adjudications per 10,000 people aged 10–19 years were total population, the number of individuals in each county ranging between 10–19 years of age, population density, and the number and percentage of African Americans.

Table 2 provides the emission amounts of each pollutant and their correlation with adjudication rate. Metal emissions were highly skewed. For example, the geometric mean emissions for all 88 Ohio counties was 246 kg for lead in 1999, with a range of 4.9 (Meigs County) to 25,932 kg (Cuyahoga County). Similarly, the manganese emissions have a large span, ranging from a mere 0.7 kg in Morgan County to 208,059 kg in Washington County, which accounts for 71% of total Mn emissions in the state based on EPA AirData estimates (Fig. 1). The metal emissions in 1999 were all correlated with adjudication rate (2003–2005 average). Additionally, emissions of air particulate matter were correlated with adjudication rate. Fig. 1 also provides the average adjudication rate from 2003 to 2005 for each Ohio County per 10,000.

The air pollutants were related to county sociodemographic characteristics, including population size, population density, and number and percentage of African Americans (Appendix Table 1). Poverty measures (median family income and percentage of family below poverty level) were not related to air pollutants. Further, the air pollutants are highly correlated (Appendix Table 2); therefore, it is difficult to differentiate the association of individual air pollutants and the rate of adjudication.

In the negative binomial regression models, the metal emissions were associated with slightly higher risk of adjudication, with about 3–4% increased risk per natural log unit of metal emission except chromium (Table 3). The associations achieved statistical significance for Mn, Hg, PM2.5, and PM10 (p<0.05). The PM2.5 and PM10 emissions had a higher risk estimate, with 12% and 19% increase per natural log unit emission, respectively. To account for the potential impact of prevalent poverty, substandard housing, and violence related to large metropolitan regions, the results from 82 counties after excluding the 6 largest ones are also shown in Table 3. The results did not markedly change from the analysis of all Ohio counties although the p values tend to increase slightly. In addition, we did not find a significant association of the combined metals with adjudications (data not shown).

4. Discussion

We found a significant relationship between certain air pollutant emissions in 1999 and adjudications between 2003 and 2005 in Ohio counties. The magnitude of the association between air metal emission and adjudication was a 3–4% increase in risk for each natural log unit increase in emissions, with Mn and Hg emissions reaching statistical significance. PM2.5 and PM10 emissions were also significantly associated with adjudication with a 12–19% increase per natural log unit emission, respectively. Causality cannot be proven in observational studies such as this one, but the association warrants further examination in other research studies. Our negative finding of an association between the combined metals with adjudications may be due to the strong correlation among the metals.

Although our study cannot indicate a causal relationship between metal exposure and youth adjudicated for criminal activity, the literature supports this association, particularly for metals such as manganese and lead. Manganese is an essential element, and is considered one of the least toxic trace elements when consumed orally (Keen and Zidenberg-Cherr, 1996; Nielsen, 1999a, 1999b); however, when inhaled manganese can travel directly to the brain through olfactory neurons (Dorman et al., 2002; Leavens et al., 2007) and cross the blood brain barrier through passive and active transport mechanisms (Aschner and Dorman, 2006). Manganese exposed rats had an increased rate of fighting and other aggressive behavior (Chandra, 1983). Occupational manganese exposure has also been linked with anxiety, aggression, impulsivity, emotional instability, psychoses, and fatigue (Collier, 1938; Mena et al., 1987; Mergler et al., 1994; Penalver, 1955a, 1955b; Schuler et al., 1957). Recently, hair manganese levels were associated with behavioral problems in children exposed through drinking water (Bouchard et al., 2007). The biological mechanism of manganese on behavior may be its effects on brain neurotransmitters. Manganese lowers levels of brain serotonin and dopamine, both of which are associated with impulse control and planning (Kimura et al., 1978; Masters et al., 1998); low levels of brain serotonin are associated with disturbances in mood, poor impulse control and aggressive behavior (Retz et al., 2004; Young and Leyton, 2002).

We did not find an association between lead and youth adjudicated for criminal activity. This is in contrast to other researchers who found a positive association between lead exposure and aggressive and delinquent adolescent behavior (Braun et al., 2008; Dietrich et al., 2001; Needleman et al., 2002; Nevin, 2000; Pihl and Ervin, 1990). Nevin (2007) observed an association between preschool blood lead and subsequent international crime rate trends. A recent study by Wright et al. (2008) found a positive association between developmental exposure to lead during childhood and adult criminal behavior in 250 young adults followed prospectively since birth in Cincinnati. Lead is known to potentially impact a large number of neurodevelopmental processes owing to the metal's ability to mimic calcium (Goyer, 1995). One potential biological endpoint underlying the impact of lead on behavior is its apparent effect on brain volume in critical neurocortical regions. A strong association between aggression and reduced prefrontal cortical size has been demonstrated (Brower and Price, 2001), and reduction in prefrontal gray matter has been associated with violent crimes in individuals with antisocial personality disorder (Raine et al., 2000). Using volumetric Magnetic Resonance Imaging (MRI), Cecil et al. (2008) observed that the brain region most affected by early lead exposure was the prefrontal gray matter. A study of Philadelphia youths enrolled in the Collaborative Perinatal Project found that the strongest predictor of arrest in males was a history of lead poisoning (Denno, 1990). A survey of male children enrolled in the Pittsburgh Youth Study found that those with higher bone Pb concentrations had higher *T*-Scores on the Delinquency and Aggressive clusters of the Achenbach Child Behavior Checklist (Needleman et al., 1996). Higher bone lead levels have also been documented in a case-control study of adjudicated delinquents (Needleman et al., 2002). Furthermore, in a similar cross-sectional ecological study, Stretsky and Lynch (2001) found a strong association between air lead concentrations in all United States counties and homicide rates. One possible explanation for our lack of an association between airborne lead and adjudications is that tetraethyl lead in gasoline was phased out of use between 1976 and 1986, the primary source of airborne lead for the Stretsky and Lynch (2001) population. Thus, the primary airborne source of lead for our juvenile population would have been from industrial emissions. Our study does not include other important routes of early exposure to lead, such as from deteriorating lead based paint.

We did not find an association between county estimated emissions and sociodemographic characteristics of median family income and percentage of family below poverty level, but we did find an association with percentage of African Americans. This finding may be explained by elevated emission concentrations in metropolitan areas containing a mix of high and low income populations. Since our analysis is limited to aggregate county data, we cannot further investigate the relationship between environmental air contamination and measures related to environmental justice, such as individual income, education, and race and ethnicity; however, using aggregate data, Mohai et al. (2011) found a significant relationship between air quality in Michigan using emission data from the EPA's Toxic Release Inventory and school attendance and performance. Using individual residence, Brajer and Hall (1992) found an inverse relationship with between ozone and fine particulate matter exposure and income in the South Coast Air Basin of California.

This ecological study has several limitations. Our analyses included aggregate county-wide data rather than individual biomarkers; thus providing a more blunt estimate of exposure. Our findings suggest that youth exposed to airborne manganese and mercury are at increased risk for criminal behavior and possible adjudication. Nevertheless, without an individual exposure matrix, we are not able to assert that there is a causal relationship.

Our exposure measures are based on the US EPA AirData. AirData contains monitoring data and reported emissions data, each with their own limitations. Although air monitoring data provides accurate measures of pollutants, the air pollution levels inferred for each county could be misinterpreted. The air captured for particle measurement may not represent the entire county or urban area air quality. The National Emission Inventory database for criteria and hazardous air pollutants compiles information from emissions inventories compiled by state and local environmental agencies, including the Toxic Release Inventory data. These emissions data are self-reported by the industry to the EPA. The National Emission Inventory database does, however, include stationary (point and nonpoint) and mobile (onroad and nonroad) sources.

Our analyses do not take into account other routes of exposure to metals other than airborne exposure. It was well-established that the hand-to-mouth behavior is a primary route of exposure to lead in small children and that early lead exposure is related to delinquency and adult criminality (Bornschein et al., 1985; Wright et al., 2004). In the US, the most significant route of lead exposure is from leaded paint residues in houses built before 1978, which was not captured by air emission data. Exposure to arsenic and cadmium is primarily via contaminated groundwater. Most mercury exposure in the United States comes from methylmercury after consumption of fish. Thus, our present data analysis likely *underestimates* the amount of metal exposure in a portion of the population as the exposure source data does not include metal exposure sources from water, diet, home dust, or soil. Adjudication data may also underestimate the volume of youth crime. Adjudication data, however, is a reliable measure of serious crime committed by youths. Variation across jurisdictions may, however, influence actual counts.

The finding of particulate matter emissions and its relationship to adjudications is not surprising, as particulate matter is comprised of metals and other air pollutants, such as acids, organic chemicals, and soil or dust particles. Though the exact mechanism by which air pollution may result in neuroinflammation and neurodegeneration is unknown, four pathways have been proposed including: systemic inflammation leading to cytokine response and neuroinflammation, direct exposure to ultrafine particles (PM0.1), exposure to compounds bound to particulate matter, and CNS damage secondary to oxidative stress (Block and Calderon-Garciduenas, 2009).

5. Conclusions

In summary, our data suggest that airborne exposure to manganese, mercury, and particulate matter are associated with increased risk of adjudication. Due to the ecological nature of this study, we cannot state that this is a causal relationship. Nevertheless, our finding that metals are related to aggressive and delinquent behavior is supported by other epidemiological and animal model studies (Chandra et al., 1981; Li et al., 2003; Masters et al., 1998; Needleman et al., 1996; Nevin, 2000; Wright et al., 2004, 2008). Manganese exposure is an emerging public health issue and this study further adds to the evidence that airborne exposure is a potential health threat. Comprehensive epidemiologic investigations of metal exposure in pediatric populations should include social health outcomes, including measures of delinquent or criminal activity and indicators of environmental injustice. Furthermore, the influence of metals on the neurotoxic pathway leading to delinquent activity should be further explored.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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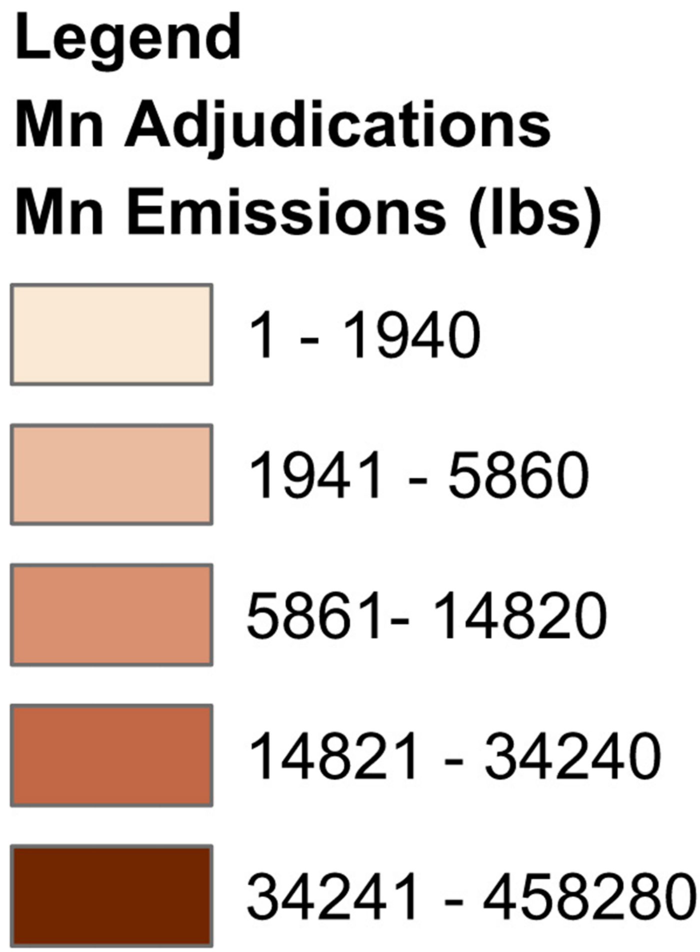

Fig. 1.

Adjudication rate by Ohio county and manganese estimated annual emissions in pounds in 1999.

Table 1

Characteristics of all Ohio counties and correlation with adjudication rate (/10,000 persons at 10–19 years).

Variable	Mean (SD)	Range	Correlation coefficient with ln adjudication rate
Total population	129,013 (216,533)	12,806–1,393,978	0.31
Area (km^2)	1205 (231)	591–1818	−0.01
Population, 10–19 years	18,689 (30,019)	1910–189,195	0.31
Population density	287 (480)	31–3044	0.32
Population density, 10–19 years	41 (67)	5–413	0.32
% Family below poverty level	7.76 (3.31)	2.80–15.75	−0.02
Median family income ($)	46,773 (7902)	33,071–76,453	0.06
Number of African Americans	14,788 (51,512)	32–382,634	0.26
% African Americans	3.84 (5.36)	0.10–27.45	0.40
% High school graduates among ≥25 years	81.23 (5.34)	51.5–92.9	0.19
No. of adjudications (2003–2005 average)	103 (199)	5–1308	0.40
Adjudication rate (/10,000 persons at 10–19 years)	45.69 (19.78)	13.90–116.19	
Ln adjudication rate (/10,000 persons at 10–19 years)	3.73 (0.45)	2.63–4.76	

Table 2

Pollutant emissions and correlation with adjudication rate in 88 Ohio counties.

Emissions	Geometric Mean (kg)	Range (kg)	Correlation coefficient of log emission with ln adjudication rate
Year 1999			
Lead	246	4.9–25,932	0.41
Manganese	86	0.7–208,059	0.38
Arsenic	6	0.1–5561	0.31
Cadmium	3	0.1–681	0.36
Chromium	42	1–24,325	0.32
Mercury	3	0.1–799	0.38
PM2.5	844	130–7024	0.40
PM10	2777	508–11,612	0.39

Table 3

Estimated risk ratios and 95% confidence intervals of 1999 metal and particulate matter emissions on the risk of adjudication during 2003–2005 in Ohio counties[a,b].

Emissions	Adjusted risk ratios and 95% confidence interval	
	All 88 counties	82 counties after excluding 6 largest metro areas
Lead	1.05 (0.99, 1.11)	1.04 (0.98, 1.10)
Manganese	1.03 (1.00, 1.06)	1.03 (0.996, 1.06)
Arsenic	1.03 (0.996, 1.07)	1.03 (0.99, 1.06)
Cadmium	1.03 (0.99, 1.07)	1.03 (0.98, 1.07)
Chromium	1.01 (0.98, 1.05)	1.00 (0.96, 1.05)
Mercury	1.04 (1.00, 1.08)	1.04 (0.99, 1.08)
PM2.5	1.12 (1.00, 1.26)	1.11 (0.98, 1.26)
PM10	1.19 (1.00, 1.41)	1.17 (0.97, 1.42)

[a]Estimates were based on a unit increase in independent variable (ln emission), which equals about 2.7 times increase in emission of each pollutant. The regression coefficient for each emission was modeled in a separate regression model.

[b]Adjusted for urban–rural residence, percentage of African Americans, median family income, percentage of family below poverty, percentage of high school graduation in 25 years and older populations, and population density.