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Pathways of inhalation exposure to manganese in children living near a ferromanganese refinery: A structural equation modeling approach

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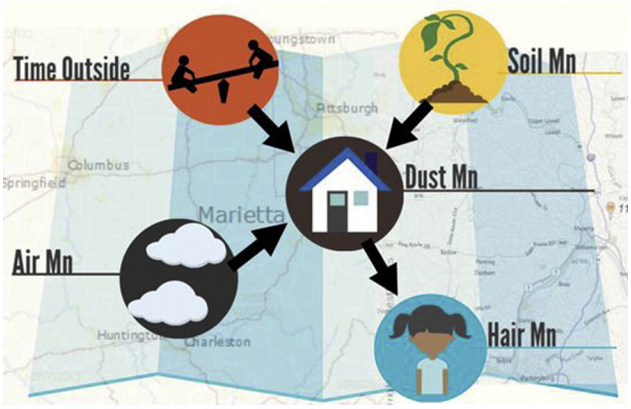
HIGHLIGHTS

- An inhalation pathway model for children's exposure to ambient Mn was hypothesized.
- Levels of Mn in air, soil and dust and children's hair were used to test the model.
- Mn in air and soil and time outside significantly contributed to household dust Mn.
- Household dust Mn was found to be a significant contributor to child hair Mn.

GRAPHICAL ABSTRACT



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ABSTRACT

Manganese (Mn) is both essential element and neurotoxicant. Exposure to Mn can occur from various sources and routes. Structural equation modeling was used to examine routes of exposure to Mn among children residing near a ferromanganese refinery in Marietta, Ohio. An inhalation pathway model to ambient air Mn was hypothesized. Data for model evaluation were obtained from participants in the Communities Actively Researching Exposure Study (CARES). These data were collected in 2009 and included levels of Mn in residential soil and dust, levels of Mn in children's hair, information on the amount of time the child spent outside, heat and air conditioning in the home and level of parent education. Hair Mn concentration was the primary endogenous variable used

Abbreviations: Mn, manganese; SEM, structural equation modeling; CARES, Communities Actively Researching Exposure Study; HVAC, heating, ventilation, and air conditioning; TWD, time-weighted distance.

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to assess the theoretical inhalation exposure pathways. The model indicated that household dust Mn was a significant contributor to child hair Mn (0.37). Annual ambient air Mn concentration (0.26), time children spent outside (0.24) and soil Mn (0.24) significantly contributed to the amount of Mn in household dust. These results provide a potential framework for understanding the inhalation exposure pathway for children exposed to ambient air Mn who live in proximity to an industrial emission source.

1. Introduction

Although manganese (Mn) is an essential nutrient necessary for normal metabolic functioning, excessive exposure may result in neurotoxic effects. Occupational exposure to Mn has been associated with neurological impacts ranging from impairment of motor function to decreases in visual perception and memory (Bouchard et al., 2008; Bowler et al., 2006; Lucchini et al., 1997). Significant associations have been identified between the level of Mn in children's hair and a number of neurodevelopmental health outcomes (Bouchard et al., 2007; Bouchard et al., 2011; Carvalho et al., 2014; Lucchini et al., 2012; Menezes-Filho et al., 2009; Riojas-Rodriguez et al., 2010; Rugless et al., 2014). A systematic review found a 50% increase in hair Mn concentration was associated with a decrease in IQ of 0.7 among children ages 5–15 (Rodriguez-Barranco et al., 2013). Neurological health outcomes in children have been associated with Mn in soil (Lucchini et al., 2012) and Mn in children's hair was found to be associated with Mn levels in ambient air (Haynes et al., 2010). In a South African study, the relationship between Mn in children's blood and Mn in classroom dust and playground soil approached statistical significance ($p = 0.10$) (Rollin et al., 2005). Understanding the sources, routes, and magnitude of Mn exposure is essential in identifying preventive strategies. It is currently not clear how these pathways are related and the relative impact each may have in an individual's total Mn exposure. One approach to model exposure pathways is structural equation models (SEMs). SEM is a multivariate statistical technique that facilitates the simultaneous testing of networks of relationships between a set of variables (Buncher et al., 1991; von Lindern et al., 2015). The flexibility of the SEM approach can provide a framework to identify potential casual pathways and evaluate multiple Mn exposure scenarios simultaneously.

The 2002 National-Scale Air Toxics Assessment (US Environmental Protection Agency, 2009) reported that of the 23 air toxics with potential for neurological effects, Mn is the most significant contributor at 28%. Mn was included in an analysis of air pollutants in a 2009 United States Environmental Protection Agency (USEPA) survey of outdoor air quality at 63 schools in 22 states, demonstrating USEPA's concern for children's potential environmental exposure to this neurotoxin in ambient air (US Environmental Protection Agency, 2010). A mean level of Mn in air of 1.46 μg/m^3 was detected at Warren Elementary School in Marietta, Ohio (US Environmental Protection Agency, 2010). This level exceeds the reference concentrations for chronic exposure to inhaled manganese set by USEPA (0.05 μg Mn/m^3), ATSDR (0.04 μg Mn/m^3), and the World Health Organization (WHO) (0.15 μg Mn/m^3) (Agency for Toxic Substances and Disease Registry, ATSDR, 2012; US Environmental Protection Agency, 1999; World Health Organization, 2000). Warren Elementary School is about 5 km from Eramet Marietta, Inc., the longest running manganese refinery in the United States. The primary aim of this study was to examine theoretical Mn inhalation exposure pathways for children living near the ferromanganese refinery enrolled in the Communities Actively Researching Exposure Study (CARES) using SEM. CARES is an epidemiological investigation of the potential neurobehavioral effects of air Mn exposure on children residing in Marietta, OH.

2. Methods

2.1. Study population

CARES was initiated in response to community concern about potential neurobehavioral impacts on children exposed to Mn (Haynes et al., 2011). Study participants were recruited via letters through schools and local radio and newspaper advertisement. Those eligible for enrollment in CARES were children ages 7–9 years who resided in the Marietta, Ohio community since birth. In addition, their biological mother must have resided in close proximity to Marietta during pregnancy with the child. Recruitment occurred from October 2008 to March 2013; data for the current analysis was obtained from participants enrolled and sampled from Jan 1, 2009 to Dec 31, 2009. The University of Cincinnati Institutional Review Board approved the CARES study and all parents signed an informed consent while the children signed an informed assent.

Each participating family completed a questionnaire capturing information about the residence including type of heating and air conditioning, where the child attended school, and how much time the child plays outside. As the amount of time children spend outdoors may impact their overall exposure to ambient Mn, detailed questions were asked regarding the number of hours per day the child spent outdoors. The Barratt Simplified Measure of Social Status (BSMSS) was also administered at the home visit (Barratt, 2012) to assess education level of the child's parent/legal guardian. The parent education score was used as a surrogate for socioeconomic status (SES) in the SEM model. Information collected on heating and air conditioning was combined into an index representing air filtration in the home, referred to as the heating, ventilation, and air conditioning (HVAC) Score. An electric, gas or heating oil furnace as the primary heating source received an HVAC Score of 2 and as a secondary heating source received an HVAC Score of 1. If the primary heating source had an air filter a score was given based on frequency of filter change: once a month = 1; once every three months = 0.75, every six months = 0.5 and annually = 0.25. If the primary source of cooling for the home was central air conditioning or individual air conditioning units, a score of 2 was assigned. If the air conditioning unit had an air filter a score was given based on frequency of filter change following the same pattern as for the heating source. A score of 1 was given if the home also had an air purifier. Scores for each response were summed to represent a total HVAC Score for the dwelling. Possible values ranged from 0 to 8 with higher HVAC Scores linked to higher household air filtration.

2.2. Soil and dust sample collection and analysis

The CARES environmental sampling team were members of the community trained to collect samples of soil and dust from residences of study participants following HUD protocols for sample collection (U.S. Department of Housing and Urban Development, HUD, 1995). Sample collection forms were completed for each dwelling including address, owner name, phone number and Geographic Information Systems (GIS) coordinates. Within 10% of the households, field duplicate soil and dust samples were collected for quality control (QC). In addition, standardized QC dust samples were prepared by the Hematology

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