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Food contamination as a pathway for lead exposure in children during the 2010–2013 lead poisoning epidemic in Zamfara, Nigeria

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ABSTRACT

In 2010, an estimated 400 to 500 children died of acute lead poisoning associated with artisanal gold mining in Zamfara, Nigeria. Processing of gold ores containing up to 10% lead within residential compounds put residents, especially children, at the highest risk. Principal routes of exposure were incidental ingestion and inhalation of contaminated soil and dusts. Several Nigerian and international health organizations collaborated to reduce lead exposures through environmental remediation and medical treatment. The contribution of contaminated food to total lead exposure was assessed during the environmental health response. Assess the influence of cultural/dietary habits on lead exposure pathways and estimate the contribution of contaminated food to children's blood lead levels (BLLs). A survey of village dietary practices and staple food lead content was conducted to determine dietary composition, caloric intakes, and lead intake. Potential blood lead increments were estimated using bio-kinetic modeling techniques. Most dietary lead exposure was associated with contamination of staple cereal grains and legumes during post-harvest processing and preparation in contaminated homes. Average post-harvest and processed cereal grain lead levels were 0.32 mg/kg and 0.85 mg/kg dry weight, respectively. Age-specific food lead intake ranged from 7 to 78 μg/day. Lead ingestion and absorption were likely aggravated by the dusty environment, fasting between meals, and nutritional deficiencies. Contamination of staple cereal grains by highly bioavailable pulverized ores could account for as much as 11%–34% of children's BLLs during the epidemic, and were a continuing source after residential soil remediation until stored grain inventories were exhausted.

Introduction

According to the World Health Organization (WHO), the 2010 Zamfara lead poisoning epidemic was an "unprecedented environmental emergency" (Moszynski, 2010) with soil lead levels exceeding 100,000 mg/kg (10%) and individual venous blood lead levels greater than 400 μg/dL (Bartrem et al., 2014; Dooyema et al., 2011; Lo et al., 2012; Plumlee et al., 2013; von Lindern et al., 2011). Within a few months of the outbreak, an estimated 400 children age five years and younger died of

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acute lead poisoning. Thousands more were severely poisoned and at risk of irreversible neurocognitive damage with geometric mean blood lead levels (BLLs) exceeding 149 μg/dL (Burki, 2012; Greig et al., 2014; Thurtle et al., 2014; Tirima et al., 2016). Emergency response efforts, commencing in two villages in June 2010, included chelation therapy for children ≤5 years old conditioned upon remediation of their homes to preclude continuing exposure. By March 2011, the Zamfara Ministry of Environment with guidance from the United States (US) based TerraGraphics Environmental Engineering (TG) had completed Phases I and II cleanup activities, remediating 468 residential compounds in seven villages and facilitating chelation therapy for 2146 children ≤5 years by Médecins Sans Frontières (MSF). In 2013, another 352 homes in Bagega village were remediated during Phase III. Overall, soil and dust exposures were reduced by 77%–98% for more than 17,000 villagers. More than 2300 children received chelation therapy that reduced individual BLLs to <30 μg/dL (Greig et al., 2014; Thurtle et al., 2014; Tirima et al., 2016).

Investigations during February 2011 pre-remediation sampling in Bagega village and July 2011 remedial effectiveness evaluations in remediated villages provided a more detailed understanding of secondary exposure pathways and risk co-factors (Bartrem et al., 2017; Tirima et al., 2016). These surveys revealed that the food supply was compromised through interactions between artisanal mineral exploitation and indigenous agricultural labor practices. Additional efforts to quantify the dietary exposure pathway continued in 2012. These findings were important in modifying subsequent remedial sustainability, environmental health, medical, advocacy, and institutional responses to the epidemic (Bartrem et al., 2017; Tirima et al., 2016). This paper focuses on the assessment of pre-remediation lead exposures from food in Bagega village in 2011–2012.

Gold deposits have been exploited in northern Nigeria since colonial times. A gold rush took place in the 1930s, mostly by European entrepreneurs using primitive mining methods (Ochonu, 2009). As gold prices increased in the late 2000s, the legacy colonial mines were revisited and developed into commercially viable sites. Artisanal mining practices in remote areas world-wide are largely driven by poverty (Mallo, 2012). Zamfara rural residents are extremely poor, subsisting on less than $2/day, with little formal education and limited employment alternatives (IFAD, 2010). Subsistence agriculture is the main economic activity in this semi-arid region and climate change is negatively impacting both crop and livestock production (Farauta et al., 2012; Odjugo et al., 2009). In 2011, Zamfara State had the highest unemployment rate in Nigeria at 42% (Royal Times Nigeria, 2016), and village rates are likely higher as agricultural sector jobs are seasonal (Nnaji, 2001). Consequently, the “gold rush” beginning in 2008–2009 was a welcome economic relief, albeit with catastrophic environmental health consequences.

Despite large revenues from this gold trade, little investment in improved mining infrastructure or technology followed (WHO, 2011). Zamfara artisanal miners use low cost milling and gravity concentration during ore processing. Manual extraction of gold from rock involves “pounding” the ore to gravel-like consistency using hammers and locally designed mortars and pestles. The crushed material is then ground using modified steel flour mills. Generally, 50 to 200 mesh (75–300 μm) uniform powdered ores are produced, mixed with water and sluiced to obtain a gold concentrate, which is then amalgamated with mercury. The mercury is evaporated by torch, leaving an unrefined sponge gold nugget. Dry processing produces enormous quantities of dust, which were deposited throughout the villages and residential areas by wind, foot traffic, and direct disposal of tailings. The use of mercury also resulted in soil, dust, water, food, and vapor exposures.

Before traditional leaders banned the practice in the villages in May 2010, ore processing took place in residential compounds and village public areas. The situation was exacerbated by the religious/cultural practice *purdah* (or *auren kulle* in Hausa), which involves the sequestration of married women in residential compounds. In order to employ women in mining operations, ores were brought into the compounds for processing, resulting in widespread contamination of living areas and throughout the villages. The Hausa household (*gida*) is a family farming unit, often containing multiple families of several generations and is the fundamental component of residence, production, distribution, transmission of culture, and reproduction (Adamu, 2009). Walled on the outside, with a gradation of space from *public to private* on the inside, the *gidas* express the gendering of space and the importance of sequestering women (Pellow, 2002).

Most post-harvest food processing is accomplished by women and children within the *gida*. Grains are dried and hand-threshed by beating on the ground and wind winnowing, and then stored in specially built ovoid mud-walled granaries. Most residential compounds are constructed from soil and thatch, although a few homes have cement floors and corrugated iron sheet roofing. In some homes, adobe bricks and plaster were made using contaminated ore tailings mixed with mud. Almost all food is processed within the compound by the women, often in the same contaminated areas where ores were processed. Women sometimes pounded ore with the same mortars and pestles used to prepare food. Flour mills were used for grinding both grain and ores. Box sluicing often took place inside compounds leading to the contamination of residential wells. As a result, the likelihood of contaminating food with ores and tailings was extremely high.

Most small-holder agriculture in Zamfara is carried out during the single rainy season from April/May through October. Staple crops such as millet (*Pennisetum*), guinea corn (sorghum, *Sorghum bicolor*) maize (corn, *Zea mays*) and rice (*Oryza sativa*) are intercropped with legumes including cowpeas (*Vigna unguiculata*), groundnuts (*Arachis hypogaea*) and soybeans (*Glycine max*). Tomatoes, hot peppers, onions, and cabbage are grown both during the rainy season and the dry season under irrigation (Bush, 2013; Ene-Obong et al., 2013). Harvest begins in September and continues through December depending on crop type. Dry season harvest from irrigated crops usually ends in March. Some families exhaust home-grown supplies by late January and purchase additional foodstuffs from wealthier neighbors or weekly markets. There is limited dietary diversity during the food shortfall period. Families often supplement their diet with foraged foods such as baobab leaves and other wild plants (Bush, 2013).

The post-harvest system for grains and opportunities for contamination are shown in Fig. 1. Most grains and pulses are left to dry in the field. Zamfara farmers sell surplus grain

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