Mercury Exposure, Cardiovascular Health, and Pulmonary Function in a Small-Scale Gold Mining Community in Northeast Ghana

by

Mozhgon Rajaee

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Doctoral Committee:

Adjunct Associate Professor Niladri Basu, McGill University, Co-chair
Professor Thomas G. Robins, Co-chair
Assistant Professor Richard L. Neitzel
Associate Professor Brisa N. Sánchez

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List of Abbreviations

ASG	Artisanal and small-scale gold
ASGM	Artisanal and small-scale gold mining
ATSDR	Agency for Toxic Substances and Disease Registry
BMF	Biomass fuel
CDC	Center for Disease Control and Prevention (US)
CRM	Certified reference material
DBP	Diastolic blood pressure
DHS	Demographic and health survey
DMA	Direct Mercury Analyzer
FEV_1	Forced expiratory volume in one second
FEV_1/FVC	Forced expiratory volume in one second divided by the forced vital capacity (ratio)
FVC	Forced vital capacity
GIS	Geographic information systems
GPS	Global positioning system
Hg	Mercury
HOH	Head of household
LMIC	Low and middle-income countries
MeHg	Methylmercury
NHANES	National Health and Nutrition Examination Survey
PFT	Pulmonary function test
PP	Pulse pressure
SBP	Systolic blood pressure
SG	Specific gravity
UNEP	United Nations Environment Program
US EPA	US Environmental Protection Agency
WHO	World Health Organization

Abstract

Small-scale gold mining is practiced globally in low and middle-income countries and is a vital component of the Ghanaian economy. Miners and non-miners in artisanal and small-scale gold mining (ASGM) communities may be highly exposed to elemental mercury (Hg), a toxicant used to isolate gold. Despite research showing elevated Hg exposure for small-scale gold miners and decreased pulmonary function with large-scale mining from respirable silica exposure, the scientific literature lacks research on how non-mining ASGM residents are exposed to Hg, how Hg exposures impact blood pressure (BP), and how ASGM impacts pulmonary function. The objective of this research is to increase understanding of Hg exposure in multi-media and its impacts on BP, and to assess pulmonary function in miners in an ASGM community. Residents in northeast Ghana from a small-scale gold mining community, Kejetia, and a comparison subsistence farming community, Gorogo were surveyed in May through July 2011 on Hg exposures, BP, and respiratory health. Participants had BP (systolic and diastolic) measured, performed spirometry, and provided urine, hair, and household soil samples. Data were collected from 97 adults from 54 households in Kejetia and 75 adults from 26 households in Gorogo. Total mean (±SD) specific gravity-adjusted urinary Hg, hair Hg, and household soil Hg were higher among Kejetia miners (29.3 ± 125 µg/L, 1.13 ± 0.81 µg/g, and 18.72 ± 53.35µg/g, respectively) than Kejetia non-miners (4.22± 6.88 µg/L, 0.56 ± 0.27 µg/g, 5.536 ± 8.990 µg/g, respectively), and Gorogo participants (0.22 ± 0.19 µg/L, 0.23 ± 0.20 µg/g, and 0.041 ± 0.023 µg/g, respectively). Close to one-third of

Kejetia participants had urinary Hg concentrations > 10 µg/L and household soil Hg above the Canadian health guideline of 6.6 µg/g Hg. Urinary and hair Hg were not significantly associated with systolic or diastolic BP for Kejetia or Gorogo participants, but follow trends observed in other studies. Abnormal lung function was elevated for predicted FEV_1 (15.0%) and FEV_1/FVC (22.0%) beyond an expected five percent in healthy populations. Percent predicted FEV_1, FVC and FEV_1/FVC were not significantly different between Kejetia and Gorogo or by mining status in Kejetia. Biomass fuel use showed some associations with adverse respiratory symptoms and reduced pulmonary function. This research adds to our understanding of how miners and non-miners in ASGM communities may be exposed to Hg and serves as a basis for further research on Hg's cardiovascular impacts and pulmonary function for small-scale gold miners.

Chapter 1 Introduction

1.1 Background

1.1.1 Global artisanal and small-scale gold mining

Artisanal and small-scale gold mining contributes approximately 12% of the global market of gold, larger than any single producer (United Nations Environment Program [UNEP], 2010). It is estimated that 10 to 15 million people work in artisanal and small-scale gold mining (ASGM) directly and 80 to 100 million people are indirectly involved or dependent on ASGM for their livelihoods (International Labor Organization, 1999; UNEP, 2010). ASGM is almost exclusively practiced in low and middle-income countries (LMICs) and often in rural areas (UNEP, 2010). It provides a significant source of employment and income for people with few alternatives and can largely influence the informal local economy (UNEP, 2010). Obstacles to formalize registered mining concessions and miners, such as requirements to travel to regional offices and fees, pose significant challenges to regulating the industry.

Utilizing mercury (Hg) to isolate gold, ASGM has surpassed fossil fuel combustion as the largest contributor to global anthropogenic Hg in the atmosphere (UNEP, 2013a). The largest regional consumers of Hg for ASGM are East and Southeast Asia, South America, and Sub-Saharan Africa (Pacyna et al., 2010). Growing concerns about the use of Hg, a potent neurotoxicant, prompted the Minamata Convention on Mercury in 2013, a global treaty aiming to reduce Hg emissions and mining, with a particular focus on regulating the ASGM sector (UNEP, 2013b; Minamata Convention on Mercury, 2015).

1.1.2 Small-scale gold mining and northeast Ghana

Gold deposits are abundant in Ghana and have resulted in artisanal and small-scale gold mining (ASGM) throughout the country (Hilson & Clifford, 2010). Small-scale gold mining accounts for just over ten percent of Ghana's national gold production, and employs over 500,000 people formally (Bawa, 2010). Numerous factors have fueled the ASGM industry, mainly through inadequate employment opportunities and the rising price of gold, which has increased over four-fold in the last decade (Ghana Chamber of Mines, 2010).

The Talensi-Nabdam district in the Upper East Region is a recently established district that is largely agrarian (about 90%) and rich in gold mineral deposits (Talensi-Nabdam District Assembly, 2010). The District has now split into two separate districts, Talensi and Nabdam, although data are not available at this level. There was a resurgence of ASGM in the Talensi-Nabdam District in the mid-1990s, aided by the Minerals Commission and ASGM licensing (Hilson, 2010). The Talensi-Nabdam district alone employs over 10,000 people, including children, in ASGM (Hilson, 2010). About 90% of the population is illiterate and 5% semi-literate (Talensi-Nabdam District Assembly, 2010). Kejetia is one of at least 15 small-scale gold mining communities in the district (Figure 1.1)

The small-scale gold mining process utilizes elemental mercury (Hg) to isolate gold. In the mining communities of Talensi-Nabdam, mining is primarily underground, but can also be colluvial (deposits at the base of hills and cliffs), eluvial (deposits from weathering), and alluvial (sediment deposits). Gold-containing ore is mined and either pounded into a powder through a mortar and pestle method or ground in a mill mechanically. Ground ore is sifted (locally known as *shanking*), a role primarily performed by women, and any larger ore is re-milled. The powdered ore from *shanking* is mixed with water and washed on an angled sluice ramp covered in carpet to catch denser particles. The dense particles captured by the carpet are then placed in a rubber mat, mixed with water, and swirled to separate the gold. Elemental Hg is added, and due to its high affinity to gold, binds to the gold particles. The gold-mercury amalgam is heated with a small torch and the Hg volatilizes to leave the valuable gold behind.

1.1.3 Mercury pollution and fate

Mercury (Hg) is a naturally occurring metal in the environment and exists in three forms: elemental (or metallic), inorganic, and organic (Clarkson & Magos; 2006). Elemental, or metallic, Hg (Hg^0) is rarely found in nature and is the most volatile form of Hg, and is a type of inorganic Hg (Risher, 2003). Inorganic Hg (Hg^{2+}) typically occurs as salts, such as mercuric chloride, mercurous chloride, mercuric sulfide (cinnabar), and mercuric acetate (Risher, 2003; UNEP, 2002). Organic Hg is bound to carbon, or methylated; this includes ethylmercury, dimethylmercury, penylmercury, and methylmercury (MeHg). Inorganic Hg is methylated and demethylated by microorganisms. After methylation, MeHg is more bioavailable and is able to bioaccumulate and biomagnify in organisms (UNEP, 2013a). Released elemental Hg can be transported in the atmosphere from 100 to 1000 km and may remain in the atmosphere for a few months to one year before it is oxidized to inorganic Hg and deposited through wet or dry deposition (UNEP, 2002). Figure 1.2 shows the transport of Hg and its speciation in the environment.

Natural sources of Hg include Hg in minerals and volcanic emissions, fires, and evasion from aquatic and terrestrial ecosystems (which may, in part, be due to anthropogenic sources originally) (Pacyna, Pacyna, Steenhuisen, & Wilson, 2006; UNEP, 2013a). Within the past five years, the largest contributor to anthropogenic Hg in the atmosphere shifted to ASGM (UNEP, 2013a; Pacyna et al., 2006). Fossil fuel combustion, particularly coal, has been the reigning top contributor to anthropogenic Hg in the atmosphere, and where much of the focus for mitigation has occurred (Pacyna et al., 2006). ASGM consumed an estimated 37% of the global Hg in 2008, while fossil fuel consumption accounted for 25% of anthropogenic emissions (UNEP, 2013a). Estimates of Hg emissions from ASGM, however, are unable to adequately account for emissions from illegal gold mining, which may be substantial (Pacyna et al, 2006). The Ghana Precious Minerals Marketing Corporation and the Ghana Minerals Commission estimate that Hg is being used at far greater quantities than what is available through licensed traders, suggesting a significant black market (Nyame, 2010). Little is known about the number of illegal ASG miners globally and their use of Hg, which may differ from formalized miners that fall under licensed regulations, but the Ghana Minerals Commission estimated that 60% of ASG miners were illegal, unregistered miners (B. Calys-Tagoe, personal communication, Jan 2014). This uncertainty is important in understanding the burden of Hg pollution from ASGM, as it is likely that most estimates are underestimating the contributions from illegal ASGM activity.

1.1.4 Human exposure to mercury and biomarkers

1.1.4.1 Organic mercury

Human methylmercury (MeHg) exposure comes primarily from fish and seafood consumption (UNEP, 2013; US Environmental Protection Agency [EPA], 1997). Methylmercury forms water soluble complexes attached to thiol (carbon-bonded sulfhydrul) groups, which allows it to pass the blood-brain and placental barriers (Clarkson and Magos, 2006; UNEP, 2013; Agency for Toxic Substances and Disease Registry [ATSDR], 1999). This places pregnant women and their developing fetuses, and young children at an even greater risk to Hg toxicity. This risk may be exacerbated in ASGM communities with higher Hg exposures (Bose-O'Reilly, Lettmeier, Roider, Siebert, & Drasch, 2008). The main route of excretion is through feces, but it is also excreted in scalp hair and urine.

Hair Hg concentrations are used to reflect blood Hg concentrations at the time of hair growth to determine Hg exposure. Hair is assumed to grow about one centimeter per month, but there is some intrapersonal variability (US EPA, 1997; Clarkson & Magos, 2006). The U.S. benchmark dose of hair Hg is 11.1 μg/g, based on neurotoxic effects observed *in utero* to MeHg in Iraqi children (US EPA, 1997).

1.1.4.2 Inorganic and elemental mercury

While the primary route of Hg exposure is through food consumption, inhalation may play a role in certain occupational settings for inorganic Hg exposure. Dentists or ASG miners may be exposed to elemental Hg through dental amalgams or occupational use in gold mining (UNEP, 2013). About 80% of inhaled elemental Hg vapors are absorbed through the lungs (UNEP, 2002).

Inorganic Hg can also be consumed through diet. Inorganic Hg can be elevated in soil near industrial sites (Nublein, Feicht, Schulte-Hostede, Seltmann, & Kettrup, 1995). Hg soil contamination in ASGM communities is not well quantified, but Hg use in ASGM suggests the potential for soil contamination. Little is known about soil-derived exposures, but unintentional ingestion of contaminated soil may be an additional concern for gold miners and those living in ASGM communities.

Urinary Hg is a good indicator of long-term elemental and inorganic mercury exposure (Wranova et al., 2008; Clarkson & Magos, 2006). Elemental Hg has a half-life of about 56-58 days in the whole-body and kidneys, with feces and urine as the main routes of excretion (Clarkson & Magos, 2006; Bluhm et al., 1992). Urinary excretion of more than 0.3 mg of Hg in 24 hours is indicative of Hg poisoning (True & Dreisbach, 2002).

1.1.5 Mercury toxicity

Mercury is associated with a variety of health effects that depend on the form of Hg exposure, including neurological, cardiovascular, renal, gastrointestinal, and respiratory effects (Clarkson & Magos, 2006; Poulin & Gibb, 2008; ATSDR, 1999, UNEP, 2002).

1.1.5.1 Organic mercury

Methylmercury exposure can cause visual field constriction, ataxia, cognitive decline, paresthesia, dysarthria, and death (Davidson, Myers, & Weiss, 2004; Clarkson & Magos, 2006). Effects are generally on areas of the central nervous system associated with sensory and motor coordination function (Poulin & Gibb, 2008; Clarkson & Magos, 2006).

Since Hg is able to pass the blood-brain and blood-placental barriers, fetal exposure to MeHg can have vast impacts on development (Clarkson & Magos, 2006). Three large cohort studies in New Zealand, the Faroe Islands, and the Seychelles Islands have examined the neurological impact of maternal exposure to MeHg to assess potential impacts on children and found decreased intelligence quotient (IQ) scores, psychological test scores, and dysfunctions in language, attention, memory, and visuospatial and motor functions (Crump, Kjellstrom, Shipp, Silvers, & Stewart, 1998; Grandjean et al., 1997; Myers et al., 2003; Davidson et al., 2010; Axelrad, Bellinger, Ryan, & Woodruff, 2007). Given these adverse health effects for the fetus and young children, there is particular concern for women of childbearing age using Hg or living in ASGM communities.

1.1.5.2 Inorganic and elemental mercury

Some small-scale gold miners are exposed to elemental Hg vapor from burning gold-mercury amalgams. Elemental Hg vapor (Hg^0) is absorbed readily in the lungs, while some particles can be swallowed and reach the gastrointestinal (GI) tract, but very little GI-absorbed Hg has been found to enter blood circulation (Sandborgh-Englund, Einarsson, Sandstrom, & Ekstrand, 2004).

High, short-term inhalational exposure to elemental Hg can cause respiratory symptoms of cough, dyspnea, chest tightness, or chest pain; acute pneumonitis; nausea; vomiting; diarrhea; eye irritation; salivation; tremors; gingivitis; emotional lability; erethism; and increased blood pressure and palpitations (ATSDR, 1999; Davidson et al., 2004; True & Dreisbach, 2002; Poulin & Gibb, 2008). High exposures can also lead to damage of renal glomeruli and tubules and death (True & Dreisbach, 2002). Even low exposures can result in more subtle deficits in performance (Davidson et al., 2004). Children exposed to high levels of elemental Hg may develop acrodynia, characterized by pains in the arms and legs, pink palms, severe diarrhea, photophobia, anorexia, restlessness, stomatitis, irritability, hypertension, and lethargy, which can continue for weeks or months (Davidson et al., 2004; True & Dreisbach, 2002). Exposure to elemental Hg for several weeks has been associated with chronic cough, and increased blood pressure and heart rate (ATSDR, 1999). Symptoms of occupational exposures > 100 µg/L of urinary Hg include headache, fever, fatigue, chills, abdominal cramps, diarrhea, decreased appetite, tremors, respiratory congestions and shortness of breath, and psychological symptoms such as irritability, increased temper, mood changes, anxiety, decreased sociability, and uncharacteristic violent behavior (Bluhm et al., 1992; Poulin & Gibb, 2008). Studies of ASGM communities have observed elevated urinary Hg reflecting high elemental Hg exposures among ASG miners (Paruchuri et al., 2010; Adimado & Baah, 2002), but it is unclear how many people are exposed to dangerous levels (Clarkson & Magos, 2006; WHO, 1980).

1.1.5.3 Cardiovascular health and mercury

Despite centuries-long knowledge that Hg is toxic (Sloan, 2012), most research has focused on the impacts to neurological health, while studies of the long-term impacts to the cardiovascular system are lacking. Research of cardiac effects has only been studied recently, and results of existing studies vary. Existing studies are limited in their scope and have yet to explain the mechanisms that Hg uses to influence cardiovascular health.

Studies have linked MeHg exposure with increases in systolic and diastolic BP. In a study of three Amazon communities, participants with higher MeHg exposure had a tendency of higher systolic and diastolic blood pressure (BP), as a function of age, but no significant association between BP and hair Hg was observed (Dorea, de Souza, Rodrigues, Ferrari, & Barbosa, 2005). A study of Faroese male whalers found that MeHg was associated with increases in systolic and diastolic BP (Choi et al., 2009). Fillion et al.'s (2006) study in the Amazon found a significant risk for elevated systolic BP with hair Hg levels greater than 10 μg/g. A study from two large U.S. cohorts examining total toenail Hg (a MeHg biomarker) and cardiovascular disease did not find any clinically relevant effects (Mozaffarian et al., 2011). Individuals with dental amalgams have been found to have significantly lower BP, heart rate, hemoglobin, and hematocrit when compared to those without amalgams (Siblerud, 1990). In a study of dentists exposed to MeHg from fish consumption and elemental Hg from dental amalgams, hair Hg was associated with an increase in diastolic BP and urinary Hg was associated with a decrease in systolic BP, after adjusting for anti-hypertensive medication use (Goodrich et al., 2012). A study of historic Hg miners with very high past urinary Hg exposures found that it was associated with increases in systolic and diastolic BP (Kobal et al., 2004). However, Siblerud (1990) and Goodrich et al.'s (2012) studies observed decreases in BP from slightly elevated levels of elemental Hg exposure. It is uncertain from these studies what the impact of high Hg exposures may be on BP of ASG miners, who do not have comparable elemental Hg exposures to dentists or Hg miners. Further, there is a potential for opposing effects of MeHg and elemental Hg on BP.

MeHg and elemental Hg exposures in an ASGM community may pose a health risk as they are at levels that are not as comparable to the general U.S. population. There have been no studies to date exploring Hg exposures in small-scale gold miners and cardiovascular health. Examining BP and Hg biomarkers in Kejetia may afford more clarity on how high MeHg and elemental Hg exposures impact BP. Hypertension is an emerging problem in Ghana, and was the fifth largest cause of outpatient morbidity (Bosu, 2010).

1.1.6 Silica, biomass fuel smoke, and health

1.1.6.1 Silicosis

Crystalline silica (SiO_2) produced from ore processing, such as in gold or coal mining, has been widely studied and associated with silicosis (Greenberg, Waksman, & Curtis, 2007). Long-term or high level exposure to crystalline silica can lead to the development of silicosis, an irreversible pulmonary fibrosis that can develop up to 45 years after exposure (Greenberg et al., 2007). Silicosis has been found to accelerate substantial pulmonary function loss among commercial miners, with the degree of the decrease proportional to the severity of silicosis and dust exposure (Ehrlich, Myers, te Water Naude, Thompson, & Churchyard, 2011; Cowie, 1998). Inhalation of crystalline silica is also associated with lung cancer and is classified as a carcinogen by the International Agency for Research on Cancer (Brown, 2009). ASG miners may be exposed to crystalline silica, which has been found to exceed 30% of some gold ore (Greenberg et al., 2007). However, silicosis research has focused on large-scale miners and overlooked silica exposures and pulmonary function of small-scale gold miners.

Silicosis is characterized by nodules in the mid and upper areas of the lung, visible through chest X-rays. These nodules may progress to cause pulmonary fibrosis (Mason & Thompson, 2010). The most common form of silicosis, chronic silicosis, develops 20 to 40 years after low to moderate silica exposures. Advanced silicosis has a five to 15 year latency period after initial high exposures to silica (Mason & Thompson, 2010).

1.1.6.2 Biomass fuel smoke

In addition to exposures from crystalline silica from gold ore processing, ASGM community members and miners may also suffer respiratory ailments due to biomass fuel smoke. Biomass cooking fuels include wood, charcoal, crop residue, and animal dung on open fires or coal pots. Residents of Kejetia, particularly women, may have respiratory exposures from silica dust and biomass fuel cooking smoke. There have been no studies to examine exposures to dust from small-scale mining and biomass cooking smoke and the impacts on pulmonary function.

Biomass fuels are commonly used for cooking in rural settings in many low and middle-income countries (LMICs), including Ghana, where ASGM often occurs (UNEP, 2010). In northeast Ghana, cooking may be done outdoors or inside mud-brick buildings with little ventilation. Biomass fuel smoke exposure can affect respiratory health, especially when coupled with a lack of ventilation (Fullerton, Bruce, & Gordon, 2008). Decreased pulmonary function, chronic obstructive pulmonary disease (COPD), and chronic bronchitis are associated with exposure to biomass fuel smoke (Regalado et al., 2006; Ramirez-Venegas, 2005; Ekici et al., 2005). Women and young children may be disproportionally exposed to biomass fuel smoke, as women manage most cooking and children are often within close proximity (Boadi & Kuitunen, 2005).

1.2 Knowledge gaps

Small-scale gold mining is a critical industry in Ghana and many other LMICs. In Ghana, approximately 30% of national exports are from gold production (Carson et al., 2005). Previous studies have found that Hg concentrations in biomarkers from miners are elevated and may pose a health risk for some individuals (Paruchuri et al., 2010; van Straaten, 2000). Despite previous research with miners, Hg exposure for non-miners living within ASGM communities is largely unknown and has been overlooked in Ghana. Soil has not been studied as a relevant exposure pathway to Hg, and data are lacking on the extent of Hg soil contamination in ASGM communities to best assess this. This is the first study of its kind to measure multiple media from human biomarkers and ecological samples from the same site and to examine the spatial distribution of Hg exposure or contamination throughout an ASGM community. This research will also support Ghana's initiatives as a signatory to the Minamata Convention on Mercury (Minamata Convention on Mercury, 2015).

Health outcomes have also received limited attention in these studies. Of particular concern is the cardiovascular impact of elevated acute and chronic, high Hg vapor exposures for miners working with elemental Hg. Research indicates that marginally elevated elemental Hg exposures are associated with decreases in blood pressure compared to unexposed populations (Siblerud, 1990; Goodrich et al., 2012), but it is uncertain if ASGM miners with higher elemental Hg exposures will follow the same trend. Miners may be exposed to respirable silica in ore dust, which can cause silicosis, an irreversible pulmonary fibrosis (Greenberg et al., 2007). Specific mining tasks and cooking fuels may result in higher exposures that adversely affect pulmonary function. The impact of ASGM and biomass cooking fuel smoke has not been studied and their impact on pulmonary function and respiratory health is unclear. This research will address a number of important data gaps in Hg exposure assessment and health effects of ASGM, which will be used to inform policies and initiatives in Ghana and worldwide.

1.3 Objectives

The objective of this research is to apply novel approaches to increase understanding of the determinants of mercury exposure, blood pressure, and pulmonary function in miners and non-miners of a small-scale gold mining community, Kejetia (Figure 1.1). A nearby subsistence farming community, Gorogo, serves as a comparison site. Utilizing hair and urine biomarkers, household soil as a potential pathway of exposure, and GIS for spatial analysis affords a greater understanding of Hg exposure to the community. This research examined the possible mining-associated risks through focusing on two health outcomes likely to be affected, blood pressure and pulmonary function, which have not been studied in small-scale mining communities. The focus on a small-scale gold mining community increased understanding of how vulnerable populations, women of childbearing age and young children, may be affected by Hg and respirable dust. The research focused on a 2011 study, which recruited 97 adults from 54 households in Kejetia and 75 adults from 26 households in Gorogo. The results can help to shape and inform actions in Ghana and internationally, given the integration of these studies in a national-level integrated assessment project that is now linking with international partners as part of the UNEP Minamata Convention on Mercury (ASGM Research Group, 2015).

1.4 Specific aims and hypotheses

1.4.1 Specific aim 1. To determine levels of Hg in hair and urinary biomarkers and household soil samples among members of Kejetia and Gorogo. The inclusion of non-miners within Kejetia is to provide a better understanding of how communities, particularly vulnerable populations, may be affected by small-scale gold mining and Hg use, and how Hg is distributed spatially within Kejetia.

Hypothesis 1A. Kejetia community participants (miners and non-miners) will have higher hair and urinary Hg levels than participants living in Gorogo.

Hypothesis 1B: Miners using Hg will have significantly elevated levels of urinary Hg in biomarkers and household soil samples than other miners.

Hypothesis 1C: Total urinary Hg and household soil Hg will be spatially auto-correlated within Kejetia and to areas of Hg use.

1.4.2 Specific aim 2. To understand the relationship between blood pressure (systolic and diastolic) and Hg biomarkers in adults in Kejetia and Gorogo. While several epidemiological studies worldwide have shown blood pressure (BP) to be affected by Hg, this has yet to be studied in a small-scale gold mining community despite the potential for high exposures.

Hypothesis 2A: Total hair Hg will be associated with an increase in systolic and diastolic BP in both communities.

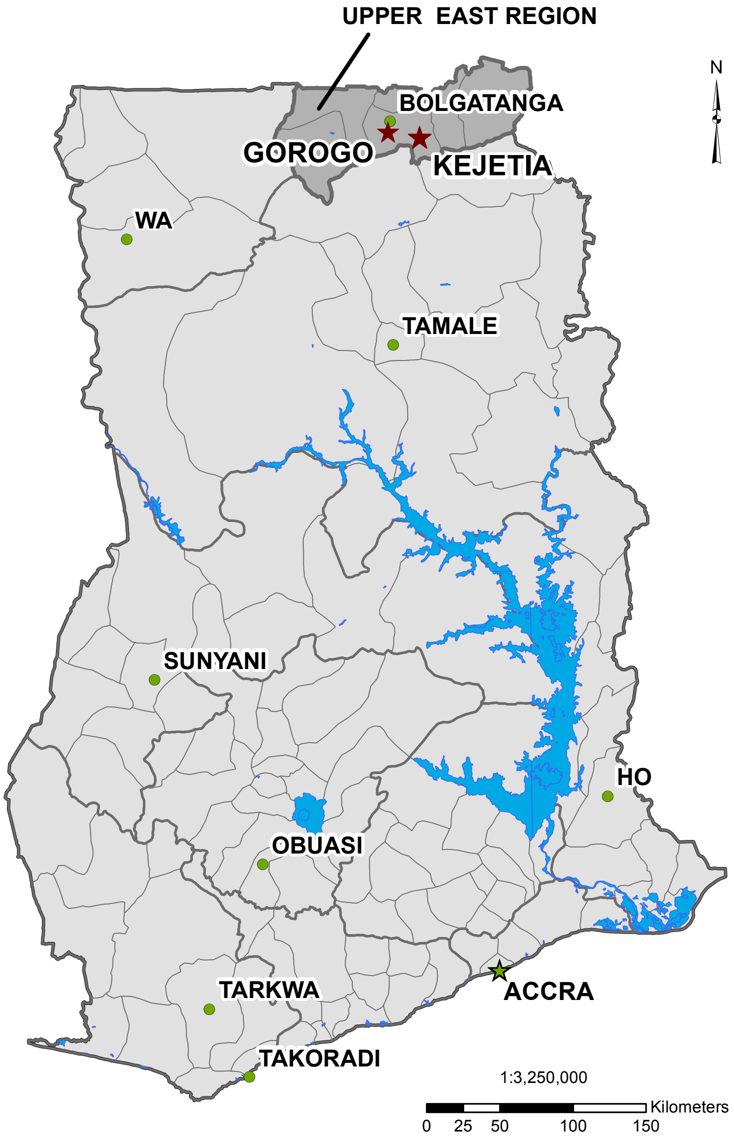
Hypothesis 2B: Total urinary Hg will be associated with a decrease in systolic BP in Kejetia.

1.4.3 Specific aim 3. To examine and understand how mining involvement may affect pulmonary function through forced expiratory volume in one second (FEV_1), forced vital capacity (FVC), the ratio of FEV_1/FVC, and respiratory outcomes, and what non-mining factors may influence pulmonary function. The unique co-exposures to respirable dust and biomass cooking smoke in small-scale mining communities have not been studied.

Hypothesis 3A: Miners involved predominantly in excavation, crushing/grinding, and sifting activities will have reduced pulmonary function (FEV_1, FVC, and FEV_1/FVC) than other miners and non-miners.

Hypothesis 3B: FEV_1, FVC, and FEV_1/FVC will be negatively associated with cooking smoke exposure for women in Kejetia and Gorogo.

Figures



Map produced from data provided by the United Nations Environmental Program's
Solar and Wind Energy Resource Assessment (SWERA), by Mozhgon Rajaee, Jun. 2012.

Figure 1.1 Map of Ghana indicating Kejetia and Gorogo, the two research communities, in the Upper East Region.

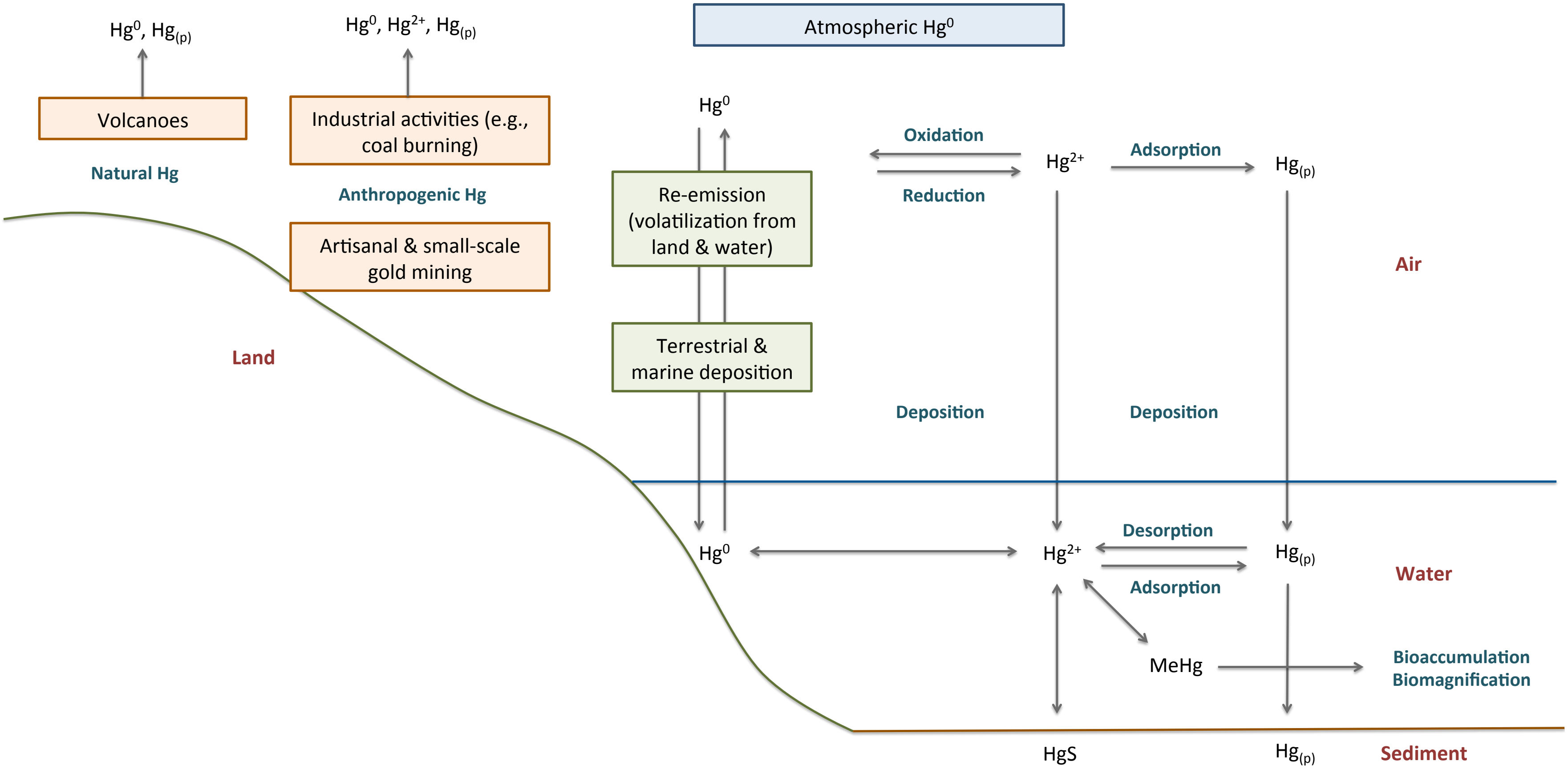


Figure 1.2 Speciation and fate of mercury in the environment (adapted from U.S. EPA, 1997; UNEP, 2013a).

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Chapter 2 Mercury exposure assessment and spatial distribution in a Ghanaian small-scale gold mining community

2.1 Introduction

Artisanal and small-scale gold mining (ASGM) is the largest contributor to global anthropogenic mercury (Hg) in the atmosphere, and employs 10 to 15 million people globally (United Nations Environment Program [UNEP], 2013a; UNEP, 2014). Eighty to 100 million people are estimated to depend on ASGM for their livelihoods or be indirectly involved (International Labor Organization, 1999; UNEP, 2010). Mercury (Hg), a neurotoxicant, is used to isolate gold ore in the ASGM process (Clarkson & Magos, 2006). There are three forms of mercury: organic, inorganic, and elemental. Each form has a different environmental fate, human exposure route, and health risks. ASGM utilizes elemental Hg, which poses a risk for human health and environmental contamination.

Gold deposits are ubiquitous in Ghana and have resulted in ASGM and large-scale gold mining across the country, putting Ghana as the ninth largest gold-producing country in the world (Ghana Chamber of Mines, 2013). ASGM has grown tremendously in recent years with the rising price of gold, deregulation of gold mining, chronic unemployment, and increasing poverty (Ghana Chamber of Mines, 2011). ASGM accounts for 35% of Ghana's national gold production and employs 500,000 to 1 million people directly or indirectly (Ghana Chamber of Mines, 2013; Hilson & Clifford, 2010).

In the Upper East Region of Ghana, where ASGM has grown rapidly, it’s estimated that over 10,000 people are employed directly by ASGM in the Talensi-Nabdam District alone (Hilson, 2010).

In Ghanaian ASGM, gold ore is excavated from surface and shallow underground mining, and some panning in streams. Ore is generally milled in a grinding machine and sifted by hand. The fine powder ore is mixed with water and sluiced on a wooden ramp covered in carpet. Denser particles in the ore, like gold, are captured in the carpet. This gold-rich ore is mixed with water in a rubber pan, where elemental Hg is added to form a gold-mercury amalgam. The amalgam is heated with a blowtorch to volatize the mercury and leave behind a more refined gold.

Hg can adversely impact many systems of the body, including the central and peripheral nervous, nephritic, digestive, and respiratory systems (Clarkson & Magos, 2006). Hg is especially dangerous as it is able to pass the blood-brain and blood-placental barrier, posing additional risks to the unborn fetus (Clarkson & Magos, 2006).

Elemental Hg released in ASGM or other industries is volatilized and remain airborne for a few months to up to a year, and over 1000 km before it is deposited (UNEP, 2002). Once deposited, however, Hg can be re-emitted from water and soil surfaces. Inorganic mercury in sediments is methylated to form methylmercury, where it can bioaccumulate in organisms and biomagnify in food chains (U.S. Environmental Protection Agency [EPA], 1997). Surface soils, water bodies, and sediments are the major biospheric sinks for Hg (UNEP, 2002).

Exposure to organic Hg, mainly methylmercury (MeHg), is primarily through consuming fish and seafood. Hair Hg concentrations reflect MeHg exposures from blood

Hg concentrations at the time of hair growth, which grows at an average of one centimeter per month (U.S. EPA, 1997; Clarkson & Magos, 2006). Elemental Hg, used in ASGM, has a half-life of approximately 56-58 days in the whole body and kidneys and can be measured in the urine to assess medium-term exposure (Clarkson & Magos, 2006; Bluhm et al., 1992). Urine and hair biological markers are used to assess elemental and MeHg exposures, respectively (Wranova et al., 2008; Clarkson & Magos, 2006).

An earlier study in Ghana's Talensi-Nabdam District observed elevated Hg exposure among ASG miners (Paruchuri et al., 2010). This research and community concerns prompted our team to conduct a follow-up cross sectional study to assess Hg exposure in hair, urine, and household soil in mining and non-mining ASGM community members in the Talensi-Nabdam District. We hypothesize that Kejetia participants and ASG miners in particular will have higher hair, urine, and household soil Hg levels than Gorogo participants and Kejetia non-miners. Urinary and household soil Hg are also hypothesized to be spatially auto-correlated within Kejetia (i.e., Hg concentrations will be more similar to their geographically nearest neighbors).

2.2 Materials and methods

2.2.1 Sampling strategy and study populations

Data were collected from two communities in the Upper East Region of Ghana, in the previous Talensi-Nabdam District, which has since split into separate Talensi and Nabdam Districts (Figure 2.1). A small-scale gold mining community, Kejetia (Figure 2.2), was selected from a prior study of ASG miners in the area (Paruchuri et al., 2010). Gorogo, a nearby, upstream, non-mining community, was selected for comparison

(Figure 2.3). Permission to work with the communities was granted by each community's traditional chief and assemblyperson in Gorogo, and Institutional Review Board (IRB) approval was obtained through the University of Michigan (HUM00028444).

From May through July 2011, participants were recruited to participate in the survey. In accordance with cultural norms, households were defined as those who eat from the same "pot". Lacking community maps and official population estimates, it was impossible to follow true random sampling.

In Kejetia, all households were assigned a set of coordinates using a handheld global positioning system (GPS; Oregon 450; Garmin International, Inc., Olathe, KS). Households were numbered and assigned to a cluster of approximately 20 households based on geographic proximity. Each day, a random number was selected from a bag to identify a household from up to three different clusters for participation. If a household was not eligible or declined participation, another number from within the cluster was pulled from the bag until an appropriate household was found.

The community of Gorogo was much more geographically dispersed, making clustering infeasible. Households were selected from convenience sampling, by spinning a plastic bottle at the geographic middle of the community and selecting the house pointed to most closely (Hoshaw-Woodard, 2001). The bottle was then spun from each participating household to find the next household to be surveyed, and from other geographic locations throughout the community. If a household was not eligible or declined participation, re-spinning the bottle in the same location as the previous spin chose a replacement household.

2.2.2 Surveys

For each household surveyed, a household head and up to three other adults (18 years or older) were interviewed on household characteristics, and their occupational and medical histories. Questions were adapted from the Ghana Demographic and Health Survey (DHS) (Ghana Statistical Service and Ghana Health Service, 2009) and the American Thoracic Society Epidemiology Standardization Project (Ferris, 1978). English surveys were administered by a team of university students and verbally translated by local Ghanaian translators in the participant’s choice language (Talen, Nabt, Gurune, Twi, Dagbani, English, or Hausa). Translators were trained on appropriate medical terms and health outcomes in local languages prior to conducting the interviews.

The head of household (HOH) or an identified alternative household participant knowledgeable about the individuals in the household completed a survey on demographics of people in the household, household characteristics and amenities, and a 24-hour dietary survey. A maximum of four adults per household, including the HOH were administered a separate survey including questions on occupational, medical, and smoking histories; and respiratory symptoms, and spirometry was performed when feasible. In households with more than four adults, the HOH provided guidance on who to interview. ASGM activities were stratified as excavation, crushing (crushing, grinding, or pounding ore), sifting (*shanking*), washing (or sluicing), amalgamation, burning (or roasting), and owning or managing a mine. Since many participants engaged in multiple mining activities, each participant was surveyed about ever-involvement in each mining activity and the main activity performed in the three months preceding the survey.

2.2.3 Sample collection

Urine and hair biological markers were collected to assess elemental and methylmercury exposure, respectively (Clarkson and Magos, 2006). Spot urine samples (5-15 mL) were collected from participants mid-morning at the time of the interview, stored at room temperature in Bolgatanga, Ghana, and frozen at -20ºC until analysis in the U.S. Samples were thawed to 4ºC and vortexed prior to analysis. Hair was cut as close to the scalp as possible from the occipital region of the head and placed on a sticky-note and stored in a plastic bag until analysis. Only the 2 cm closest to the scalp was used for analysis. Hair samples were washed once with acetone and twice with deionized water, and dried for mercury analysis (Paruchuri et al., 2010; Goodrich et al., 2012).

Household surface soil was collected from a common area, designated by the HOH. Each household soil sample is a composite of five subsamples taken from the four corners and center of an approximate 30 cm^2 square area (US EPA, 1992). Samples were collected from the top 1-2 cm of soil into sealed WhirlPak bags. Samples were stored at room temperature in Bolgatanga, Ghana and 4ºC until analysis in the U.S. All samples were dried at 110ºC for 16 hours and sifted through a 2 mm polymer sieve to remove any detritus or stones.

2.2.4 Sample mercury analysis

Total mercury was measured using a Direct Mercury Analyzer-80 (DMA-80; Milestone, Inc., Shelton, CT), following U.S. EPA Method 7473 (U.S. EPA, 2007). Certified reference materials (CRMs; urine: QMEQAS, Institut National de Santa Publique Quebec; hair: National Institute for Environmental Studies Japan; dogfish liver:

DOLT-4, National Research Council Canada; soil: San Joaquin Soil 2709, U.S. National Institute of Standards and Technology) were analyzed approximately every ten samples, blanks every five samples and sample replicates at least every nine samples. All soil samples were run in duplicate and blanks every two samples (four replicates).

The average recovery of CRMs was greater than 92% for NIES hair and DOLT-4, and 97% for QMEQAS urine in Kejetia and Gorogo sample analyses. For San Joaquin soil CRM, the average recovery was 101.4% and 85.3% for Kejetia and Gorogo, respectively. In Kejetia and Gorogo samples, within-day variation was <5% for NIES hair and QMEQAS urine, <10% for DOLT-4, and <20% for San Joaquin soil. The average within-day variation of replicates of participants' samples was low for hair (4.0% in Kejetia, 5.8% in Gorogo) and urine (4.7% in Kejetia, 8.3% in Gorogo). Soil samples, analyzed in duplicate due to expected higher variation, had an average within-day variation of 6.7% in Kejetia and 8.5% in Kejetia.

The average theoretical mercury detection limit (TMDL; 3 × standard deviation of the ng Hg of blanks + average ng Hg of blanks) for hair was 0.126 ng Hg in Kejetia and 0.044 ng Hg in Gorogo. No hair samples were below the TMDL. The average TMDL for urine was 0.136 ng Hg for Kejetia (3 samples < TMDL) and 0.046 ng Hg for Gorogo (21 samples < TMDL). The average TMDL for household soil was 3.030 ng Hg for Kejetia 0.083 ng Hg for Gorogo. No soil samples were below the TMDL.

Specific gravity (SG) was measured using a pocket refractometer (PAL-10S, Atago U.S.A., Inc., Tokyo, Japan) to adjust urine samples by urinary dilution using the mean urinary specific gravity (1.016; Lee et al., 1996; Voinescu et al., 2002). The equation is as follows, where p refers to a participant's personal urinary Hg and urinary SG values, and the average urinary SG is 1.016:

$$SG - adjusted\ urinary\ Hg_p = \frac{(Avg.urinary\ SG - 1)}{(Urinary\ SG_p - 1)} \times Urinary\ Hg_p$$

2.2.5 Statistical and spatial analyses

The data were analyzed using SPSS Statistical Software (v.22; IBM, Chicago, IL). Since Hg biomarkers and household soil were not normally distributed, they were log-transformed for independent t-tests. Bivariate analyses were also performed non-parametrically (e.g., Spearman's ρ). One-way analysis of variance (ANOVA) was used to assess bivariate correlations of Hg biomarkers and household soil with mining status, mining activities, sex, and education level. Correlations between ever-involvement in each mining activity were assessed through Chi-square tests. Statistical analyses were performed with specific gravity-adjusted and unadjusted urinary Hg. All results are reported with mean ± standard deviation, unless otherwise indicated.

Maps of households in each community were created using ArcGIS (v. 10.1; Esri, Redlands, CA). GPS coordinates were measured at each participant's household. We were unable to geocode three households due to logistical issues. These three households were exempted from geospatial analyses. This included two households from Kejetia and one from Gorogo. Global Moran's I statistic was used to analyze spatial autocorrelation of Hg concentrations across the Kejetia community in urine and household soil. In each assessment, Euclidean distance and inverse distance weighting were used to account for Kejetia's non-grid organization and to place a larger influence on nearby neighbor Hg concentrations than more distant Hg concentrations.

2.3 Results

There were 97 participants from 54 households in Kejetia and 75 participants from 26 households in Gorogo (Table 2.1). One Gorogo current miner was excluded from analyses. Kejetia participants, on average, were younger (mean: 31.4±10.8 years) and more male (51.5%) than Gorogo participants (51.5±18.8 years and 45.3% male). Gorogo participants were largely farmers (94.7%), while only 72.9% of Kejetia participants were current miners. Smoking rates and cigarette pack-years were low, particularly among females. Education rates were low in both communities, with 38.6% and 81.3% of participants in Kejetia and Gorogo, respectively, reporting either only obtaining some preschool or no schooling.

While 72.9% of Kejetia participants were current miners, 77.3% had engaged in mining at any time previously (Table 2.2). The most common mining activity was amalgamation (50.5%), and, as expected, owning or managing a mine the least common (21.6%). Mining activities were performed differentially by sex. More males engaged in excavation, crushing, washing, and amalgamation, while females more frequently engaged in sifting ore. Ever amalgamation and burning were significantly correlated ($\alpha < 0.05$) to all other mining activities in Kejetia, as many miners engaged in multiple mining activities in a given day or week (data not shown). Among Kejetia miners, ever amalgamation was only significantly correlated to ever excavation, crushing, washing, and burning; and ever burning was only significantly associated to ever excavation, washing, and amalgamation.

Comparing mean biomarker and soil Hg concentrations showed substantial differences between the two communities (Table 2.3). Kejetia participants had significantly higher mean unadjusted and SG-adjusted urinary Hg and household soil Hg (30.9 µg/L, 22.8 µg/L, and 15.55 µg/g, respectively) than Gorogo participants (0.161 µg/L, 0.216 µg/L, and 0.041 µg/g, respectively). Mean hair Hg was more similar in the two communities, but was still significantly lower in Gorogo (0.231 µg/g) compared to Kejetia (0.974 µg/g). Hair and urinary Hg displayed a positive relationship (Figure 2.4). In bivariate analyses, SG-urinary Hg was significantly correlated to hair Hg in Kejetia (Spearman's $\rho=0.765$, $p<0.001$) and Gorogo ($\rho=0.405$, $p=0.017$). Household soil was significantly correlated to urinary Hg in Kejetia ($\rho=0.238$, $p=0.023$) (Figure 2.5).

Kejetia current miners had significantly higher mean unadjusted and SG-adjusted urinary Hg, and hair and household soil Hg (39.5 µg/L, 29.3 µg/L, 1.13 µg/g, and 18.72 µg/g, respectively) than Kejetia non-miners (6.61 µg/L, 4.22 µg/L, 0.558 µg/g, and 5.546 µg/g, respectively). Among Kejetia participants, those reporting ever-using Hg in amalgamation or burning, had significantly higher unadjusted and SG-adjusted urinary Hg, and hair and household soil Hg (n=54, 49.8±194 µg/L, 36.6±141 µg/L, 1.27±0.858 µg/g, and 36.07±85.70 µg/g, respectively) than never-Hg users (n=43, 5.27±10.6 µg/L, 3.92±5.76 µg/L, 0.627±0.370 µg/g, and 7.506±15.90 µg/g, respectively; data not shown). Kejetia males had significantly higher mean unadjusted and SG-adjusted urinary Hg, and hair and household soil Hg (n=34, 54.6±204 µg/L, 39.8±148 µg/L, 1.24±0.858 µg/g, and 23.50±64.64 µg/g, respectively) than Kejetia females (n=41, 5.03±10.5 µg/L, 4.21±7.44 µg/L, 0.799±0.615 µg/g, and 23.31±68.31 µg/g, respectively; data not shown).

The World Health Organization (WHO) recommends a health-based limit of 50 μg/L inorganic Hg (creatinine-adjusted) for occupational exposure to protect workers from tremors and Hg-induced non-specific symptoms (Clarkson & Magos, 2006; WHO, 1980). In Kejetia, 4.3% (8.7% unadjusted) of participants had SG-adjusted urinary Hg concentrations above this recommended limit. Twenty-six percent of Kejetia participants had moderately high SG-adjusted urinary Hg concentrations >10 μg/L Hg, below which is expected to be asymptomatic (Risher, 2003). Hair Hg concentrations for all participants were all below the U.S. EPA benchmark dose of 11.1 μg/g total hair Hg (US EPA, 1997), and high exposures > 10.0 μg/g Hg designated by the WHO and UNEP (2008). A third of all Kejetia households had soil Hg concentrations exceeding the Canadian Soil Quality Guideline of 6.6 μg/g inorganic Hg for residential sites (Canadian Council of Ministers of the Environment [CCME], 1999).

Urinary Hg and household soil Hg were both spatially auto-correlated, suggesting that Hg concentrations in each media is not randomly distributed throughout the community. The mean household urinary Hg (log-transformed) was significantly auto-correlated ($p = 0.007$, z-score of 2.67, Moran's index = 0.2687). Figure 2.6 displays the urinary Hg concentrations estimated throughout Kejetia from our sampling data. Household soil Hg was also significantly auto-correlated ($p < 0.001$, z-score of 11.28; Moran's index = 1.179). Figure 2.7 displays soil Hg concentrations estimated throughout Kejetia from our sampling data, and indicate greater clustering of high Hg concentrations.

2.4 Discussion

Our study found that Kejetia, a small-scale gold mining community, had significantly higher personal urinary and hair Hg and household soil Hg concentrations than Gorogo, a subsistence farming community. Approximately one-third of Kejetia participants had urinary Hg concentrations above the recommended limit of 50 µg/L Hg and household soil Hg concentrations above the Canadian Soil Quality Guideline of 6.6 µg/g Hg (WHO, 1980; CCME, 1999). Exposures to current miners in Kejetia were significantly higher than non-miners. Mining involvement and use of Hg was common in Kejetia—just over 50% of Kejetia participants performed amalgamation. Urinary Hg was significantly correlated to ever involvement in excavation, washing, amalgamation, burning, and owning a mine in Kejetia. Soil Hg was significantly correlated to whether Kejetia participants were current miners and if they had ever burned Hg. Urinary and hair Hg were significantly correlated in Kejetia and Gorogo participants, and urinary Hg to household soil in Kejetia.

Kejetia participants had higher urinary Hg concentrations (30.9±148.5 µg/L) than observed in most other studies of ASGM communities in southern Ghana (means ranging from 2.6 to 34.2 µg/L; Adimado & Baah, 2002; Asante et al., 2007). Slight differences in the ASGM process and practices, such as communities built solely around ASGM, may be leading to higher exposures in the Upper East Region than in southern Ghana where people may not live as close to mining activities. Kejetia miners from our study had similar, but slightly elevated, urinary Hg levels from a 2010 study of Kejetia miners (mean: 38.9±95.7 µg/L; Paruchuri et al., 2010), and other studies of ASG miners (means ranging from 0.56 to 17.0 µg/L; Abrefah et al., 2011; Kwaansa-Ansah, Basu, & Nriagu, 2010; Asante et al., 2007; Paruchuri et al., 2010). Urinary Hg in Gorogo (0.161±0.131 μg/L) was lower than observed in other non-ASGM communities (means from 0.69 to 3.1 μg/L; Kwaansa-Ansah et al., 2010; Asante et al., 2007). While < 10 μg/L Hg is expected to be asymptomatic (Risher, 2003), women of childbearing age are recommended to be exposed to as little Hg as possible (Clarkson & Magos, 2006). The 24 Kejetia participants with SG-adjusted urinary Hg concentrations > 10 μg/L may be at risk for Hg-induced toxicity (Clarkson & Magos, 2006; WHO, 1980).

Hair Hg concentrations were lower in Gorogo (0.231±0.202) than observed in other non-mining populations in Ghana (means ranging from 0.717 to 2.35 μg/g; Anim, Agorku, & Anim, 2011; Voegborlo, Matsuyama, Adimado, & Akagi, 2010; Donkor, Bonzongo, Nartey, & Adotey, 2006; Kwaansa-Ansah et al., 2010). Other studies of non-miners have included more urban participants that may have a higher diet of fish contributing to higher hair Hg concentrations. Studies of other ASGM communities generally had higher hair Hg concentrations than in Kejetia (0.974±0.748), but this varied (means ranging from 0.62 to 4.27 μg/g; Adimado & Baah, 2002; Donkor et al., 2006). Kejetia miners (1.13±0.809 μg/g) had similar hair Hg concentrations to Kejetia miners surveyed in 2010 (1.2±1.4 μg/g; Paruchuri et al., 2010) and to other ASG miners across Ghana (means ranging from 1.1 to 2.14 μg/g; Paruchuri et al., 2010; Donkor et al., 2006; Kwaansa-Ansah et al., 2010). Most participants had hair Hg concentrations between 1-2 μg/g, a "normal level" (WHO & UNEP, 2008).

External contamination is a major challenge in using hair as a biomarker for MeHg in ASGM communities. Sherman et al. (2015) examined Hg stable isotopes in urine and hair to assess their validity as biomarkers for elemental and MeHg.

The study used hair and urinary Hg from Kejetia miners collected in our 2011 study and other miners sampled in 2010. Total urinary Hg had Hg isotope ratios similar to those found in ore deposits, and accurately reflect exposure to inorganic elemental Hg used in ASGM. Hair Hg, however, had a low percentage of MeHg as total Hg (7.6-29%), suggesting that the majority of hair Hg was exogenously adsorbed elemental Hg (Sherman et al., 2015). It is likely that hair Hg overestimates exposure to MeHg from fish and seafood consumption in ASGM communities (Sherman et al., 2015). Our hair samples were washed with acetone and deionized water, but other studies have found that these procedures likely do not remove adsorbed, external Hg contamination (Wranova et al., 2008). It is possible to analyze hair samples for MeHg specifically, but this requires a larger mass of hair, and sample quantities are often limited as many Ghanaians have hair < 2 cm.

Mean Kejetia household soil Hg (15.55±46.89 µg/g) was higher than measured in studies of 19 other ASGM areas across Ghana except for one study of four sites in the Western and Central Regions, which measured soil from active amalgamation and burning sites and found mean soil levels of 0.93, 6.09, 21.6, and 185.93 µg/g (Bonzongo, Donkor, Nartey, & Drude de Lacerda, 2004; Rajaee et al., 2015). Our study, however, focused on common areas where people spent their time to more appropriate reflect personal exposures for community residents. In other studies across Ghana, 21 out of 23 (91%) ASGM areas measured mean soil levels below the Canadian Soil Quality Guideline for residential areas at 6.6 µg/g Hg, and 12 out of 23 (52%) below 0.300 µg/g Hg (Rajaee et al., 2015; Bonzongo et al., 2004; Adjorlolo-Gasokpoh, Golow, & Kambo-Dorsa, 2012; Azanu, 2010; Ahiamadjie et al., 2011; Amonoo-Neizer et al., 1996; Donkor et al., 2006; Samlafo, Adua Aidoo, Sarsah, Quarshie, & Serfor-Armah, 2011; Oppong, Voegborlo, Agorku, & Adimado, 2010; Tetteh et al., 2010; Quarshie, Nyarki, & Serfor-Armah, 2011). High household soil Hg concentrations exceeding the Canadian Soil Quality Guideline for residential areas, which is set to protect human and environmental health, indicate an additional concern and potential pathway of exposure (CCME, 1999). Household soil Hg in Gorogo (0.041±0.023 µg/g) was lower than observed in other non-ASGM areas (means ranging from 0.099 to 0.170 µg/g; Donkor et al., 2006; Tetteh et al., 2010; Rajaee et al., 2015). Kejetia household soil Hg was significantly correlated to urinary Hg, suggesting that Hg burning is occurring at or around participants' homes or locally depositing around the community. The spatial autocorrelation of household soil and urinary Hg in Kejetia further supports this hypothesis.

Mercury is a known toxicant with numerous adverse health effects, and evidence in Kejetia and elsewhere show that its use is common in ASGM communities, posing potential risks for miners and community residents. Alarmingly, almost 17% of non-mining participants in Kejetia had urinary Hg concentrations above 10 µg/L, suggesting that merely living within the community exposes residents to Hg vapor, even without engaging in mining directly. This is particularly important for pregnant women, women of childbearing age, and young children, that also reside in these communities and are more vulnerable to the impacts of Hg exposure (Clarkson & Magos, 2006).

Soil Hg is not thought to be a significant source of exposure to Hg, but people do ingest some soil and dust (U.S. EPA, 2011). High concentrations of Hg in the soil may result in an additional, often ignored exposure pathway for people living in ASGM communities. In 2010, approximately 400 children were killed and thousands adversely affected from lead poisoning at an ASGM community in northwestern Nigeria (Plumlee et al., 2013; Dooyema et al., 2012). Processing the naturally gold and lead-rich ore lead to extreme contamination in soil samples and plant foodstuffs. Ingestion of soils and inhaled dust were the dominant exposure pathways, while contaminated water and foodstuff consumption were lesser but still significant exposure pathways (Plumlee et al., 2013). This case spurred our current study to examine soil Hg contamination as a potential exposure pathway. The US EPA estimates that adults (>21 years) consume 50 mg of soil and dust per day, while children 1 to 21 years ingest 110 mg of soil and dust per day (US EPA, 2011). These US-based assumptions, however, are inadequate for West Africans with different dietary habits, housing with soil floors, climate, local environment, and other factors (Plumlee et al., 2013). It is unclear what appropriate soil and dust ingestion rates are for rural Ghanaians, but the dusty conditions during the long dry season from October through April anecdotally imply higher ingestion rates (Talensi-Nabdam District Assembly, 2010). Children and youth, who ingest higher quantities of soil and dust, may have a larger burden of Hg exposure from soil than adults.

Despite known health risks of using Hg, there have been few viable alternatives for ASG miners. Miners have rejected retorts, a device that captures and condenses burned Hg for reuse, with complaints largely over a slower process and a lack of transparency (Amegbey & Eshun, 2004, cited in Nyame, 2010).

As the share of global anthropogenic Hg from ASGM grows, there is increasing worldwide concern about its use. The Minamata Convention on Mercury is a global treaty working to reduce Hg emissions and mining with a particular focus on regulating the ASGM sector (UNEP, 2013b). Convention signatories, such as Ghana, are expected to take initiatives to reduce and when feasible eliminate the use of Hg and to develop a national action plan (Article 7, Annex C) including various elements such as reduction targets and baseline estimates of Hg used in ASGM (UNEP, 2013b). Studies such as this one provide necessary support for the Minamata Convention's assessment of baseline Hg use and pollution in ASGM, particularly filling a knowledge gap in northern Ghana, since most studies have focused on southern Ghana.

2.5 Conclusion

This study increases our understanding of Hg exposures among miners and non-miners living in an ASGM community to better explain pathways of exposure and the distribution of Hg contamination in these types of communities. Urinary and household soil Hg concentrations were significantly higher for current miners than non-miners in Kejetia, and in Kejetia participants compared to Gorogo participants. Most participants with elevated urinary and household soil Hg concentrations above health guideline values were miners, but some non-miners approached and exceeded these values, suggesting a health risk for non-mining residents of ASGM communities, particularly for susceptible populations.

Tables

Table 2.1 Demographic information of Kejetia and Gorogo participants.

		Kejetia			Gorogo
		All	Miners[a]	Non-Miners[a]	All
n participants		97	71	26	75
n households		54	41	18	26
Sex	% Male	50 (51.5%)	43 (60.6%)	7 (26.9%)	34 (45.3%)
Age	Mean (SD)	31.4 (10.8)	30.6 (9.6)	33.8 (13.6)	51.5 (18.8)
BMI	Mean (SD)	22.7 (3.2)	22.1 (2.7)	24.5 (3.7)	21.8 (3.1)[b]
Occupation					
	Current Miner	71 (73.2%)	-	-	0
	Ex-Miner	4 (4.2%)	0	4 (15.4%)	10 (13.3%)
	Farmer	7 (7.3%)	5 (7.0%)	2 (7.7%)	71 (94.7%)
	Cook (food, pito)[c]	15 (15.6%)	5 (7.0%)	10 (38.5%)	3 (4.0%)
	Vendor	18 (18.8%)	7 (9.9%)	11 (42.3%)	7 (9.3%)
	Other	12 (12.5%)	6 (8.5%)	6 (23.1%)	7 (9.3%)
Smoking					
	Smoking in home	45 (46.9%)	39 (54.9%)	6 (23.1%)	39 (52.0%)
	Current smoker	15 (15.6%)	14 (19.7%)	1 (3.8%)	14 (18.7%)
	Ex-smoker	7 (7.3%)	6 (8.5%)	1 (3.8%)	9 (12.0%)
n ever-smokers with pack-years[d]		16	15	1	14
	Cigarette pack-years[d]	15.8 (26.6)	15.1 (27.4)	25.5	3.9 (2.1)
Education					
	No school	28 (29.2%)	16 (22.9%)	12 (46.2%)	52 (69.3%)
	Nursery/preschool	9 (9.4%)	6 (8.6%)	3 (11.5%)	9 (12.0%)
	Primary	27(28.1%)	24 (34.3%)	3 (11.5%)	6 (8.0%)
	Middle/JSS	20 (20.8%)	18 (25.7%)	2 (7.7%)	1 (1.3%)
	Secondary/SSS, tech.	11 (11.5%)	5 (7.1%)	6 (23.1%)	5 (6.7%)
	Higher than secondary	1 (1.0%)	1 (1.4%)	0	2 (2.7%)

[a] Refers to current and non-current miners

[b] n = 74 for Gorogo: All

[c] Includes individuals that cook food or pito, an alcoholic beverage made from millet

[d] Cigarette pack-years only include ever-smokers

Table 2.2 Ever mining involvement for Kejetia participants. Participants were surveyed on ever-engaging in each mining activity.

	Kejetia		Miners[a]		Females		Males	
Mining Activity	n	Percent	n	Percent	n	Percent	n	Percent
Any mining activity	75	77.3	71	100.0	31	66.0	44	88.0
Excavation	40	41.2	39	54.9	2	4.3	38	76.0
Crushing	45	46.4	44	62.0	7	14.9	38	76.0
Sifting	45	46.4	42	59.2	30	63.8	15	30.0
Washing	46	47.4	45	63.4	13	27.7	33	66.0
Amalgamation	49	50.5	47	66.2	16	34.0	33	66.0
Burning	31	32.0	31	43.7	7	14.9	24	48.0
Owning	21	21.6	20	28.2	1	2.1	20	40.0

[a] Refers to current miners only

Table 2.3 Biomarkers and household soil Hg concentrations for all participants.

	Kejetia			
	All	Miners[a]	Non-miners[a]	Gorogo
Urine *n*	92	68	24	70
Urinary Specific Gravity (SG)				
Mean (SD)	1.018 (0.007)[d]	1.017 (0.007)	1.020 (0.006)	1.014 (0.006)
Urinary Hg (μg/L)				
Mean (SD)	30.9 (148.5)[d]	39.5 (172.1)[e]	6.61 (13.2)	0.161 (0.131)
Median	2.94	4.83	1.41	0.114
IQR[b]	1.04, 11.0	1.26, 12.9	0.742, 5.23	0.079, 0.217
Min - Max	0.160 - 1372	0.160 - 1372	0.199 - 58.1	0.026 - 0.580
>10 μg/L Hg (%)	25 (27.2%)	21 (30.9%)	4 (16.7%)	0
>50 μg/L Hg (%)	8 (8.7%)	7 (10.3%)	1 (4.2%)	0
SG-adj. Urinary Hg[c] (μg/L)				
Mean (SD)	22.8 (107.8)[d]	29.3 (124.9)[e]	4.22 (6.88)	0.216 (0.194)
Median	3.35	5.18	1.18	0.154
IQR[b]	1.14, 10.5	1.92, 12.7	0.733, 3.61	0.095, 0.261
Min - Max	0.188 - 998	0.188 - 998	0.212 - 25.8	0.042 - 1.24
>10 μg/L Hg (%)	24 (26.0%)	20 (29.4%)	4 (16.7%)	0
>50 μg/L Hg (%)	4 (4.3%)	4 (5.9%)	0	0
Hair Hg (μg/g) *n*	70	51	19	59
Mean (SD)	0.974 (0.748)[d]	1.13 (0.809)[e]	0.558 (0.272)	0.231 (0.202)
Median	0.783	0.967	0.419	0.181
IQR[b]	0.408, 1.22	0.589, 1.47	0.329, 0.781	0.119, 0.244
Min - Max	0.132 - 3.69	0.132 - 3.69	0.237 - 1.10	0.037 - 1.37
Household Soil Hg (μg/g) *n*	54	41	13	26
Mean (SD)	15.55 (46.89)[d]	18.72 (53.35)[e]	5.546 (8.990)	0.041 (0.023)
Median	3.052	3.768	1.999	0.039
IQR[b]	1.857, 9.320	1.858, 20.61	1.352, 6.703	0.027, 0.043
Min - Max	0.2967 - 330.04	0.2967 - 330.04	0.2967 - 33.96	0.013 - 0.114
>6.6 μg/g Hg[f] (%)	18 (33.3%)	15 (36.6%)	3 (23.1%)	0

[a] Refers to current miners and non-current miners

[b] Interquartile range (25th percentile, 75th percentile)

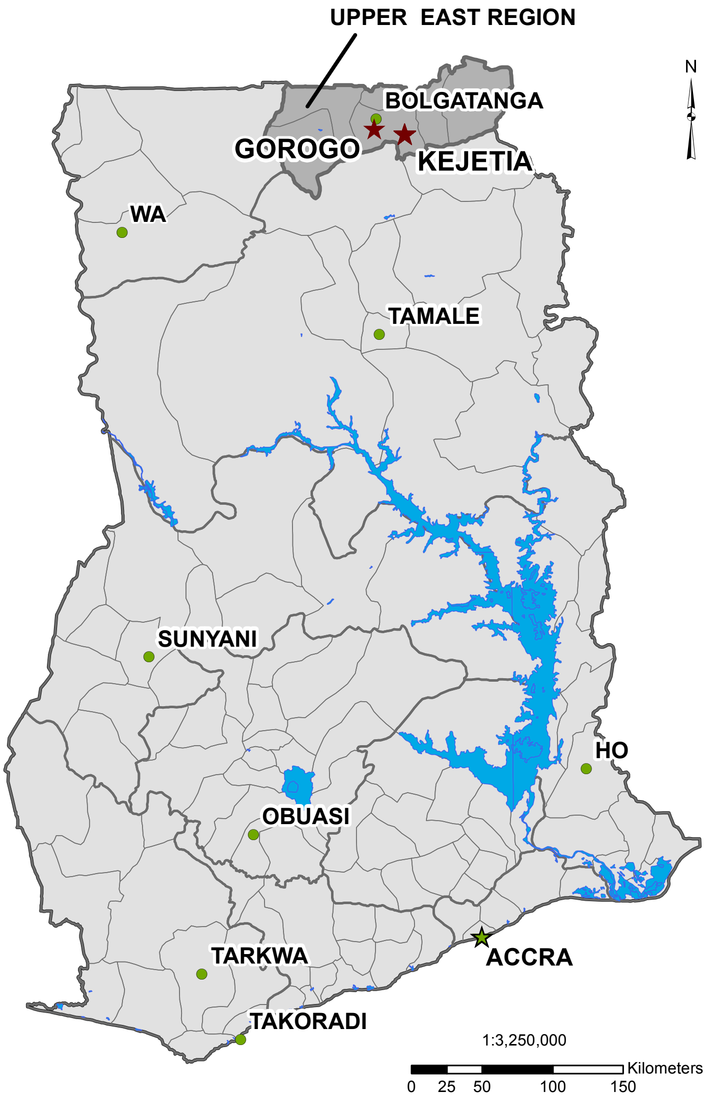
[c] Specific gravity adjustment equation: Urinary Hg * [(1 - avg. SG]/[Urine SG - 1])

[d] Gorogo vs. Kejetia t-test comparing means of log-transformed data (except for specific gravity), $p < 0.001$

[e] Miners vs. non-miners t-test comparing means of log-transformed data, $p < 0.05$

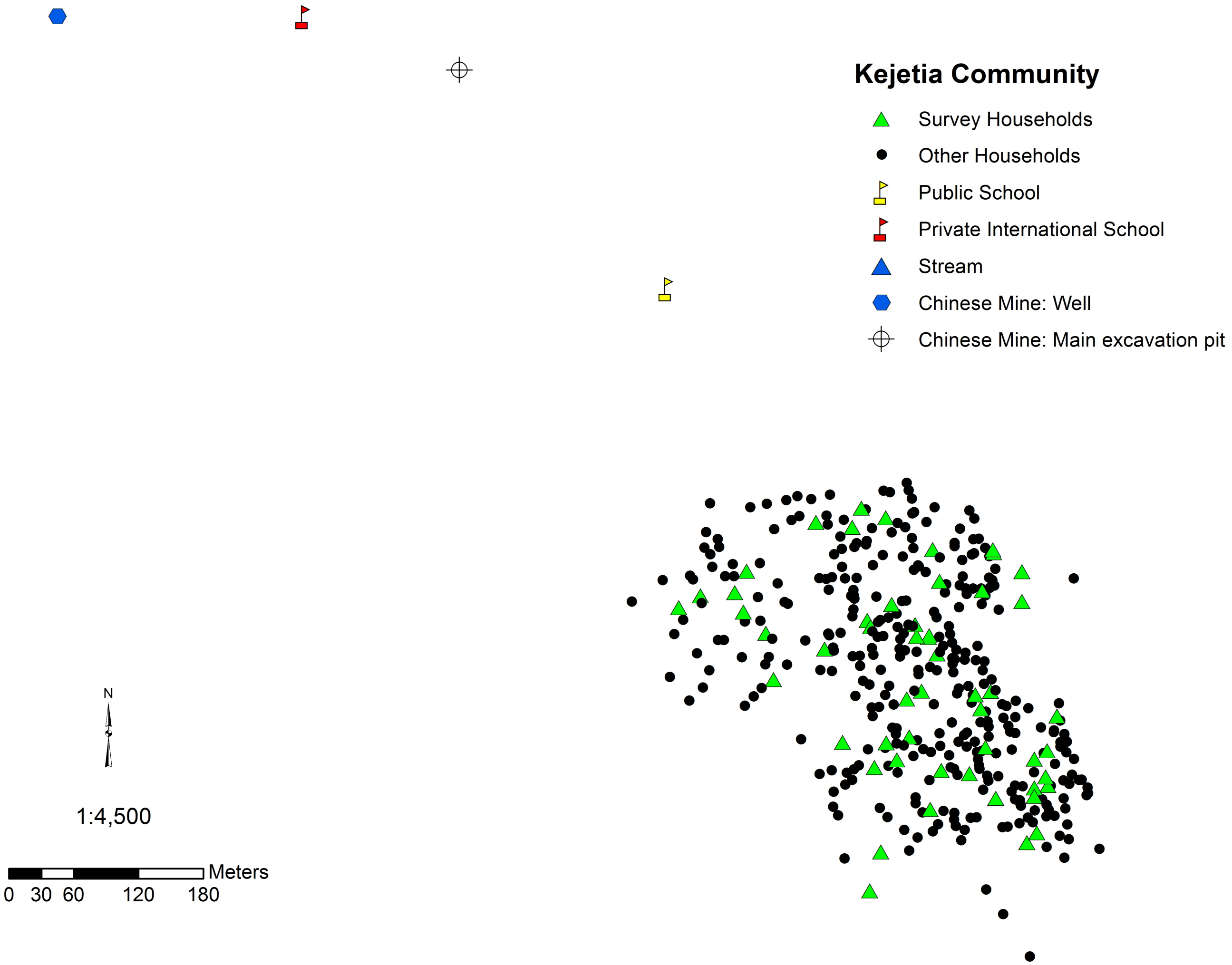
[f] Canadian Soil Quality Guideline of 6.6 μg/g inorganic Hg for residential sites (CCME, 1999).

Figures



Map produced from data provided by the United Nations Environmental Program's
Solar and Wind Energy Resource Assessment (SWERA), by Mozhgon Rajaee, Jun. 2012.

Figure 2.1 Map of Ghana indicating Kejetia and Gorogo, the two research communities, in the Upper East Region.



Map produced by Mozhgon Rajaee, February 2015.

Figure 2.2 Map of the Kejetia community, indicating households surveyed and community markers.

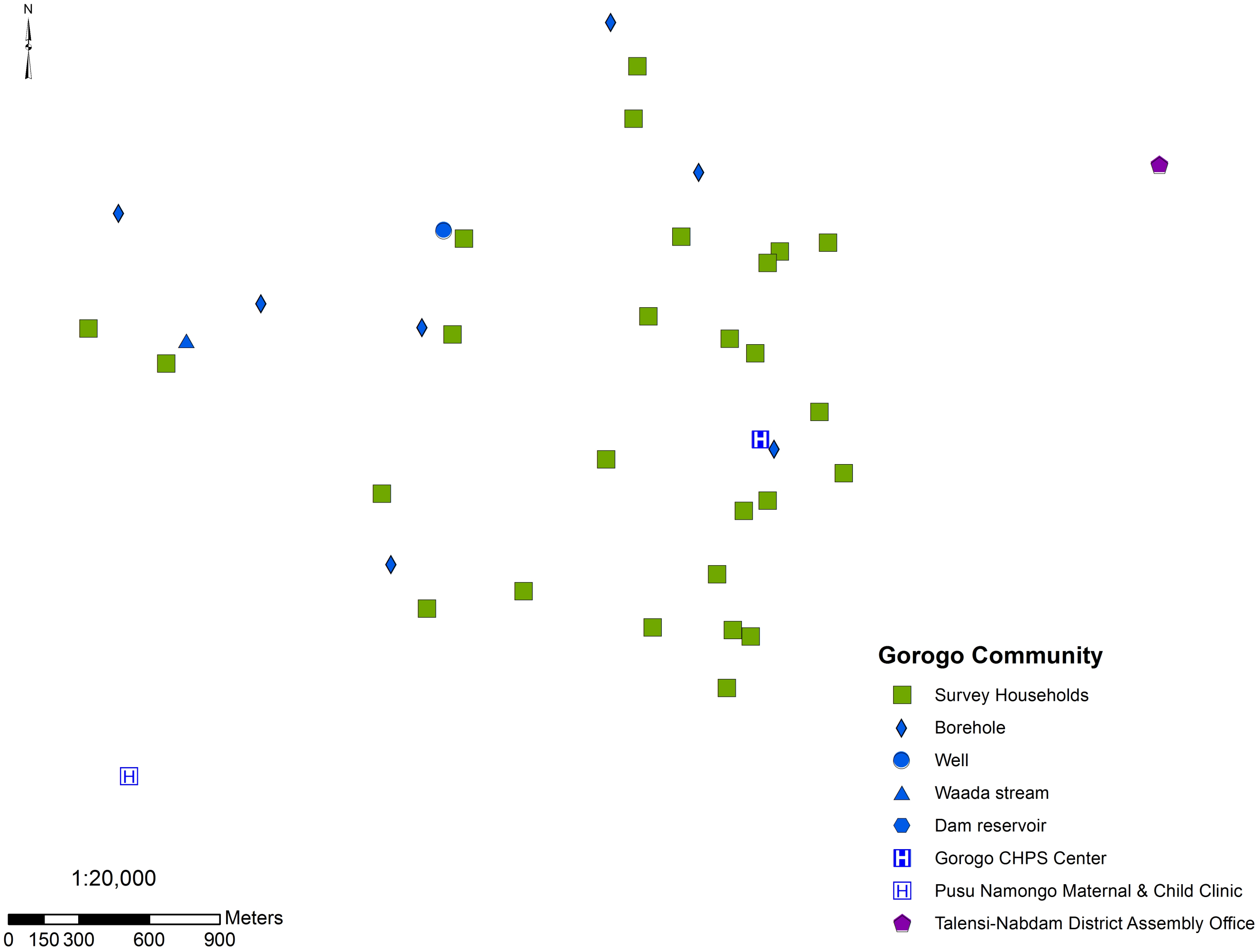


Figure 2.3 Map of Gorogo households surveyed and community markers.

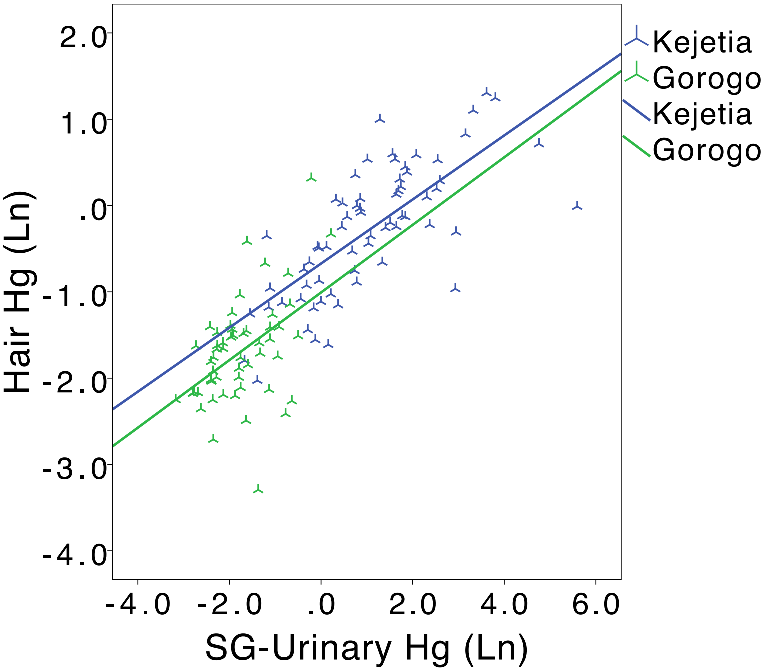


Figure 2.4 Personal urinary Hg by hair Hg concentrations (log-transformed).

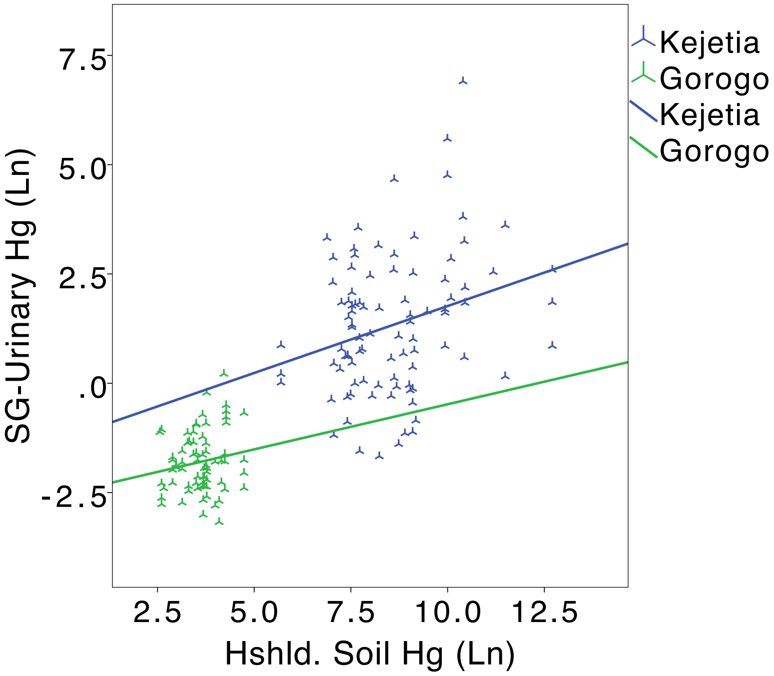
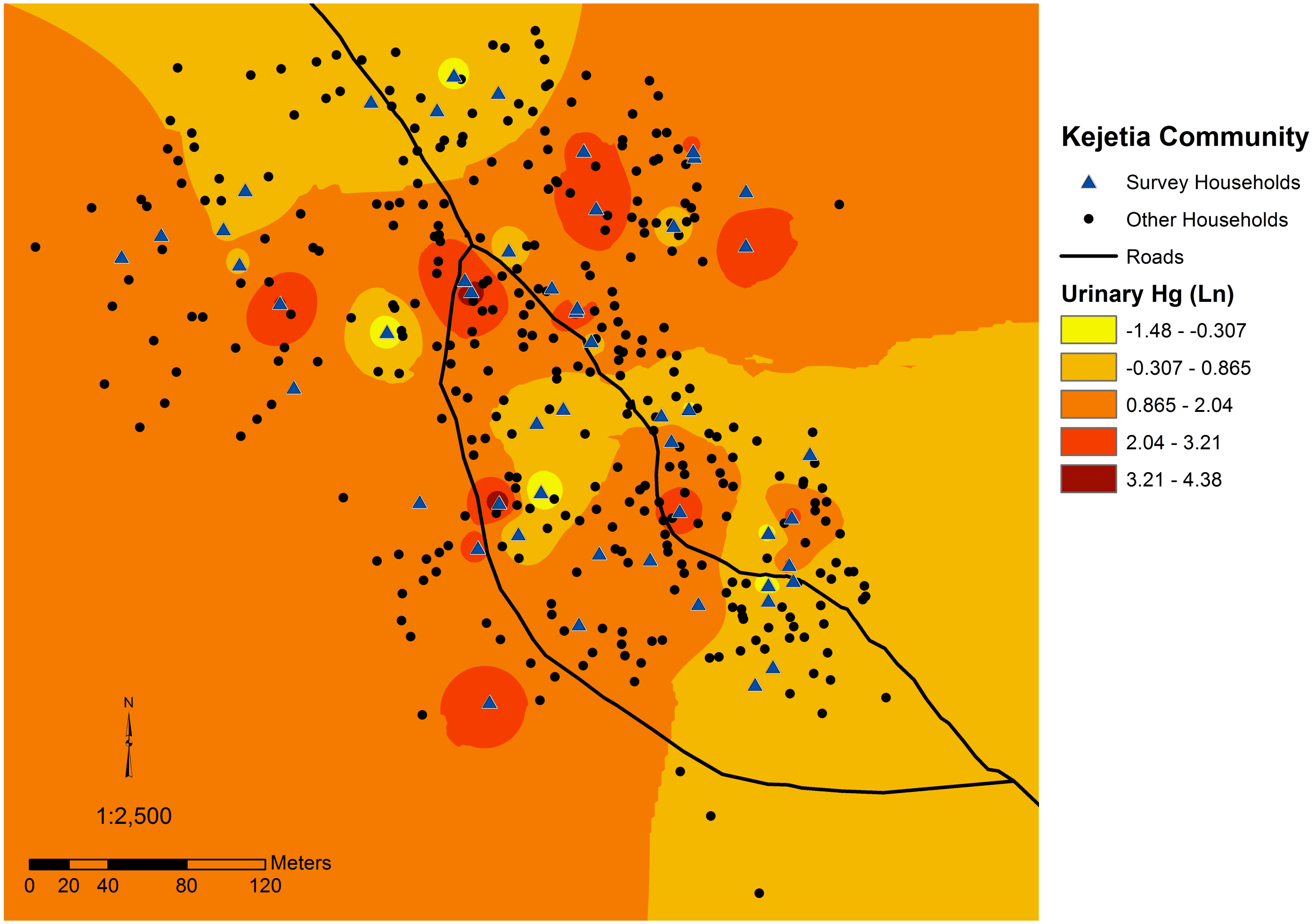
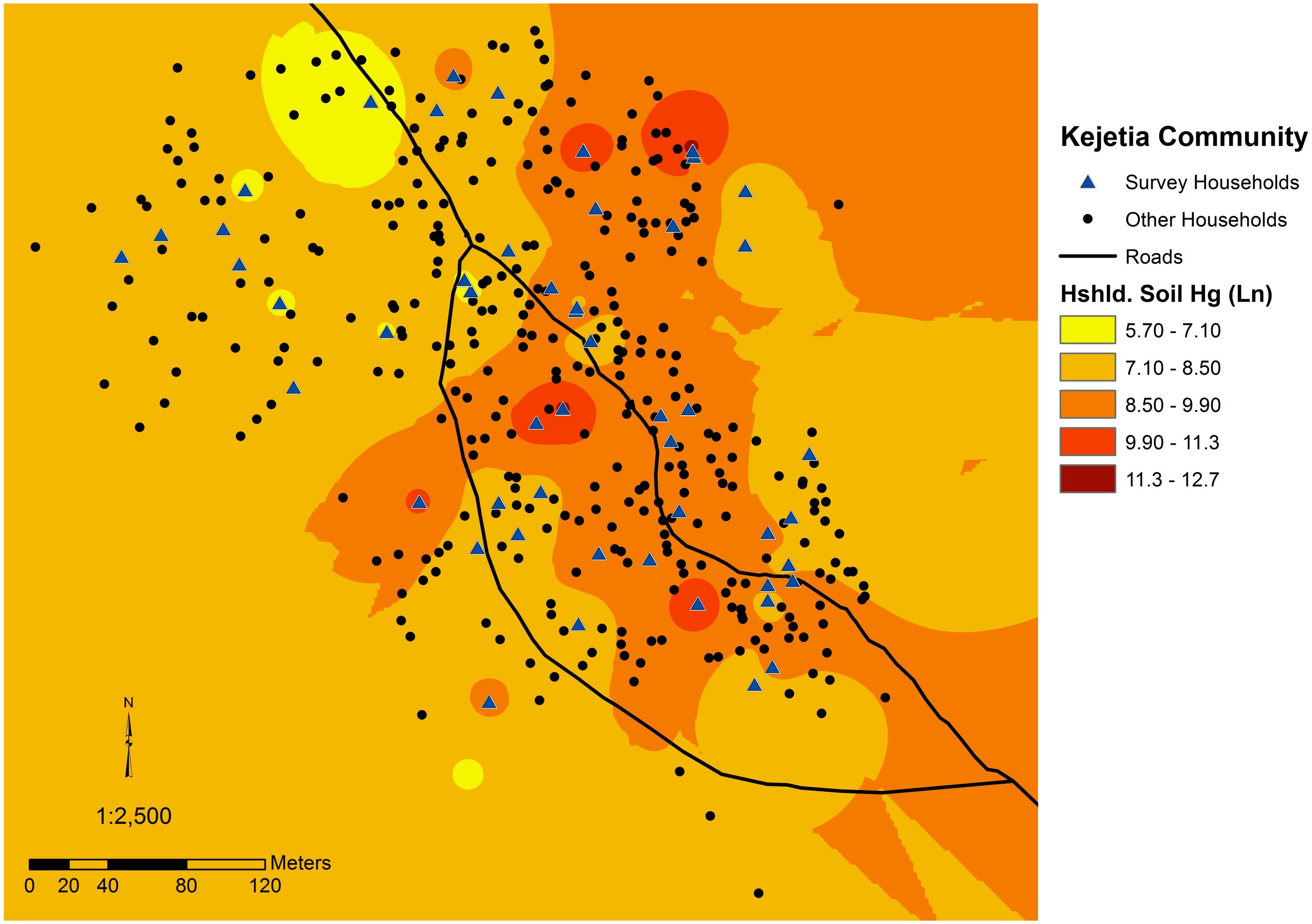


Figure 2.5 Household soil Hg by personal urinary Hg concentrations (log-transformed).



Map produced by Mozhgon Rajaee, February 2015.

Figure 2.6 Map of Kejetia including an estimation of mean urinary Hg (log-transformed) throughout the community. Darker red indicates higher estimated urinary Hg concentrations for residents based on household locations.



Map produced by Mozhgon Rajaee, February 2015.

Figure 2.7 Map of Kejetia including an estimation of mean household soil Hg (log-transformed) throughout the community. Darker red indicates higher estimated household soil Hg concentrations.

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Chapter 3 Associations between organic and inorganic mercury exposure and blood pressure in a Ghanaian small-scale gold mining community

3.1 Introduction

Mercury is an established pollutant of global concern given the body of evidence concerning its neurological impacts (Clarkson and Magos, 2006; Karagas et al. 2012). In recent years there is increasing concern over the impact of mercury (Hg) on the cardiovascular system, though studies have been limited with variable results. Hg has been associated with increases in carotid intima-media thickness and obstruction, coronary heart disease, myocardial infarctions, cerebrovascular accidents, cardiac arrhythmias, heart rate variability, atherosclerosis, carotid artery disease, and renal dysfunction (Houston, 2011; Karagas et al., 2012).

The mechanisms through which Hg affects blood pressure are not well defined, but point toward oxidative stress (Wiggers et al., 2008; Salonen et al., 1995). Increases in oxidative stress from lipid peroxidation and reduced antioxidant capacity can promote endothelial and renal dysfunction, which can increase the risk of hypertension and atherosclerosis, and result in the elevation of pulse pressure (Félétou & Vanhoutte, 2006; Touyz, 2004; Houston, 2011; Ryan, Waack, Weno, & Heistad, 1995; Ceravolo et al., 2003). While the majority of the research shows Hg to increase oxidative stress, endothelial dysfunction, and subsequently blood pressure, Rhee and Choi (1989) found that inorganic Hg can cause a decrease in renal blood flow while renal activity remains constant, as inorganic Hg may inhibit sodium and chloride reabsorption in the kidneys (Norn, Permin, Kruse, & Kruse, 2008).

Most research concerning the cardiovascular impact of Hg has focused on methylmercury (MeHg) exposure and blood pressure. This form of Hg exposure mainly comes from seafood consumption, and exposures have generally been associated with increases in systolic blood pressure (SBP) and diastolic blood pressure (DBP). For example, MeHg-associated increases in SBP have been found in studies of male whalers from the Faroe Islands (Choi et al., 2009), community members from communities along the Brazilian Amazon (Fillion et al., 2009), and adult Inuit from Nunavik (Valera, Dewailly, & Poirier, 2009). Exposure-related increases in DBP have also been reported in the aforementioned study of Farose whalers as well as a study of U.S. Michigan dentists (Choi et al., 2009; Goodrich et al., 2012).

Unlike MeHg, much less is known about the cardiovascular effects of inorganic Hg exposure. Some animal studies have shown that elemental Hg exposure reduces heart rate, lowers blood pressure and causes arrhythmias (Massaroni et al., 1995; Rhee & Choi, 1989; Rossoni et al., 1999). There is some limited evidence from human population studies. Individuals with elevated urinary Hg and dental amalgams (a major source of elemental Hg exposure) have been found to have significantly higher BP and lower pulse, hemoglobin, and hematocrit compared to individuals without dental amalgams (Siblerud, 1990). Studies have observed significant decreases in SBP with urinary Hg (Park, Lee, Basu, & Franzblau, 2013; Goodrich et al., 2012; Siblerud, 1990), and one study has observed significant increases in SBP and DBP with historic Hg miners (Kobal et al., 2004). Park et al.'s study indicates that inorganic Hg exposure even at background levels may be associated with sub-clinical changes in cardiovascular function. Population surveys have indicated widespread exposure to inorganic forms of Hg in many countries (e.g., USA, Canada; Center for Disease Control, 2009; Nicolae, Ames, & Quiñonez, 2013).

Exposures to inorganic Hg are perhaps highest amongst members of artisanal and small-scale gold mining (ASGM) communities. This form of mining utilizes elemental Hg to bind gold, and has recently been suggested to be the largest overall contributor to global anthropogenic Hg in the atmosphere (United Nations Environment Program, 2013). ASGM communities are unique in their potentially high exposure to elemental Hg used in the mining process. Biological markers of elemental and organic Hg concentrations are predominantly measured through urine and hair, respectively (Wranová et al., 2008; Clarkson & Magos, 2006).

Hypertension is a growing problem in Ghana, like other developing countries, and was the fifth largest cause of outpatient morbidity in 2008 (Bosu, 2010). An estimated 3.5 million Ghanaians over 15 years of age have hypertension (Bosu, 2010). A 1973 study reviewing rural Ghanaian villages found the prevalence of hypertension (defined as DBP >95 mmHg) to be 2.5% for participants aged 16-54 years, and 4.5% for all participants over 16 years (Pobee, Larbi, Belcher, Wurapa, and Dodu, 1977). A 2010 review of hypertension studies in Ghana found that the prevalence of hypertension ranged from 19 to 48%; and estimated hypertension prevalence at 20% in rural areas and 25% in urban areas (Bosu, 2010). In addition to the problem of rising hypertension, less than one-third of hypertensive adults from Ghanaian studies in 2005 were even aware that they had hypertension (Bosu, 2010).

There have been no studies to-date exploring Hg exposures in small-scale gold miners and cardiovascular health. This unknown relationship with high Hg exposures and the growing problem of hypertension may pose a problem for small-scale gold miners in Ghana and across the world. This study seeks to elucidate the relationship of hair and urinary Hg with cardiovascular health through assessing blood pressure and heart rate. Based on previous research, we hypothesized that hair Hg would be associated with an increase in systolic and diastolic BP and urinary Hg would be associated with a decrease in systolic BP in Kejetia.

3.2 Materials and methods

3.2.1 Study populations

Two study populations were identified in the Upper East Region of Ghana: Kejetia, a small-scale gold mining community and Gorogo, a subsistence farming community. Participants were recruited by household in a cross sectional study from May through July 2011. Members of each household were defined as those who eat from the same "pot", with up to four adults interviewed per household. Institutional Review Board (IRB) approval was obtained through the University of Michigan (HUM00028444). Permission to work with the community was given by both communities' traditional chief and the Assemblyperson representing the community in Gorogo.

A household head was interviewed on household characteristics (including demographics, water use and cooking fuel). The household head and up to three other adult (18 years or older) household members were interviewed on their occupational and medical histories. Questions were adapted from the Ghana Demographic and Health

Survey (Ghana Statistical Service and Ghana Health Service, 2009), and the American Thoracic Society's Epidemiology Standardization Project (Ferris, 1978).

In Kejetia, all households were divided into 20 clusters. In each cluster, households were randomly assigned a number, and two to three households were sampled within each cluster by drawing a number at random from a bag. Only one household from one to three clusters was interviewed per day. Due to the large geographic dispersion of the Gorogo community, households were selected through convenience sampling. A bottle was spun at a community landmark initially and the household in the bottle's direction was selected (Hoshaw-Woodard, 2001). Spinning a bottle at the preceding participating household identified subsequent households. One Gorogo participant was excluded for being a current miner. More detailed methods are explained in Rajaee et al. (2015).

3.2.2 Mercury exposure assessment

Urine was collected to assess elemental Hg exposure and hair to assess methylmercury exposure (Clarkson & Magos, 2006). Spot urine samples (5-15 mL) were collected by participants at the time of the interview, stored at room temperature in Ghana, and frozen until analysis in the U.S. Hair was cut as close to the scalp as possible from the occipital region of the head and placed on a sticky-note and stored in a plastic bag until analysis. Only the 2 cm closest to the scalp was used for analysis (Paruchuri et al., 2010).

Total Hg was measured using a Direct Mercury Analyzer-80 (DMA-80; Milestone, Inc., Shelton, CT), following U.S. EPA Method 7473 (US Environmental

Protection Agency, 2007). Urine (500 μL) was vortexed and hair washed with acetone and deionized water before analysis. Certified reference materials (CRMs; urine: QMEQAS, Institut National de Santa Publique Quebec; hair: NIES Japan; dogfish liver: DOLT-4, National Research Council Canada) were analyzed approximately every ten samples, blanks every five samples, and sample replicates at least every nine samples. The detection limit, recovery rates of CRMs, and within-day variations for urine and hair samples are provided in Rajaee et al 2015.

Specific gravity (SG) was measured using a pocket refractometer (PAL-10S, Atago U.S.A., Inc., Tokyo, Japan) to adjust urine samples by urinary dilution using the mean urinary specific gravity in Kejetia and Gorogo (1.016; Lee, Park, & Kim, 1996; Voinescu, Shoemaker, Moore, Khanna, & Nolph, 2002). The equation is as follows, where *p* refers to a participant's personal urinary Hg and urinary SG values:

$$SG - adjusted\ urinary\ Hg_p = \frac{(Avg.urinary\ SG - 1)}{(Urinary\ SG_p - 1)} \times Urinary\ Hg_p$$

Statistical analyses were performed with specific gravity-adjusted and non-adjusted urinary Hg.

3.2.3 Blood pressure and pulse assessment

Participants had their systolic and diastolic blood pressure (BP) and heart rate (HR) measured three times according to American Heart Association standards (AHA; Pickering et al., 2005) using a manual sphygmomanometer (Omron HEM-432C; Omron Healthcare, Inc., Lake Forest, IL) about 2 cm above the right elbow, above the brachial artery as we have previously detailed (Goodrich et al., 2012). Participants were asked to sit on a chair or stool (with back support when possible) for the duration of the occupational survey, to allow for participants to rest for at least 10 minutes before measurements were taken. Three measurements were averaged for each participant's blood pressure and pulse. Variability of each individual's replicates averaged 4.7% (SBP), 5.4% (DBP), and 3.5% (pulse).

BP values were classified by AHA standards for hypertensive status, with apparent hypertension defined as SBP ≥ 140 mmHg or DBP ≥ 90 mmHg (Pickering et al., 2005; AHA, 2012). Pulse pressure was calculated from the difference between the systolic and diastolic BP. One (n=1) male participant from Kejetia was excluded from analyses for taking anti-hypertensive medication at the time of the survey (his urinary Hg was 167.2 µg/L unadjusted and 116.3 µg/L adjusted for specific gravity).

3.2.4 BMI and smoking

Each participant's body mass index (BMI) was calculated by dividing the participant's weight (kg) by his/her squared height (m), to assess obesity. Participant's smoking history was assessed to classify participants as current, ex, and never smokers. Participants were classified as never-smokers if they had smoked less than 100 cigarettes in their lifetime. Smoking pack-years reflects the average packs (20 cigarettes per pack) of cigarettes smoked per day for the duration of his/her smoking years.

3.2.5 Statistical analyses

Data were analyzed using SPSS Statistical Software (v.22; IBM, Chicago, IL). Urinary and hair Hg biomarkers that were not normally distributed were analyzed using

Spearman correlations for bivariate analyses. Multivariate linear regressions were used to determine factors that influenced blood pressure measures (SBP, DBP, pulse, pulse pressure, and mean arterial pressure). Sex and smoking status (current and ex) were all controlled for in regression models, in addition to the exposure variables of interest: hair and urinary Hg (unadjusted and specific gravity-adjusted). Multivariate analyses were performed for all participants, by community, and by mining status in Kejetia.

All linear regression models were ran including and excluding outliers with emergency high BP (SBP ≥ 180 or DBP ≥ 110 mmHg) or SG-adjusted urinary Hg > 45 µg/L. Participants with emergency high BP (three in Kejetia and one in Gorogo) were counseled at the time of the interview to seek advice from a medical professional. That data presented here depicts only analyses excluding participants with emergency high BP or SG-adjusted Hg > 45 µg/L. Participants excluded for emergency high BP all had SG-adjusted urinary Hg concentrations below 6.5 µg/L. Three Kejetia participants with very high urinary Hg levels were excluded as outliers (SG-adjusted urinary Hg was 998.0, 268.4, and 106.5 µg/L for outliers).

3.3 Results

There were 96 participants from 54 households in Kejetia and 75 participants from 26 households in Gorogo. Table 3.1 outlines the demographics, BMI and smoking histories of participants, stratified by community and sex. Kejetia participants were younger than Gorogo participants, with 66.7% in Kejetia under the age of 35, but only 22.7% in Gorogo under 35 years. Kejetia participants were predominantly current miners (72.9%), but many people engaged in multiple work activities in both communities (data not shown). The majority of participants in Kejetia and Gorogo had a normal BMI (18.5 to 24.9), but women in Kejetia and Gorogo had higher rates of overweight BMI (25.0 to 29.9). Smoking, while less common, was almost exclusively seen in males and predominantly among miners in Kejetia. Seventeen (17.7%) of Kejetia participants and 16 (21.3%) of Gorogo participants had apparent hypertension (SBP ≥ 140 mmHg or DBP ≥ 90 mmHg) (table 3.1).

Urinary and hair Hg biomarkers are reported in Table 3.2. Both biomarkers were not normally distributed, with a right-skew. In Kejetia the median (interquartile range; IQR) unadjusted urinary Hg concentration was 2.71 (1.03, 2.71) µg/L and the mean specific gravity-adjusted urinary Hg was 3.1 (1.13, 3.10) µg/L (n=91). The median hair Hg concentration was 0.782 (0.404, 0.782) µg/g (n=69) in Kejetia. Hg concentrations in urine (adjusted and unadjusted) and hair were significantly higher in Kejetia than Gorogo participants and Kejetia miners than non-miners. In Gorogo, urinary Hg was very low, with a median SG-adjusted Hg concentration of 0.154 (0.095, 0.154) µg/L (n=70). Median hair Hg concentrations in Gorogo were 0.181 (0.119, 181) µg/g (n=59).

In bivariate analyses concerning Hg exposure biomarkers, SG-adjusted urinary and hair Hg were significantly correlated to each other in Kejetia (Spearman's $\rho = 0.757$, $p < 0.001$) and Gorogo ($\rho = 0.405$, $p = 0.002$). As displayed in the scatterplots in Figure 3.1, there were no significant correlations between SG-adjusted urinary Hg to SBP or DBP in Kejetia or Gorogo. Hair Hg was not significantly correlated to any BP or pulse measures in either community, although it had a positive trend in Gorogo. Pulse pressure was negatively correlated to SG-adjusted urinary Hg in Gorogo ($\rho = -0.261$, $p = 0.029$), but not in Kejetia. SG-adjusted urinary Hg was significantly correlated to pulse in Kejetia (ρ = -0.214, p = 0.042) and Gorogo (ρ = -0.323, p = 0.006). Figure 3.2 displays the mean SBP and DBP by quintiles of SG-adjusted urinary Hg in Kejetia. While the SG-urinary Hg concentrations are not significantly different by quintile group, the graph does indicate that the trend may be non-linear as elemental Hg exposures increase.

In other bivariate analyses, age was significantly correlated to SBP (Kejetia: ρ = 0.349, p < 0.001; Gorogo: ρ = 0.366, p = 0.001), DBP (Kejetia: ρ = 0.454, p < 0.001; Gorogo: ρ = 0.264, p = 0.022), and pulse pressure (Gorogo: ρ = 0.350, p = 0.002). BMI and smoking pack-years were not significantly correlated to BP measures. Pack-years was significantly correlated to SG-adjusted urinary Hg in Kejetia (ρ = 0.220, p = 0.044), as only one of 15 current smokers was a non-miner.

Multivariate linear regression models were performed including all participants and excluding four outliers with emergency high BP (SBP ≥ 180 mmHg or DBP ≥ 110 mmHg) and three outliers with SG-adjusted urinary Hg concentrations greater than 45 μg/L. Hair and urinary Hg were run in separate models, and models with urinary Hg did not include Gorogo, as urinary Hg values were all very low. Each model was adjusted for potential confounders (sex and smoking status).

Table 3.3 displays the results of linear regression models associating hair Hg levels and BP outcomes, while excluding outliers. Overall, the adjusted R^2 values of the model were low (maximum was 0.209) and no significant associations were observed with hair Hg. In Kejetia and Gorogo, the association of hair Hg on SBP is positive (β=0.662, p=0.74; and β = 2.28, p = 0.86, respectively), and with DBP it is negative (β=-1.85, p=0.32; and β = -1.18, p = 0.88, respectively), though none of these are statistically significant. Increasing hair Hg was associated with an increase in pulse pressure in

Kejetia (β=2.05, p=0.15) and increasing pulse in Gorogo (β = 3.19, p = 0.13). The relationship with the female sex, current smoking and ex-smoking status were largely negative with SBP, DBP, pulse, and pulse pressure in Kejetia and Gorogo, with an exception for pulse with female sex, and current smokers in Gorogo, and DBP with ex-smokers in Kejetia and Kejetia miners (all not significant). Models include participants with emergency high BP yielded similar results (data not shown).

Analyses with SG-adjusted urinary Hg (table 3.4) show no significant association with SBP, DBP, pulse pressure, or pulse. For Kejetia current miners, the association between SG-adjusted urinary Hg and DBP was negative (β = -0.225, p = 0.12), and approaching a significantly positive association with pulse pressure (β = 0.199, p = 0.064). The female sex was associated with decreases in SBP, DBP, pulse pressure, and pulse. Current and ex-smoking statuses were associated with varying relationships in each model. Models including unadjusted urinary Hg, participants with emergency high BP, or SG-adjusted urinary Hg concentrations > 45 µg/L were similar or had wider confidence intervals, with no significant associations with urinary Hg and BP outcomes (data not shown).

3.4 Discussion

There is increasing concern about the cardiovascular effects of mercury (Hg) exposure, and that organic MeHg and inorganic Hg^{2+} may affect the cardiovascular system and blood pressure differentially. In small-scale gold mining communities, inorganic, elemental Hg exposures are high for community members and miners. Little is known about the Hg-associated effects on blood pressure in such groups, and the high exposures may represent a unique opportunity to increase understanding of Hg-associated cardiovascular risk. Here we conducted a cross-sectional epidemiological study to assess the relationships between exposures to both MeHg and inorganic Hg with blood pressure. As with past studies from this region (Paruchuri et al., 2010) exposures to MeHg were relatively low whereas exposures to inorganic Hg were high. When the exposure data were associated with blood pressure measures, though relationships were in the expected direction based on past studies, they were not of statistical significance. We are limited in particular by a small number of participants with elevated urinary and hair Hg concentrations and a small sample size overall.

In the current study the relationship between hair Hg (which reflects exposure to MeHg) and SBP was not significant, though it does follow the trend seen in other studies, which have found an increase in SBP in relation to hair or blood Hg (Valera et al., 2009; Goodrich et al., 2012; Dorea, de Souza, Rodrigues, Ferrari, & Barbosa, 2005; Choi et al., 2009; Fillion et al., 2006). Only one study of U.S. adults from the National Health and Nutrition Examination Survey (NHANES) found a significant decrease in SBP of about 0.05 mmHg with a 10% increase in blood Hg (Park et al., 2013). For DBP, the work here found a negative (albeit, non-significant) association between elevated hair Hg and DBP, and this contrasts other research, which have all observed an exposure-associated increase in DBP (Park et al., 2013; Valera et al., 2009; Goodrich et al., 2012; Dorea et al., 2005; Choi et al., 2009; Fillion et al., 2006). Goodrich et al. (2012) estimated a 2.76 mmHg increase in DBP for every 1 μg/g increase in hair Hg. The overall lack of significant finding here is perhaps due to lower hair Hg levels in our study than these other studies. Hair samples from ASG miners or community residents may also overestimate MeHg exposure, thus clouding any association. Sherman et al. (2015) found that hair Hg from a subsample of our Kejetia miners collected in 2011 and other Kejetia miners sampled in 2010 had a low percentage of MeHg as total Hg (7.6-29%), suggesting that the majority of the total Hg is exogenously adsorbed elemental Hg.

For exposures to inorganic Hg, the levels reported here were high as expected for current miners. The median value (4.24 µg/L) was similar to our past work in this same community (3.6 µg/L; Paruchuri et al., 2010) as well as values found in other ASGM communities (Gibb & O'Leary, 2014). These exposure values are much greater than values from other studies in which Hg-associated decreases in SBP have been reported. For example, Park et al.'s (2013) study of healthy U.S. adults had a 95% confidence limit of 0.47-0.54 µg/L urinary Hg and Goodrich et al. (2012) measured urinary Hg concentrations ranging from 0.03 to 5.54 µg/L Hg (median: 0.63 µg/L).

Three studies of U.S. adults observed significant decreases in SBP (Park et al., 2013; Goodrich et al., 2012; Siblerud, 1990) and one observed a significant decrease in DBP with urinary Hg (Siblerud, 1990). Park et al. (2013) estimated a 0.114 mmHg decrease in SBP with a 10% increase in urinary Hg and Goodrich et al. (2012) estimated a 1.80 mmHg decrease in SBP with every 1 µg/L increase in urinary Hg. While these studies help contextualize our study, the average urinary Hg concentrations were far lower than in our Kejetia participants. One study of Slovenian Hg miners (n=54) with elevated historic Hg exposures observed significant increases in SBP and DBP with an average annual past exposure of 69.3 µg/L Hg and a current measure of 2.5 µg/L Hg in their urine (Kobal et al., 2004). Given this research, we hypothesized that inorganic Hg-associated reductions in blood pressure would be apparent and help increase understanding of the relationship at higher exposures. However, as noted in Figure 3.2, it is possible that there is a non-linear trend that we were unable to measure with only three participants with > 70 µg/L urinary Hg in Kejetia. The impact on BP may be more deleterious for miners with higher exposures to elemental Hg.

Hair and urinary Hg had positive associations with pulse pressure, but were not statistically significant. Other studies observed that blood Hg was positively associated with increasing pulse pressure (Valera, Dewailly, & Poirer, 2008; Valera et al., 2009; Pederson et al., 2005). The association of urinary Hg levels on pulse pressure has not been explored previously. Elevated pulse pressure is recognized as a risk factor for cardiovascular disease (Dart & Kingwell, 2001). Studies have observed decreased heart rate variability with blood Hg (Valera et al., 2008; Valera et al., 2011; Valera et al., 2012). This negative trend of association for pulse with urinary and hair Hg may be more pronounced in Kejetia, where many people are younger and engage in physical activity through mining, whereas Gorogo participants were older and possibly more sedentary.

While we did not see a significant relationship with hair or urinary Hg and blood pressure, our work generally follows the trends seen in the literature. Our study was limited by a small sample size, particularly of participants with urinary Hg greater than 50 µg/L, though it should be mentioned that the average urinary Hg value in population surveys is usually <5 µg/L Hg. It is possible that there is a non-linear trend with urinary Hg to BP, and higher elemental Hg exposures may elucidate a positive association with SBP or DBP, as seen in the study of historic Hg miners (Kobal et al., 2004). Kejetia and Gorogo vary greatly in demographics, as Kejetia is a younger and more transient community. This plays an important role, as age is associated with an increase in BP, but running stratified models by community help to account for these differences. Hypertension is rising in Ghana as it becomes more industrialized (Bosu, 2010), underscoring the value in understanding the relationship of Hg to BP and cardiovascular health, particularly for the over 500,000 people employed in ASGM (Bawa, 2010).

3.5 Conclusion

Mercury is a known toxicant that many ASG miners are exposed to at elevated levels, but no studies have examined the relationship between Hg and blood pressure in these populations. While we did not see a significant relationship between hair or urinary Hg and BP, there is an indication of a potential non-linear relationship for urinary Hg and BP. Further studies utilizing larger samples sizes of participants with > 10 μg/L urinary Hg would help to clarify this relationship.

Tables

Table 3.1 Demographics and blood pressure of participants in Kejetia and Gorogo, and stratified by mining status.

		Kejetia			
		All	Miners[a]	Non-miners[a]	Gorogo
n participants		96	70	26	75
n households		54	41	18	26
Sex	% Male	49 (51.0%)	42 (60.0%)	7 (26.9%)	34 (45.3%)
Age	Mean (SD)	31.4 (10.9)	30.6 (9.7)	33.8 (13.6)	51.5 (18.8)
BMI[b]					
	< 18.5	5 (5.2%)	4 (5.7%)	1 (3.8%)	12 (16.0%)
	18.5 to 24.9	73 (76.0%)	59 (84.3%)	14 (53.8%)	52 (69.3%)
	25 to 29.9	13 (13.5%)	5 (7.1%)	8 (30.8%)	10 (13.3%)
	30 or higher	5 (5.2%)	2 (2.9%)	3 (11.5%)	1 (1.3%)
	Mean (SD)	22.7 (3.2)	22.1 (2.7)	24.5 (3.7)	21.8 (3.1)
Smoking					
	Current smoker	15 (15.6%)	14 (20.0%)	1 (3.8%)	14 (18.7%)
	Ex-smoker	7 (7.3%)	6 (8.6%)	1 (3.8%)	9 (12.0%)
n ever-smokers with pack-years[c]		16	15	1	14
	Cigarette pack-years[c]	15.8 (26.6)	15.1 (27.4)	25.5	3.9 (2.1)
Blood Pressure	Mean (SD)				
	Systolic BP (mmHg)	123.5 (15.4)	122.6 (12.4)	125.8 (21.7)	126.1 (20.0)
	Diastolic BP (mmHg)	76.7 (11.9)	75.2 (10.3)	80.6 (14.9)	75.4 (11.5)
	Pulse Pressure[d] (mmHg)	46.9 (9.3)	47.5 (8.2)	45.2 (11.8)	50.7 (13.3)
	Pulse	77.1 (1.6)	77.0 (1.5)	77.2 (1.7)	74.6 (3.2)
BP Classifications[e]					
	Normal	38 (39.6%)	27 (38.6%)	11 (42.3%)	30 (40.0%)
	Prehypertension	41 (42.7%)	32 (45.7%)	9 (34.6%)	29 (38.7%)
	Apparent hypertension	17 (17.7%)	11 (15.7%)	6 (23.1%)	16 (21.3%)
	Hypertension Stage 1	12 (12.5%)	9 (12.9%)	3 (11.5%)	8 (10.7%)
	Hypertension Stage 2	5 (5.2%)	2 (2.9%)	3 (11.5%)	8 (10.7%)

[a] Refers to current miners and non-current miners

[b] For BMI, n = 74 for Gorogo: Overall, and n = 40 for Gorogo: Female due to missing data for one participant

[c] Cigarette pack-years only include ever-smokers

[d] Pulse pressure = systolic - diastolic BP

[e] Normal BP is SBP < 120 and DBP < 80; prehypertension BP is SBP: 120-139 or DBP: 80-89; apparent hypertension is SBP ≥ 140 or DBP ≥ 90; hypertension stage 1 is SBP: 140-159 or 90-99; hypertension stage 2 is SBP ≥ 160 or DBP ≥ 100.

Table 3.2 Mercury concentrations in urine and hair samples of participants.

		Kejetia			
		All	Miners[a]	Non-miners[a]	Gorogo
Urine	*n*	91	67	24	70
Urinary Specific Gravity (SG)					
	Mean (SD)	1.018 (0.007)[d]	1.017 (0.007)	1.020 (0.006)	1.014 (0.006)
Urinary Hg (μg/L)					
	Mean (SD)	29.4 (148.6)[d]	37.6 (172.7)[e]	6.61 (13.2)	0.161 (0.131)
	Median	2.71	4.24	1.41	0.114
	IQR[b]	1.03, 2.71	1.24, 4.24	0.742, 1.41	0.079, 0.114
	Min - Max	0.160 - 1372.3	0.160 - 1372.3	0.199 - 58.1	0.026 - 0.580
SG-adj. Urinary Hg[c] (μg/L)					
	Mean (SD)	21.7 (107.9)[d]	28.0 (125.3)[e]	4.22 (6.88)	0.216 (0.194)
	Median	3.1	5.17	1.18	0.154
	IQR[b]	1.13, 3.10	1.90, 5.17	0.733, 1.18	0.095, 0.154
	Min - Max	0.188 - 998.1	0.188 - 998.1	0.212 - 25.8	0.042 - 1.24
Hair Hg (μg/g)	*n*	69	50	19	59
	Mean (SD)	0.958 (0.742)[d]	1.11 (0.807)[e]	0.558 (0.272)	0.231 (0.202)
	Median	0.782	0.945	0.419	0.181
	IQR[b]	0.404, 0.782	0.571, 0.945	0.329, 0.419	0.119, 0.181
	Min - Max	0.132 - 3.69	0.132 - 3.69	0.237 - 1.10	0.037 - 1.37

[a] Refers to current miners and non-current miners

[b] Interquartile range (25th percentile, 75th percentile)

[c] Specific gravity adjusted urinary Hg: Urinary Hg * [(1 - avg. SG]/[Urine SG - 1])

[d] Gorogo vs. Kejetia t-test comparing means of log-transformed data (except for specific gravity), $p < 0.001$

[e] Miners vs. non-miners t-test comparing means of log-transformed data, $p < 0.05$

Table 3.3 Results of linear regression models for blood pressure measures and hair Hg concentrations. Each line represents a separate model. Analyses were restricted to participants without emergency high BP statuses (n=4). Statistically significant results are in bold font.

			Adjusted	Intercept	Hair Hg (μg/g)	Female	Current smoker	Ex-smoker
	Model	n	r^2	β	β (*p*-value)			
Systolic BP	Gorogo	58	0.004	136.8	2.28 (0.86)	-14.2 (0.08)	-14.7 (0.10)	-9.80 (0.36)
	Kejetia	67	0.164	130.0	0.662 (0.74)	**-13.6 (< 0.001)**	-8.57 (0.11)	-6.95 (0.29)
	Kejetia: Current miners	50	0.067	129.2	0.621 (0.79)	**-11.4 (0.012)**	-7.73 (0.20)	-6.13 (0.40)
Diastolic BP	Gorogo	58	-0.062	79.0	-1.18 (0.88)	-3.92 (0.41)	-3.24 (0.54)	-3.10 (0.63)
	Kejetia	68	-0.019	79.3	-1.85 (0.32)	-3.54 (0.29)	-3.30 (0.50)	2.52 (0.68)
	Kejetia: Current miners	50	-0.028	78.2	-1.23 (0.51)	-3.95 (0.27)	-3.04 (0.53)	3.00 (0.62)
Pulse pressure[a]	Gorogo	58	0.029	57.8	3.46 (0.70)	-10.3 (0.056)	-11.4 (0.057)	-6.71 (0.35)
	Kejetia	67	0.209	51.3	2.05 (0.15)	**-9.44 (< 0.001)**	-5.23 (0.16)	**-9.59 (0.04)**
	Kejetia: Current miners	50	0.118	51.0	1.85 (0.24)	**-7.48 (0.014)**	-4.70 (0.24)	-9.13 (0.07)
Pulse	Gorogo	58	0.172	74.3	3.19 (0.13)	0.285 (0.82)	1.616 (0.25)	**-3.83 (0.025)**
	Kejetia	67	0.014	78.0	-0.265 (0.37)	-0.886 (0.09)	-0.553 (0.48)	-1.80 (0.07)
	Kejetia: Current miners	50	-0.014	77.8	-0.302 (0.34)	-0.565 (0.35)	-0.340 (0.67)	-1.60 (0.11)

[a] Pulse pressure is SBP – DBP

Table 3.4 Results of linear regression models for blood pressure measures and specific gravity-adjusted urinary Hg concentrations. Each line represents a separate model. Analyses were restricted to participants without emergency high BP statuses (n=4) and urinary Hg concentrations < 45 µg/L (n=3). Statistically significant results are in bold font.

	Model	n	Adjusted r^2	Intercept	SG-Urinary Hg (µg/L)	Female	Current smoker	Ex-smoker
				β	β (*p*-value)			
Systolic BP	Kejetia	86	0.084	128.4	-0.037 (0.81)	**-9.93 (0.003)**	-1.06 (0.80)	-7.53 (0.16)
	Kejetia: Current miners	64	0.053	126.8	-0.026 (0.88)	**-8.82 (0.027)**	0.413 (0.93)	-5.00 (0.39)
Diastolic BP	Kejetia	86	0.006	77.9	-0.151 (0.27)	-3.17 (0.29)	3.76 (0.32)	-0.187 (0.97)
	Kejetia: Current miners	64	0.057	76.8	-0.225 (0.12)	-3.27 (0.33)	5.62 (0.14)	2.04 (0.68)
Pulse pressure[a]	Kejetia	85	0.120	50.4	0.117 (0.24)	**-6.86 (0.002)**	-4.82 (0.08)	**-7.33 (0.038)**
	Kejetia: Current miners	64	0.126	50.0	0.199 (0.06)	**-5.55 (0.028)**	-5.21 (0.06)	-7.04 (0.06)
Pulse	Kejetia	85	0.034	77.7	-0.026 (0.19)	-0.807 (0.07)	-0.253 (0.64)	**-1.52 (0.032)**
	Kejetia: Current miners	64	0.010	77.4	-0.012 (0.57)	-0.27 (0.59)	-0.013 (0.98)	**-1.50 (0.049)**

[a] Pulse pressure is SBP – DBP

Figures

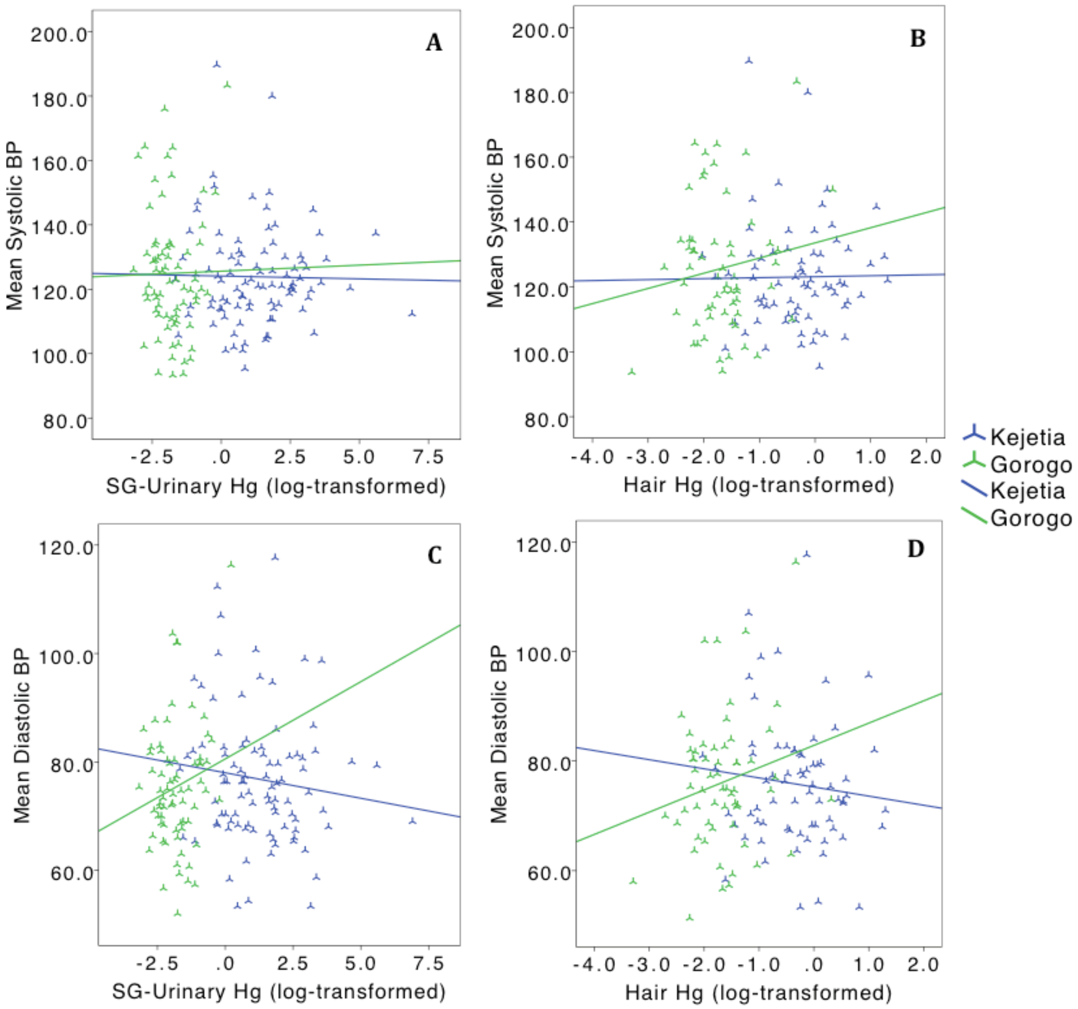

Figure 3.1 Scatterplots of BP by specific gravity-adjusted urinary Hg and hair Hg for Kejetia and Gorogo participants. Systolic BP is represented at top with SG-adjusted urinary Hg (A) and hair Hg (B), and diastolic BP is displayed at bottom with SG-adjusted urinary Hg (C) and hair Hg (D).

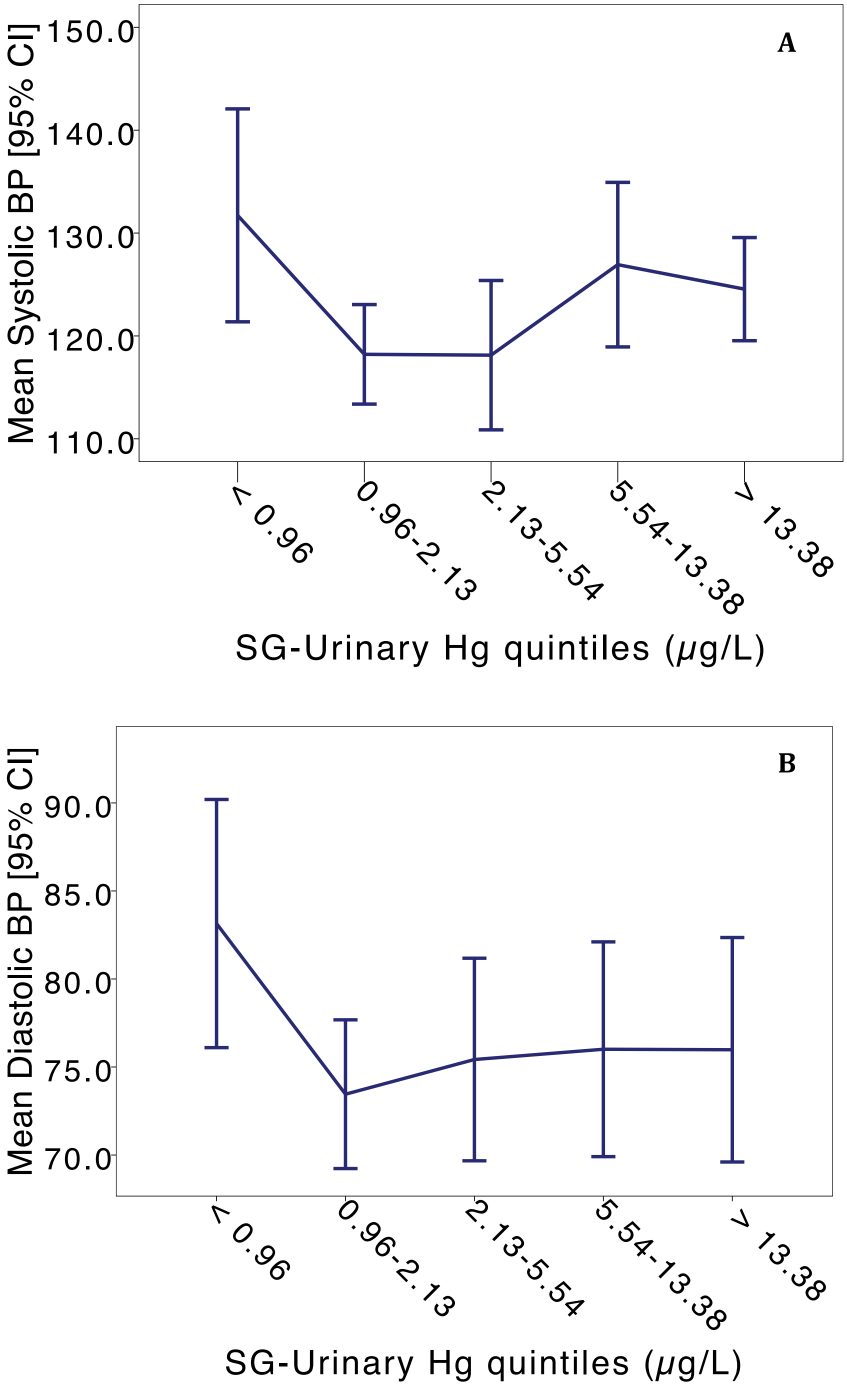

Figure 3.2 Mean systolic (A) and diastolic BP (B) by quintiles of SG-adjusted urinary Hg concentrations in Kejetia. Error bars represent 95% confidence intervals.

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Chapter 4 Pulmonary function and respiratory health of Ghanaian small-scale gold miners

4.1 Introduction

Ghana is one of the most important gold-producing countries in the world, second only to South Africa in gold production from the African continent (Tschakert & Singha, 2007). Small-scale gold mining accounts for 10.5% of Ghana's national gold production, and employs between 500,000 and 1 million people, mostly in rural areas (Bawa, 2010; Hilson & Clifford, 2010). Though small-scale mining has existed for centuries in southern Ghana, it has only expanded to northeast Ghana relatively recently (Hilson, 2010). In the Talensi-Nabdam District (now separate Talensi and Nabdam Districts), in the Upper East Region, where this study was conducted, the practice of small-scale gold mining has grown enormously over the past 20 years owing to chronic unemployment in cities, deregulation of gold mining in Ghana, and the rising price of gold (Hilson & Clifford, 2010). As of 2010, it is estimated that over 10,000 men, women, and children are employed directly in the Talensi-Nabdam District's small-scale gold mines, making the industry an economic cornerstone of the district (Hilson, 2010).

This increase in small-scale gold mining in Ghana raises a number of public health concerns. Mineworkers and the surrounding community may be exposed to chemical agents present in gold ore or added for processing, such as mercury used to form amalgams (Aryee, 2003). Several pathways of inhalational exposure to crystalline silica may exist during ore processing. Based on observations by our team, miners often work without respiratory protection or protective gloves or boots. Sanitation infrastructure is often lacking. Healthcare services are often limited, as small-scale mining mostly occurs in impoverished areas (Barry, 1996). Officials cannot provide resources to unlicensed mining communities, which are illegal in Ghana, as they cannot collect taxes from mining activities (Hilson, Hilson, & Pardie, 2007).

The process of small-scale gold begins with the excavation of gold-containing ore. In northern Ghana, ore is often extracted from surface and shallow mining, and a small amount is recovered from panning in streams. Miners use dynamite to blast deep tunnels into the bedrock, and then extract ore manually using shovels or picks inside the tunnels. Ore is processed in one of two ways. If it does not visibly contain gold, it is processed using large generator-powered grinding machinery to produce a fine powder. If it does, it is crushed using a large mortar and pestle. The resulting powder is then sifted by hand, usually by women using a cloth over a basin. Pieces that do not fall through are further crushed and re-sifted. The powdered ore is then mixed with water to create an emulsified mixture. In the process of washing, also known as sluicing, the paste is rinsed with additional water over a strip of carpet on a ramp. The denser particles in the ore, including most of the gold, are captured in the carpet. A few grams at a time of this gold-containing mixture are then mixed with water in a rubber pan. The gold particles are gently separated out by hand swirling the pan. A few drops of elemental mercury are added to the gold particles to form a gold-mercury amalgam. The amalgam is then heated using a blowtorch to volatilize the mercury, leaving more concentrated, though not completely refined, gold.

The crushing, grinding, and sifting processes all generate dust, which is a potential source of inhalational exposure to silica. Crystalline silica content of dust associated with some gold ore can exceed 30% (Greenberg, Waksman, & Curtis, 2007). A study of two ASGM communities in northwestern Nigeria found that gold vein ores were dominated by crystalline silica (Plumlee et al., 2013). Long-term or high-level inhalation exposure to crystalline silica (SiO_2) can lead to the development of silicosis, an irreversible pulmonary fibrosis (Greenberg et al., 2007). Chronic silicosis, the most common form, develops 20 to 40 years after initial low to moderate initial silica exposures. Advanced silicosis can develop within five to 15 years after high initial exposures, and advanced silicosis can develop within a few weeks of very high exposures (Mason & Thompson, 2010). Silicosis classically is identified by the presence of bronchial opacities on chest radiographs. Exposure to silica can accelerate decrements to lung function, which can occur even in the absence of such opacities on a chest x-ray. Silicosis has been shown to accelerate substantial pulmonary function loss among miners, with the degree of the decrease proportional to the severity of silicosis (Ehrlich, Myers, Naude, Thompson, & Churchyard, 2011; Cowie, 1998).

In addition to exposure to silica via the mining process, members of this community can be exposed to biomass fuel (BMF) smoke. Cooking is often performed either outdoors or inside mud-brick dwellings without windows or roof ventilation, typically using BMF in coal pots or open fires. Women typically do the cooking, and are most likely to be exposed to BMF smoke. Infants and toddlers, who often accompany their mothers during cooking, are likely concomitantly exposed. Cooking smoke from BMF can affect respiratory health, especially when coupled with lack of ventilation

(Fullerton, Bruce, & Gordon, 2008). Studies among women who cook with BMF have shown a correlation between duration of BMF smoke exposure and a decline in pulmonary function (Regalado et al., 2006), an increased likelihood of developing chronic bronchitis (Dossing, Khan, & al-Rabiah, 1994; Ekici et al., 2005), as well as morbidity and mortality associated with the development of Chronic Obstructive Pulmonary Disorder (COPD) similar to that seen in tobacco smokers (Ramirez-Venegas et al., 2005). It should be noted that acute respiratory infections in children under five years of age comprise the largest single category of deaths from indoor air pollution from BMF (Smith & Mehta, 2003). It is also important to consider the contribution of tobacco smoke exposure in the development of COPD and other respiratory illnesses (Behera & Jindal, 1991).

Since 2009, our group has conducted studies to document exposures and the health status of workers and community populations to examine associations between exposures and adverse health effects in small-scale gold mining communities in the Talensi-Nabdam District of Upper East, Ghana (Paruchuri et al., 2010; Renne et al., 2011). In 2011, our team conducted a comparative study of a small-scale gold mining community, Kejetia, and a non-mining, subsistence farming community, Gorogo, in the same district that examined respiratory health in addition to other exposures and measures of health status. There are two main a priori areas of concern for potential adverse respiratory effects to workers and the surrounding community that we examined: 1) inhalational exposure to crystalline silica expected to be present in gold ore, which is directly associated with the mining process; and 2) the use of biomass fuels for cooking, associated with the general living conditions of such communities. We hypothesized that longer time spent in mining, as a proxy for silica exposure, and cooking with BMF will be associated with a decrease in pulmonary function.

4.2 Materials and methods

4.2.1 Study populations

Data were collected May-July 2011 from participants in a small-scale gold mining community, Kejetia, and one non-mining comparison community in the Talensi-Nabdam District in Ghana's Upper East Region. The non-mining community, Gorogo, was selected over other communities because of its lack of gold mining, comparable population size, ease of access, and its hydrologically upstream location relative to local gold mining sites. Institutional Review Board (IRB) approval was obtained through the University of Michigan (HUM00028444). Permission to work with the communities was given by each community's traditional chief.

4.2.2 Participant sampling strategy

Neither site had community maps, distinct village boundaries or official population estimates, creating challenges for random sampling. In both communities, households are defined as individuals that eat from the same "pot", in accordance with local cultural norms. In Kejetia, a set of coordinates was recorded for every household in the community using a handheld global positioning system (GPS; Oregon 450; Garmin International, Inc., Olathe, KS). Households were then assigned to twenty clusters of approximately 20 households each based on geographic proximity. Each household was then assigned a number within its cluster. Each day, households were selected by randomly pulling numbers from a bag. Up to three households were interviewed per day, each from a different cluster. Each cluster had two to three participating households in total. If a household was not eligible or declined participation, another number from within the cluster was pulled from the bag until an appropriate household was found. In Gorogo, the greater geographic dispersion of the community made definition of clusters not feasible. Instead, convenience sampling was done by spinning a plastic bottle at a landmark at the geographic middle of the community and selecting the house that the bottle pointed to most closely. The bottle was then spun from each participating household to find the next household to be surveyed, and from different geographic locations throughout the community. If a household was not eligible or declined participation, a replacement house was chosen by re-spinning the bottle in the same location as the previous spin. The convenience sampling method did appear to cover a substantial fraction of the geographic spread of the community.

4.2.3 Surveys

Surveys written in English were administered by a team of university students and verbally translated by local Ghanaian translators in the language of choice of the participants (Talen, Nabt, Gurune, Twi, Dagbani, English, or Hausa). Translators were trained prior to conducting interviews on the appropriate vocabulary and medical terms of health outcomes in the local languages. At each identified household, a request was made to identify the head of household (HOH). Preference for the interviews was given to the HOH, followed by their spouse or any adult (age 18 or older) who appeared knowledgeable about the individuals in the household. The HOH or identified alternative completed a survey on demographics and relationships of people in the household, as well as household characteristics and amenities, including cooking methods to assess BMF exposure. Participants were asked to list all cooking fuels ever used in the household as well as their main source of cooking fuel and cooking locations (to assess indoor and outdoor cooking, where indoor cooking locations included in the house and in a separate building).

A maximum of four adults per household, including the HOH, were administered a separate adult member survey, which included occupational history, smoking history, and respiratory symptoms, and spirometry was offered. When there were more than four adults, decisions on who to interview were made with guidance from the HOH. All the information in the current paper came from the household and adult member survey. Survey questions were adapted from the Ghana Demographic and Health Survey (Ghana Statistical Service and Ghana Health Service, 2009), the British Medical Research Council Questionnaire (MRCQ) on Respiratory Symptoms, and the American Thoracic Society's Epidemiology Standardization Project (Ferris, 1978). Participants were asked to give the number of years in each mining activity (excavation, crushing/grinding, sifting, washing, amalgamation, and burning). A composite variable was created to capture the minimum number of years a participant performed all mining activities ("minimum years mining"). Minimum years mining were split into two sets of mining activities to distinguish activities likely to have higher dust exposure (excavation, crushing, and sifting) from activities with lower dust exposure (washing, amalgamation, and burning). Current miners were defined as having engaged in a mining activity within the previous three months. Ex-miners have engaged in mining activities, but not within the previous three months.

4.2.4 Smoking

Smoking history was obtained for each participant, and included the year of starting smoking, current number of cigarettes smoked per day, number of years smoking, current smoking status, and pipe tobacco use. Participants were classified as current, ex, and never smokers. Those who had smoked less than 100 cigarettes in their lifetime were classified as never-smokers. In these populations, recall was difficult for many individuals regarding smoking history.

4.2.5 Respiratory symptoms

Participants were interviewed on a standard set of respiratory symptoms as well as history and treatment of asthma, tuberculosis (TB), and other respiratory illnesses. Symptom outcomes were defined as follows:

1. Usual cough: Answered yes to “do you usually cough first thing in the morning?” or “Do you usually cough during the rest of the day or at night?”
2. Cough longer than three months: Answered yes to “do you cough like this on most days/nights for as much as three or more months in each of the last two years?”
3. Usual phlegm production: Answered yes to “do you usually bring up any phlegm from your chest during the day or at night?”

4. Phlegm production longer than three months: Answered yes to “do you bring up phlegm like this on most days/nights for as much as three or more months in each of the last two years?”
5. Chronic bronchitis: Answered yes to symptom 2 (cough longer than three months) and to symptom 4 (phlegm production longer than 3 months).
6. Breathlessness when walking: Answered yes to “do you get short of breath walking with other people of your own age on level ground?”
7. Severe breathlessness when walking: Answered yes to “do you have to stop for breath when walking at your own pace on level ground?”
8. Wheezing: Answered yes to “have you had this wheezing or whistling when you did not have a cold or flu?”
9. Chest tightness: Answered yes to “have you been woken up with a feeling or tightness in your chest at any time in the last 12 months?”
10. Shortness of breath: Answered yes to either “have you had an attack of shortness of breath that came on during the daytime when you were at rest at any time in the last 12 months?” Or “have you been woken by an attack of shortness of breath at any time in the last 12 months”?

4.2.6 Pulmonary function assessments

Pulmonary function assessments were performed using EasyOne Diagnostic spirometers (NDD Medical Technologies, Andover, MA) following American Thoracic (ATS) guidelines (Miller et al., 2005; ATS, 1995). The lung function indices of primary interest are the Forced Expiratory Volume in the first second (FEV_1) and the Forced Vital

Capacity (FVC) of the maneuver. The FEV_1 represents the amount of air a person blows out in the first second after a blowing out a deep breath hard and fast. The FVC represents the total amount of air a person exhales. Study personnel demonstrated spirometry maneuvers for each participant. Participants were able to stop after they performed three maneuvers (i.e., blows) correctly, and performed up to six maneuvers per session if initial maneuvers were considered invalid. The spirometers stored data on the best three exhalation maneuvers. All devices were verified to be properly calibrated at the beginning of the study. Study staff analyzed all recorded maneuvers for validity. Each participant's session of maneuvers was rated based on reproducibility of maneuvers, with a reproducible cut off of <0.15 L for FEV_1 and FVC between blows (Miller et al., 2005; American Thoracic Society, 1995). Participants were not excluded from analysis for a failure to meet reproducibility requirements. Weight was measured using a bathroom scale and height was measured without shoes using a measuring stick fixed to a level platform. Age, weight, and height were recorded for each participant before performing maneuvers.

Prediction equations for FEV_1, FVC, and the FEV_1/FVC ratio are based on the National Health and Nutrition Examination Survey (NHANES) III equations for African Americans adults (Hankinson, Odencrantz, & Fedan, 1999). The lower limit of normal (LLN) for FEV_1, FVC, and the FEV_1/FVC ratio are based on the lower fifth percentile of normal performance based on this NHANES III population. The LLN was used to assess abnormality instead of an arbitrary cut off of 70% of predicted to reduce any overestimation of dysfunction that may occur in older individuals (Pellegrino et al., 2005).

4.2.7 Statistical analyses

Data were entered and analyzed in Microsoft Excel (v. 2010) and SPSS v. 21 (IBM). The outcome variables of interest were respiratory symptoms and percent predicted pulmonary function measurements FEV_1, FVC, and FEV_1/FVC. The exposure variables of interest included mining, smoking status and pack-years, and type of primary cooking fuel. Statistical significance was assessed as $\alpha = 0.05$. Linear regressions of PFTs did not include covariates of age or height, as these are accounted for in the prediction equations. Because of differential sex roles in cooking, however, sex was included in linear regression models.

4.3 Results

4.3.1 Demographics and mining

Fifty-four households from Kejetia and 27 households from Gorogo participated in the study. There were 172 participants total: 97 from Kejetia and 75 from Gorogo. The number of persons participating per household varied from one to four. Fifty-two percent of participants in Kejetia and 45% in Gorogo were male. Very few individuals refused participation, and most individuals cited lack of time as the main reason. No individuals refused for reasons obviously related to health status.

Participant demographic are detailed in Table 4.1. Gorogo had a higher mean age than Kejetia. Mean BMI was similar between the two populations, but Gorogo had a higher prevalence (16.2%) of underweight (BMI < 18.5) participants than Kejetia (5.2%) (data not shown). Seventy-one percent of residents from Kejetia reported current involvement in mining activity. Because there was only one Gorogo participant who was classified as a current miner, she was excluded from analyses for consistency. Nearly all participants in Gorogo reported farming as their current occupation (94.7%), compared to only 7.2% in Kejetia. Cooking as an occupation was more common in Kejetia (15.5%) than in Gorogo (4.0%).

In Kejetia, the mean minimum number of years in any mining activity was 8.00 (± 7.03) for males and 2.93 (± 4.92) for females (Table 4.1). Of Kejetia current miners, the mean minimum number of years in any mining activity was 7.3 (± 6.7) years, with 31.4% mining for greater than a minimum of ten years and 47.1% greater than a minimum of five years (data not shown). The mean minimum number of years was 6.6 (±6.1) in excavation, crushing or sifting, and 5.5 (±6.7) in washing, amalgamation and burning for Kejetia current miners. Kejetia and Gorogo ex-miners (n=4 and n=10, respectively) had lower mean minimum numbers of years in any mining activity (5.6 ± 7.1 years and 4.6 ± 3.5 years, respectively) than Kejetia current miners. There was a significant correlation for years spent in excavation to years in crushing, washing, and amalgamation; crushing to washing and amalgamation; and washing to amalgamation for all ever miners and Kejetia ever-miners (r for pair comparisons ranged from 0.700 to 0.946; all had $p < 0.001$). For Gorogo ex-miners, years spent in excavation to washing and owning; crushing to sifting; washing to amalgamation, burning and owning; and amalgamation to burning were significantly correlated to each other (r for pair comparisons ranged from 0.770 to 0.965; all had $p < 0.001$).

4.3.2 Smoking

In Kejetia, 30% of males and no females were current smokers, and in Gorogo, 38.2% of males and 2.4% of females were current smokers (Table 4.1). Mean pack-years for ever-smokers was significantly higher in Kejetia than in Gorogo (16.8 and 3.9, respectively), and higher in Kejetia among current smokers than among ex-smokers (18.0 and 9.0, respectively; data not shown). In Kejetia, all current smokers reported having done some mining activity. Never smokers were younger than current smokers in both communities (mean of 30 and 38 years in Kejetia, respectively, and 49 and 54 years in Gorogo, respectively), and current smokers younger than ex-smokers (62 years) in Gorogo. Percent predicted pulmonary function test (PFT) measurements (FEV_1, FVC, and FEV_1/FVC) were not significantly different for current, ex and never smokers in Kejetia or Gorogo (data not shown). Pipe tobacco use was uncommon; only two males in Kejetia and one male in Gorogo reported ever having used pipe tobacco regularly.

4.3.3 Spirometry maneuvers and pulmonary function tests

Among the 172 participants, 159 attempted to perform spirometry maneuvers. Ten of those who did not perform spirometry refused. Four refused because of health reasons (such as feeling ill or pregnancy). No participants refused based on a report of breathing problems. Other reasons for refusing included religious fasting and difficulty with correctly performing the forced exhalation maneuver during preliminary practice. Current and ex-miners were combined as ever-miners for analyses of PFTs, as there was only one valid FEV_1 and FVC measurement for females and one valid FEV_1 for males in Kejetia.

There were a greater number of valid FEV_1 measurements (119 of the 159 sessions) than FVC measurements (95 sessions), because a number of participants performed the maneuver correctly during the first couple of seconds, but failed to continue blowing long enough for a reliable FVC (data not shown). Valid maneuvers for FEV_1 and FVC were slightly higher in Kejetia than Gorogo (FEV_1: 78.0% and 70.6%, and FVC: 62.6% and 55.9% in Kejetia and Gorogo, respectively). Males had higher frequencies of valid FEV_1 and FVC maneuvers than females in both communities, except FVC in Kejetia is approximately equal between sexes.

Based on the NHANES prediction equations for healthy U.S. African Americans, the mean percent predicted FEV_1, FVC, and FEV_1/FVC were not significantly different for Kejetia and Gorogo by sex, nor when comparing never and ever-miners in Kejetia (Table 4.2). The mean PFT measurements were lower than predicted for a healthy population, although they were similar for males and females in Kejetia and Gorogo, except percent predicted FEV_1 was lower for Gorogo males than females (p=0.276). Although the sample size is limited, Kejetia male ever-miners have a significantly smaller percent predicted FEV_1/FVC ratio than never miners (p=0.002). When comparing Kejetia participants' PFT measurements between those who have ever engaged in any type of mining activity and those who have not, no significant differences were observed, although those who had ever done excavation (n=23) had mean percent predicted FEV_1/FVC ratios nearly significantly lower as compared to those who had not (n=30; FEV_1/FVC were 91.2 ± 11.8 and 96.4 ± 5.5, respectively, p=0.06).

Using the NHANES prediction equation for the lower limit of normal (LLN) (based on a cutoff of 5% of a healthy population, equal to approximately two standard deviations below the mean), the prevalence of PFTs below the LLN was elevated among Gorogo participants and Kejetia females for FEV_1 and FEV_1/FVC (Table 4.2). FEV_1 and FEV_1/FVC ratio abnormality were higher in Gorogo than in Kejetia. In Kejetia, females had higher rates of abnormal FEV_1 and FEV_1/FVC ratios than males. The percent predicted FEV_1 in Gorogo and percent predicted FEV_1/FVC ratio abnormality in Kejetia and Gorogo were significantly increased from 5%. No participants had abnormal FVC measures, except for Gorogo females. Abnormal lung function varied with age with no obvious trend (data not shown).

4.3.4 Reported history of respiratory diseases

Two participants reported ever having had tuberculosis, and three participants reported ever having had asthma. Usual cough, usual phlegm production, chest tightness, and shortness of breath were the most common respiratory symptoms (Table 4.3). Usual phlegm and phlegm production for more than three months were more common in Kejetia than Gorogo. The prevalence of many symptoms in Kejetia and Gorogo were similar between males and females, except for cough for longer than three months in Kejetia and breathlessness and severe breathlessness when walking in Gorogo. In bivariate analyses, no symptoms of interest were significantly associated with any of the measures of pulmonary function (percent predicted FEV_1, FVC, FEV_1/FVC) (data not shown). When stratified by mining activity involvement in Kejetia, only phlegm production for longer than three months, chronic bronchitis, breathlessness when walking, severe breathlessness when walking, and shortness of breath were significantly correlated with a mining activity, in different directions (Table 4.4). Mean percent predicted FEV_1, FVC, FEV_1/FVC were not significantly associated with mining involvement overall and by specific mining activity (data not shown).

4.3.5 Cooking smoke

The most commonly used cooking fuels were charcoal, wood, and crop residues (by 146, 110, and 64 households, respectively, across the two locations), and these were the only fuel sources used as the primary source for cooking (Table 4.5). Only participants living in Gorogo used crop residues for cooking. Electricity, kerosene, biogas, straw, and animal dung were not used by any participants. LPG and natural gas were used by only a few households (four and two, respectively). Seven male participants in Kejetia lived in households that only purchased food from vendors rather than cooking. All male and female participants in Gorogo cooked indoors (including in the house or in a separate building), whereas in Kejetia, 36.2% of female participants and 25.6% of male participants cooked indoors (three participants cooked both indoors and outdoors). Charcoal was almost exclusively used in a coal pot (98.8%), while wood and crop residues were exclusively used in open fires (data not shown). In Kejetia, charcoal was primarily used outdoors (82.1%), while half (52.5%) of wood users cooked outdoors. In Gorogo, however, charcoal, wood, and crop residues were used exclusively indoors. All Gorogo participants' households cooked in a room serving separately as a kitchen, compared to 23.3% of Kejetia participants (data not shown).

In bivariate analyses among Kejetia participants, there were no significant differences in PFTs by cooking fuel use or stove type (data not shown). In analyses restricted to Kejetia males, percent predicted FEV_1 was significantly higher for cooking indoors (97.7 ± 12.9%, n=5) compared to not cooking indoors (86.7 ± 10.1%, n=28, p=0.038), excluding non-cooking males.

In Gorogo, mean percent predicted FEV_1/FVC were significantly lower for main use of an open fire (87.7 ± 13.0%, n=32) compared to coal pot use (100.7 ± 2.4%, n=5, p = 0.034) (data not shown). Similarly, the mean percent predicted FEV_1/FVC ratio was significantly lower for main wood fuel (85.0 ± 13.9%, n=23) compared to participants using charcoal or crop residue (96.8 ± 5.9%, n=14, p=0.001) in Gorogo. For Gorogo females, percent predicted FEV_1 was significantly lower for any use of charcoal fuel and any coal pot use (82.8 ± 22.7% for both, n=16), as compared to no charcoal or coal pot use (103.8 ± 16.6%, n=8, p=0.030). This difference, however, was not significant when comparing charcoal or coal pot as the main method versus other cooking fuels and stove types.

4.3.6 Regression analyses

Regression analyses were conducted for numerous models—four models for each PFT measure: all participants, separately for the two communities, and restricted to those reporting ever-mining involvement. Linear regressions for all participants included covariates of sex; smoking status (current and ex, versus never); main wood cooking fuel use, main crop residue cooking fuel use (charcoal as the reference category); the minimum years of mining in excavation, crushing, or sifting; and Gorogo community participant (Kejetia participants as reference) (Table 4.6). Regression models of each community excluded the community covariate and models of Kejetia participants excluded main crop residue cooking fuel use, as no Kejetia participants used crop residues.

Models of all Kejetia participants and ever-miners showed no significant associations with percent predicted PFTs with any covariates (Table 4.6). In Gorogo, there was a significant association only between wood cooking fuel for the percent predicted FEV_1/FVC ratio (β=-18.3, p=0.01).

For each respiratory symptom, three logistic models (not including those restricted to reporting ever mining involvement) were examined for those with ten or more participants reporting the respiratory symptom in question. Logistic regression for respiratory symptoms included the same covariates and, in addition, age (Table 4.7). Logistic regressions were only conducted for usual cough, usual phlegm production, phlegm production longer than three months, breathlessness when walking, severe breathlessness when walking, wheezing, chest tightness, and shortness of breath.

Logistic regression models (Table 4.7) showed mixed results for Kejetia and Gorogo. Minimum years mining in excavation, crushing, or sifting was counter-intuitively significantly associated with chest tightness (OR: 0.905; CI: 0.825, 0.992) and shortness of breath (OR: 0.882; CI: 0.783, 0.993) in Kejetia. This counter-intuitive, seemingly protective relationship of mining was also seen with usual cough, usual phlegm production, and wheezing in Kejetia and all participants. Chest tightness had a significant association with wood cooking fuel compared to charcoal fuel (OR: 3.83; CI: 1.11, 13.2) in Kejetia. Current smoking status as compared to never smoking had a significantly elevated odds of usual cough (OR=6.47; CI: 1.13, 37.0) (not shown on table), but no other significant associations for Kejetia participants. In Gorogo, crop residue cooking fuel use had markedly lower odds of usual cough than charcoal cooking fuel use (OR=0.040; CI: 0.004, 0.424). Current and ex-smoking status were only associated with greater odds of chest tightness (OR=12.8; CI: 1.18, 138; and OR: 30.4; CI: 2.10, 439; respectively) in Gorogo. No covariates had any significant associations with shortness of breath in Gorogo.

4.4 Discussion

The aim of this study was to determine the impact of small-scale gold mining involvement and biomass fuel smoke on pulmonary function and respiratory health. We did observe higher rates of abnormal percent predicted FEV_1 and FEV_1/FVC measures than the lower fifth percentile of normal performance based on healthy U.S. African American adults (Pelegrino et al., 2005). In Kejetia, this trend is driven by lower percent predicted values among the female participants. Restrictive lung diseases are characterized by reduced FEV_1 and FVC, while the FEV_1/FVC ratio may be normal or slightly increased (Pellegrino et al., 2005). Obstructive diseases like COPD are marked by a reduction in FEV_1 in relation to the FVC, causing a reduced FEV_1/FVC ratio, namely below the LLN (Pellegrino et al., 2005). Silicosis can cause both restrictive and obstructive disease patterns as it develops (Greenberg et al., 2007). These rates of abnormality suggest higher obstructive disease to be apparent in both communities.

The prevalence of usual cough and breathlessness when walking are lower in Kejetia than other studies of rural and urban adults have observed (Gamsky, Schenker, McCurdy, & Samuels, 1992, Gallotti et al., 2006; Nriagu et al., 1999). Chronic bronchitis and shortness of breath prevalence in Kejetia is similar to some other studies among rural

Canadian swine farmers (Dosman et al., 1988) and urban South African adults (Nriagu et al., 1999). Usual phlegm production, usual phlegm production for longer than three months, and wheezing are higher in Kejetia than found in other groups of rural and urban adults (Dosman et al., 1988; Gallotti et al., 2006; Nriagu et al., 1999). In Gorogo, cough for longer than three months, usual phlegm production, usual phlegm production for longer than three months, chronic bronchitis, breathlessness when walking, wheezing, and shortness of breath are all generally lower than other potentially exposed and non-exposed groups (Gamsky et al., 1992; Gallotti et al., 2006; Nriagu et al., 1999; Dosman et al., 1988).

Analyses did not show an obvious relationship between mining involvement and pulmonary function abnormality. Bivariate analyses of PFT measures did not show a clear pattern, although participants that had engaged in mining activities generally had minimally higher FEV_1, FVC, and FEV_1/FVC measures than those with no mining involvement. Similarly, linear regressions were in the counter-intuitive direction for FEV_1 and FEV_1/FVC for Kejetia and Gorogo, but not significantly associated with decrements in lung function. Bivariate analyses of respiratory symptoms and mining involvement in Kejetia were also often in the counterintuitive direction (i.e., symptoms less common in those having reporting participation in mining activities compared to never participating), with the exception of chronic bronchitis, breathlessness and severe breathlessness when walking.

One should be circumspect in over-interpreting these seemingly negative results. We suspect that the ore dust to which miners are exposed contains silica, but do not have any data on this. The latency period for silicosis development is longer than most people in Kejetia have resided there, so some potential effects of this exposure may not yet be apparent. Kejetia is a younger, more transient population with only 31.4% of miners having mined for greater than a minimum of ten years and 47.1% having done a minimum of five years of mining. Since chronic silicosis, the most common form, typically appears 20 to 40 years after initial exposure to respirable silica dust, it is possible that these miners are too early in their mining careers to show pulmonary function changes associated with silicosis. While accelerated silicosis can develop within five to 15 years of initial exposure to respirable silica dust, the exposure to respirable silica, which is unknown in this study, may not be great enough to cause this heightened effect (Mason & Thompson, 2010). It is possible that this elevated FEV_1/FVC ratio abnormality is an early sign of pulmonary obstruction, which is characterized by a reduced FEV_1/FVC ratio (Pellegrino et al., 2005). The Healthy Worker Effect may also place a selection bias on participants in Kejetia, as adults with pulmonary dysfunction may not be able to continue mining and may choose to leave the community and return to a familial village.

Smoking, rarely practiced by females, was slightly more common among Gorogo than Kejetia participants. Smoking pack-years were lower in Kejetia and Gorogo than in U.S. American populations (Center for Disease Control and Prevention, 2005), which may explain the relatively low associations with respiratory outcomes. Chronic respiratory symptoms of cough, phlegm production, and breathlessness have been reported more often among smokers in a small Italian community (Gallotti et al., 2006), which may explain the significantly elevated odds ratio for current smokers and ex-smokers to have a usual cough in Kejetia.

Our analyses showed some associations between use of biomass fuels like charcoal and wood and adverse respiratory symptoms and reduced pulmonary function in the Gorogo population and in some Kejetia models. Main wood fuel use was associated with a significant decrease in the percent predicted FEV_1/FVC ratio in Gorogo. In Kejetia, cooking fuel use was not significantly associated with decrements in PFTs. In Gorogo, use of wood cooking fuel had a 25 times lower odds (CI: 0.004, 0.424) of a usual cough than using charcoal. Wood cooking fuel had a 3.83 times higher odds (CI: 1.11, 13.2) of chest tightness than using charcoal cooking fuel in Kejetia. Wood cooking fuel did have slightly elevated odds ratios for other respiratory symptoms in Kejetia, but were not statistically significant. Other studies have also observed elevated odds of respiratory symptoms from wood cooking fuel use (Zelikoff, Chen, Cohen, & Schlesinger, 2002; Titcombe & Simcik, 2011; Lisouza et al., 2011; Oanh, Reutergardh, & Dung, 1999; Partnership for Clean Indoor Air, 2012).

There is strong evidence of the influence of BMF smoke on negative respiratory health and pulmonary function (Regalado et al., 2006; Ramirez-Venegas et al., 2006; Ekici et al., 2005; Zelikoff et al., 2002), and the type of biomass fuel may also play a significant role. BMF smoke has been associated with increased chronic bronchitis (Ekici et al., 2005), and chronic wood smoke exposure has specifically been associated with chronic bronchitis and pulmonary fibrosis (Zelikoff et al., 2002). A study with Malawian adults found that adults using wood as their primary cooking fuel had significantly worse lung function than adults using charcoal, and that wood use was a significant predictor of FEV_1 (Fullerton et al., 2011). Wood BMF was associated with pulmonary dysfunction measured from FEV_1, FVC, and FEV_1/FVC and airway inflammation in Nigerian adults

(Oluwole et al., 2013). A Nepalese study of adults found that participants using biomass fuel were twice as likely to have an FEV_1/FVC ratio below the LLN (8.1%) than those using LPG (3.6%) (Kurmi et al., 2013). Studies examining air pollution and biomass fuels (BMFs) have found that particulate matter (PM) and polycyclic aromatic hydrocarbons (PAHs), which both have adverse health effects, were higher for wood and charcoal fuel than crop residues, kerosene/charcoal mixes, and liquid petroleum gas (LPG) (Titcombe & Simcik, 2011; Lisouza et al., 2011), and another found PAH and PM emissions from wood to be close to double that of charcoal (Oanh et al., 1999; Partnership for Clean Indoor Air, 2012). A study in Malawi and Nepal comparing total inhalable endotoxins, which have been associated with respiratory illnesses, found that endotoxin levels were higher in homes using wood fuel than homes using charcoal fuel (Semple et al., 2010).

Sex is anecdotally important in predicting exposure to BMF smoke, as women do the majority of cooking in both communities. Early life exposures to BMF smoke may be common for all participants, which may explain decreased pulmonary health but the lack of significant associations when all participants are exposed. Because participants in Gorogo cook almost exclusively indoors using an open fire, where there is little or no ventilation, the effect of BMF smoke on pulmonary function may be greater than observed in Kejetia, where cooking is done primarily outdoors. In Kejetia, abnormal FEV_1 and FEV_1/FVC is higher among females than males, and in Gorogo, FVC and FEV_1/FVC are higher among females than males. This difference may be due to the differential sex roles in cooking.

It is possible that the prediction equations may not be appropriate for the study participants, as they are based on U.S. African Americans. However, given the West African ancestry of many African Americans, the equations may be a better fit than using a South African equation, for example. A study of male Ghanaian gold miners found that the European Community for Steel and Coal (ECSC) equations fit better than other African prediction equations, but still needed a conversion factor of 0.87 (Bio, Sandhra, Jackson, & Sherwood Burge, 2005). While U.S. African American NHANES equations may be better fitting of available prediction equations, they may still be inadequate for our population. Increased rates of abnormal percent predicted FEV_1 and FEV_1/FVC measures in Gorogo emphasize that other exposures or factors may be decreasing respiratory health and pulmonary function.

A number of limitations may have affected the results of our study. A set of criteria was established to ensure the comparison community was as comparable to Kejetia as possible, but choices among communities were limited, and there were substantial differences in the population structure between Kejetia and Gorogo. For many older participants in Gorogo, difficulty performing the spirometry maneuver may have skewed the results. Final regression models attempted to adjust for the differences between these communities. Inaccuracies in translation may have compromised the information relayed between participants and researchers during performance of the maneuvers and during surveys, but the entire research team was trained prior to collecting spirometry data to reduce this problem.

As we did not have information on the total number of years that miners did excavation, crushing, and/or sifting, we used a variable of the minimum number of years doing any one of those activities. This may not have accurately captured the actual length of time that participants were involved in these activities. Since participants were not clinically evaluated by medical professionals, there may have been false reporting and an information bias in reported respiratory symptoms. Smoking pack-years were calculated based on the assumption that an individual smoked the same number of cigarettes on average throughout the entirety of his/her smoking period. In a resource-limited setting lacking basic sanitation, infrastructure, and access to healthcare, a variety of other unforeseen health problems may have also confounded results.

4.5 Conclusion

This study is the first to investigate pulmonary function and respiratory symptoms with small-scale miners, to the authors' knowledge. In a setting where there are multiple stressors from occupational and household activities, it is difficult to isolate causes of respiratory dysfunction. However, our study demonstrates that pulmonary obstruction is elevated in both the small-scale gold mining and subsistence farming communities. This may be due to mining or biomass fuel smoke exposures, but also may result from inadequate pulmonary function prediction equations for the Upper East Ghanaian populations. Further research is needed with larger sample sizes and with more detailed questionnaires to further assess the impact of multiple stressors on respiratory health in small-scale mining communities.

Tables

Table 4.1 Demographic, occupational, and smoking information for Kejetia and Gorogo participants by sex.

		Kejetia		Gorogo	
		Male	Female	Male	Female
n participants		50	47	34	41
Age (years)	Mean (SD)	32.0 (8.9)	30.8 (12.6)	54.2 (18.7)	49.3 (18.9)
BMI[a]	Mean (SD)	22.1 (2.5)	23.4 (3.7)	20.9 (2.7)	22.4 (3.4)[b]
Height (cm)	Mean (SD)	171 (7)	162 (6)	169 (6)	161 (7)
Occupation[c]					
	Current Miner[d]	86.0%	59.6%	0.0%	0.0%
	Ex-Miner[d]	2.0%	6.4%	14.7%	12.2%
	Farmer	8.0%	6.4%	97.1%	92.7%
	Cook[e]	0.0%	31.9%	0.0%	7.3%
	Vendor	8.0%	29.8%	2.9%	14.6%
	Other	8.0%	17.0%	11.8%	7.3%
Minimum Years Mining[f]	Mean (SD)	8.00 (7.03)	2.93 (4.92)[g]	0.62 (1.65)	0.61 (2.25)
Smoking Status					
	Current Smokers	30.0%	0.0%	38.2%	2.4%
	Ex-Smokers	14.0%	0.0%	26.5%	0.0%
	Never Smoked	56.0%	100.0%	35.3%	97.6%
Pack years[h]	Mean (SD)	16.8 (27.2)	-	4.2 (2.0)	0.5

[a] BMI is body mass index, calculated by: weight(kg)/height(m)^2

[b] n = 40 for Gorogo: Female

[c] Participants were able to select more than one occupation

[d] Current miners engaged in a mining activity within the last 3 months

[e] This includes individuals that cook food or pito, an alcoholic beverage made from millet

[f] Minimum years in any mining activity (excavation, crushing, sifting, washing, amalgamation, burning, or owning)

[g] n=46 for Kejetia: Female

[h] Pack years of ever (current and ex) smokers

Table 4.2 Mean percent predicted FEV_1, FVC, and FEV_1/FVC values and percent abnormalities by sex and mining status among Kejetia participants.

		Percent Predicted FEV_1			Percent Predicted FVC			Percent predicted FEV_1/FVC		
Population		*n*	Mean (SD)	Abnormal[a]	*n*	Mean (SD)	Abnormal[a]	*n*	Mean (SD)	Abnormal[a]
Kejetia	Male	40	89.4 (12.3)	7.5%	30	92.7 (11.9)	0.0%	29	94.5 (9.0)	3.4%
	Female	31	87.8 (12.7)	12.9%	27	92.9 (10.9)	0.0%	24	93.7 (9.4)	20.0%
Gorogo	Male	24	83.5 (16.0)	25.0%	22	94.6 (12.8)	0.0%	21	89.7 (13.3)	23.8%
	Female	24	89.8 (22.8)	20.8%	16	94.8 (21.7)	6.3%	16	89.1 (12.7)	25.0%
Kejetia Miners:										
Never Miners	Male	5	93.8 (20.2)	0.0%	5	92.7 (20.7)	0.0%	5	102.1 (3.8)[b]	0.0%
	Female	9	88.8 (9.4)	11.1%	10	94.3 (10.8)	0.0%	8	91.0 (4.5)	11.1%
Ever-Miners	Male	35	88.7 (11.1)	8.6%	25	92.7 (10.0)	0.0%	24	92.9 (9.0)	4.2%
	Female	22	87.4 (14.0)	13.6%	17	92.0 (11.2)	0.0%	16	95.1 (10.9)	25.0%

[a] Abnormality defined as a PFT measure below the lower limit of normal (LLN) defined by NHANES

[b] Independent T-test comparing never miners to ever-miners in Kejetia for PFTs (stratified by sex); p-value < 0.05

Table 4.3 Percent of respiratory symptoms in Kejetia and Gorogo for each community and stratified by sex.

	Kejetia (%)		Gorogo (%)	
Symptom	Male	Female	Male	Female
Usual cough	32.0	23.4	26.5	34.1
Cough longer than three months	12.0	6.4	0.0	0.0
Usual phlegm production	40.0	39.1	8.8	7.3
Phlegm production longer than three months	20.0	25.5	2.9	4.9
Chronic bronchitis	8.0	4.3	0.0	0.0
Breathlessness when walking	8.0	4.3	5.9	14.6
Severe breathlessness when walking	6.0	10.6	2.9	17.1
Wheezing	16.0	14.9	5.9	4.9
Chest tightness	50.0	55.3	32.4	34.1
Shortness of Breath	28.0	29.8	14.7	17.1

Table 4.4 Respiratory symptoms by mining activity in Kejetia.[a]

		Usual cough	Cough > 3 mo.	Usual phlegm	Phlegm > 3 mo.	Chronic bronchitis	Breath -lessness[b]	Severe breath -lessness[b]	Wheezing	Chest tightness	Shortness of breath
	n	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
Any mining activity	75	29.3	9.3	41.9	9.1*	8.0*	8.0*	10.7**	14.7	46.7	30.7
No mining activity	22	22.7	9.1	31.8	26.7	0.0	0.0	0.0	18.2	50.0	22.7
Excavated	40	27.5	10.0	22.5	22.5	10.0	5.0	2.5	12.5	45.0	15.0**
Never excavated	57	28.1	8.8	22.8	22.8	3.5	7.0	12.3	17.5	57.9	38.6
Crushed	45	33.3	13.3	48.9	28.9	11.1	6.7	4.4	20.0	53.3	26.7
Never crushed	52	23.1	5.8	31.4	17.3	1.9	5.8	11.5	11.5	51.9	30.8
Sifted	45	31.1	11.1	45.5	13.5*	11.1	4.4	11.1	15.6	55.6	33.3
Never sifted	52	25	7.7	34.6	33.3	1.9	7.7	5.8	15.4	50.0	25.0
Washed	46	21.7	10.9	41.3	28.3	10.9	4.3	6.5	15.2	52.2	21.7
Never washed	51	33.3	7.8	38.0	17.6	2.0	7.8	9.8	15.7	52.9	35.3
Amalgamated	49	22.4	10.2	35.4	24.5	8.2	4.1	8.2	12.2	55.1	24.5
Never amalgamated	48	33.3	8.3	43.8	20.8	4.2	8.3	8.3	18.8	50.0	33.3
Burned	31	22.6	9.7	29.0	16.1	6.5	9.7	9.7	9.7	51.6	25.8
Never burned	66	30.3	9.1	44.6	25.8	6.1	4.5	7.6	18.2	53.0	30.3
Owned	18	27.8	5.6	28.6	16.7	5.6	0.0*	0.0**	16.7	44.4	22.2
Never owned	79	27.8	10.1	42.7	24.1	6.3	7.6	10.1	15.2	54.4	30.4

[a] Independent T-test comparing participants' respiratory symptoms that have engaged in the mining activity to those that have not engaged in them

[b] Breathlessness when walking

* $p < 0.05$

** $p < 0.01$

Table 4.5 Cooking fuel sources, stove types, and cooking location by community and sex.

	Kejetia				Gorogo			
	Female		Male		Female		Male	
	n	Percent	n	Percent	n	Percent	n	Percent
Main Fuel Source								
Charcoal	32	68.1	35	72.9	8	19.5	5	14.7
Wood	15	31.9	6	12.5	21	51.2	22	64.7
Crop Residue	0	0.0	0	0.0	12	29.3	7	20.6
No Cooking	0	0.0	7	14.0	0	0.0	0	0.0
Main Stove Type								
Open fire	15	31.9	6	14.0	34	82.9	29	85.3
Coal pot	32	68.1	35	81.4	7	17.1	5	14.7
Open stove	0	0.0	2	4.7	0	0.0	0	0.0
Location								
Indoors[a]	17	36.2	11	25.6	41	100.0	34	100.0
Outdoors	33	70.2	33	76.7	0	0.0	0	0.0
Rooms per household								
1-5	46	97.9	48	96.0	14	34.1	7	20.6
>5	1	2.1	2	4.0	27	65.9	27	79.4

[a] Indoors includes in the house or in a separate building

Table 4.6 Linear regression results for percent predicted FEV_1, FVC, and FEV_1/FVC. Each line represents a separate model. Charcoal cooking fuel is included in Kejetia models and wood and crop residue cooking fuels included in Gorogo models.

				Min. years mining[b]		Wood cooking fuel[c]		Crop residue cooking fuel [c]	
	Model[a]	n	Adjusted R^2	β	p-value	β	p-value		
Percent Predicted FEV_1	All	111	-0.047	0.272	0.45	-3.31	0.44	-2.59	0.68
	Gorogo	48	-0.061	0.299	0.84	-15.1	0.15	-13.2	0.23
	Kejetia	63	-0.610	0.083	0.80	2.50	0.53	-	-
	Kejetia ever-miners	51	-0.089	0.081	0.83	0.597	0.91	-	-
Percent Predicted FVC	All	89	-0.059	-0.164	0.65	2.38	0.57	-1.38	0.83
	Gorogo	38	-0.171	-0.044	0.97	-0.741	0.94	-4.97	0.63
	Kejetia	51	0.014	-0.357	0.27	5.10	0.21	-	-
	Kejetia ever-miners	38	-0.004	-0.548	0.14	6.86	0.18	-	-
Percent Predicted FEV_1/FVC	All	84	0.038	0.085	0.76	-5.14	0.11	2.78	0.57
	Gorogo	37	0.129	0.718	0.42	-18.3	0.01	-6.56	0.35
	Kejetia	47	-0.129	0.061	0.82	0.330	0.92	-	-
	Kejetia ever-miners	36	-0.129	0.044	0.90	0.598	0.90	-	-

[a] Each row represents a separate model. Covariates included in the models are sex and current and ex-smoking status (never-smoking as reference) for all models. Models of all participants include a covariate to account for Gorogo community participants.

[b] Minimum years of mining in excavation, crushing or sifting.

[c] Main fuel source (charcoal fuel as reference). Crop residue only included in models of all and Gorogo participants. Kejetia models excluding 7 male miners that do no cooking in their household.

Table 4.7 Logistic regression of respiratory symptoms. Each line represents a separate model. Charcoal cooking fuel is included in Kejetia models and wood and crop residue cooking fuels included in Gorogo and combined models.[a]

			Respiratory Symptom	Nagelkerke	Min. years mining[c]		Wood cooking fuel[d]		Crop Residue cooking fuel[d]	
Model[a]	Respiratory Symptom	N	n[b]	R^2	OR	95% CI	OR	95% CI	OR	95% CI
All	Usual Cough	162	47	0.126	0.985	(0.904, 1.07)	0.666	(0.278, 1.60)	0.065	(0.007, 0.588)
	Usual phlegm production	161	41	0.263	0.958	(0.881, 1.04)	1.67	(0.628, 4.44)	2.76	(0.362, 21.1)
	Phlegm production longer than 3 months	162	24	0.198	1.00	(0.915, 1.10)	1.97	(0.668, 5.82)	3.06	(0.208, 45.0)
	Breathlessness when walking		13	0.135	1.06	(0.933, 1.20)	3.56	(0.666, 19.1)	7.96	(0.791, 80.0)
	Severe breathlessness when walking		14	0.139	1.06	(0.940, 1.20)	0.840	(0.189, 3.74)	1.97	(0.268, 14.5)
	Wheezing		17	0.135	0.981	(0.879, 1.09)	1.87	(0.518, 6.75)	7.04	(0.611, 81.1)
	Chest tightness		73	0.145	0.945	(0.876, 1.02)	2.13	(0.875, 5.20)	4.41	(1.17, 16.6)
	Shortness of breath		38	0.109	0.936	(0.856, 1.02)	1.73	(0.661, 4.50)	1.95	(0.356, 10.6)
Gorogo	Usual Cough	75	23	0.259	1.15	(0.841, 1.57)	0.355	(0.082, 1.54)	0.040	(0.004, 0.424)
	Chest tightness		25	0.227	1.07	(0.810, 1.42)	2.10	(0.372, 11.9)	4.75	(0.772, 29.2)
	Shortness of breath		12	0.104	1.15	(0.864, 1.54)	-	-	-	-
Kejetia	Usual Cough	87	24	0.102	0.934	(0.836, 1.04)	1.10	(0.336, 3.62)	-	-
	Usual phlegm production	86	35	0.085	0.956	(0.874, 1.05)	1.93	(0.662, 5.65)	-	-
	Phlegm production longer than 3 months	87	21	0.071	1.01	(0.915, 1.11)	1.77	(0.563, 5.58)	-	-
	Wheezing		13	0.045	0.993	(0.887, 1.11)	1.65	(0.427, 6.34)	-	-
	Chest tightness		48	0.175	0.905	(0.825, 0.992)	3.83	(1.11, 13.2)	-	-
	Shortness of breath		26	0.129	0.882	(0.783, 0.993)	1.39	(0.423, 4.53)	-	-

[a] Each row represents a separate model. Covariates included in the models but not included here are sex, age, current smoking and ex-smoking status (never-smoking as reference) for all models and Gorogo community for overall models.

[b] Number of participants with the corresponding respiratory symptom

[c] Minimum years mining in excavation, crushing or sifting

[d] Main fuel source; charcoal is the reference; only Gorogo participants use crop residue fuels; excluding 7 male miners from Kejetia that do no cooking in their household

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Chapter 5 Conclusion

5.1 Objectives and significance

Up to 100 million people around the world are dependent on artisanal and small-scale gold mining (ASGM) for their livelihoods, predominantly in low and middle-income countries (International Labor Organization, 1999; UNEP, 2010). ASGM has continued to grow with increasing poverty and the allure from the rising price of gold (Hilson, 2010). The sector is now the largest single producer of gold globally (UNEP, 2010). Hg emissions to the atmosphere are increasing as the ASGM sector grows, placing it as the largest contributor to global anthropogenic Hg (UNEP, 2013a). There are numerous public and environmental health concerns for ASG miners, particularly around Hg exposure and toxicity. Very little data exists, however, on how ASGM communities and miners are exposed to Hg and the health outcomes of involvement in small-scale mining.

Ghana is an excellent case study for research, as there is a long history of gold mining, it is relatively well-resourced for conducting research, and Ghana has a vested interest as a signatory to the Minamata Convention on Mercury (Minamata Convention on Mercury, 2015). As a signatory member of the Convention, Ghana is expected to develop a National Action Plan on reducing Hg use in ASGM (Article 7, Annex C; UNEP, 2013b). This work provides currently lacking, but necessary data on baseline Hg use and contamination to inform the National Action Plan. The National Action Plan also requires steps to eliminate open burning of amalgams and burning in residential areas, and the development of strategies to prevent exposure for vulnerable populations, which are relevant problems for Kejetia and other ASGM communities.

This study used an ASGM study site in northeastern Ghana to follow an exposure-disease model. While there are data examining Hg exposures among small-scale miners, there is little known about the exposures for ASGM community residents not engaged in mining. Utilizing hair and urine biomarkers, household soil, and GIS for spatial analysis affords a greater understanding of personal Hg exposures to the community. Our study demonstrated that elemental Hg exposures via urinary Hg are elevated for mining and non-mining community residents in Kejetia. Household soil exposures were often elevated above health guidelines and it is estimated that many residential areas throughout the Kejetia community have elevated soil Hg. These exposures are critical for women of childbearing age and young children, who are more vulnerable to neurotoxicity from Hg. Although we did not see significant associations with blood pressure outcome measures with Hg biomarkers, these exposures may cause other adverse health effects or have other cardiovascular effects on very highly exposed miners. Increased respiratory symptoms and abnormal pulmonary function may be in part due to widespread biomass cooking fuel use and exposures from a young age that affect the majority of rural participants or greater rates of respiratory infections. Decrements in pulmonary function may not have been observed in our study as they may not develop for years after miners have stopped mining, owing to the latency period for the development of silicosis from respirable silica exposure. This study furthers our understanding of how small-scale gold miners and non-miners in ASGM communities are exposed to Hg and potential health impacts of these exposures, and respiratory health from mining involvement.

5.2 Major results and discussion

5.2.1 Mercury exposure assessment

It is well established that small-scale gold miners are exposed to potentially harmful levels of Hg, but few have integrated Hg measurements across multiple media and little is known about exposures to non-miners living in ASGM communities. Our study assessed Hg exposure in hair, urine, and household soil from miners and non-miners in Kejetia, and non-miners in Gorogo.

Use of Hg in ASGM was common in Kejetia, with just over 50% of participants having performed amalgamation. Kejetia participants had significantly higher SG-adjusted urinary Hg concentrations than Gorogo participants (Table 2.3). Urinary Hg concentrations were highest among Kejetia participants that had ever used Hg, followed by current miners. Miners' urinary Hg exposures in Kejetia were higher than observed in many other ASGM Ghanaian studies (Adimado & Baah, 2002; Asante et al., 2007; Abrefah et al., 2011; Kwaansa-Ansah, Basu, & Nriagu, 2010; Paruchuri et al., 2010). In Kejetia, 4.3% of participants had SG-adjusted urinary Hg concentrations above the WHO recommended health-based limit of 50 µg/L inorganic Hg for occupational exposure (Clarkson & Magos, 2006). Twenty-six percent of Kejetia participants had moderately high urinary Hg concentrations > 10 µg/L Hg (Risher, 2003). While most participants with elevated urinary Hg levels were miners, even some non-miners had elevated levels, underscoring the risk to residents living in ASGM communities but intentionally not using Hg or engaging in mining.

Most participants had hair Hg concentrations between 1-2 µg/g, which the WHO designates as "normal" (WHO & UNEP, 2008). Hair Hg concentrations for participants were all below the US EPA benchmark dose of 11.1 µg/g total hair Hg (US EPA, 1997), high exposures > 10.0 µg/g Hg designated by the WHO and UNEP (2008), and exposures measured in other ASGM communities across Ghana (Adimado & Baah, 2002; Donkor et al., 2006; Paruchuri et al., 2010; Kwaansa-Ansah et al., 2010).

A third of all Kejetia households had soil Hg concentrations exceeding the Canadian Soil Quality Guideline of 6.6 µg/g inorganic Hg for residential sites (Canadian Council of Ministers of the Environment [CCME], 1999). Soil Hg was generally higher in Kejetia than soil measured from other ASGM sites throughout Ghana, despite being from common household areas over mining areas (Rajaee et al., 2015). Kejetia household soil was significantly correlated to whether participants were current miners, if they had ever burned Hg, and urinary Hg (Figure 2.5). Urinary Hg and household soil Hg were both spatially auto-correlated (Figures 2.6 and 2.7, respectively), suggesting that people who live in "high Hg concentration areas" are more likely to have elevated urinary or household soil Hg.

This exposure assessment provides a more holistic examination of exposure pathways and environmental fate of Hg in ASGM communities. Over 15% of non-mining participants in Kejetia had SG-adjusted urinary Hg concentrations above 10 µg/L, suggesting that merely living within an ASGM community exposes residents to elemental Hg vapor. Soil has not been considered a significant source of Hg exposure in the past, but given extremely high contamination levels and other catastrophic events in northwestern Nigeria from lead soil contamination (Plumlee et al., 2013), it is important to consider it as a potential exposure pathway. These exposures are particularly important for women of childbearing age and young children living in ASGM communities that may have greater exposures via hand-to-mouth contact or be more vulnerable to the impacts of Hg toxicity (Clarkson & Magos, 2006).

5.2.2 Cardiovascular health impacts

There is increasing concern about the cardiovascular effects of mercury (Hg) exposure, and that organic methylmercury (MeHg) and inorganic Hg^{2+} may affect the cardiovascular system and blood pressure differentially. In ASGM communities, where inorganic, elemental Hg exposures are high for community members and miners, little is known about the Hg-associated effects on blood pressure. The high Hg exposures may increase our understanding of Hg-associated cardiovascular risk. As with past studies from this region (Paruchuri et al., 2010) exposures to MeHg were relatively low whereas exposures to inorganic Hg were high.

Despite ASG miners having known elevated elemental Hg exposure levels, there have been no studies to explore the relationship between Hg exposures and blood pressure in this exposure group. Most research on Hg's cardiovascular health impacts have focused on MeHg exposure and blood pressure (BP); much less is known about the cardiovascular effects of inorganic Hg exposure. Hypertension has risen in recent years in Ghana. The national prevalence is 20% for rural areas and 25% for urban areas (Bosu, 2010). Hypertension was prevalent in 17.7% of Kejetia and 21.3% of Gorogo participants, placing Kejetia just below and Gorogo just above the rural national rate.

Urinary and hair Hg were not significantly associated with systolic or diastolic BP (SBP, DBP) for Kejetia or Gorogo participants, but our results follow trends seen in the literature. The positive relationship between hair Hg and SBP was not significant, though it does follow the increasing trend seen in other studies (Valera et al., 2009; Goodrich et al., 2012; Dorea, de Souza, Rodrigues, Ferrari, & Barbosa, 2005; Choi et al., 2009; Fillion et al., 2006). The overall lack of significant finding here is perhaps due to lower hair Hg levels in our study than these other studies. Urinary Hg also followed the literature for a decreasing trend in BP (Park et al., 2013; Goodrich et al., 2012; Siblerud, 1990), but was not statistically significant. Hg vapor exposures were much greater in Kejetia than levels from other studies in which Hg-associated decreases in SBP or DBP have been reported. There appears to be a non-linear trend in urinary Hg's relationship to SBP and DBP (Figure 3.2) that may be difficult to capture with a small sample size of very high urinary Hg exposures. As seen in a study of Slovenian historic Hg miners, which observed a significant increase in SBP and DBP with urinary Hg (Kobal et al., 2004), it is possible that higher Hg vapor exposures may show a positive association with BP in future studies.

5.2.3 Respiratory health and pulmonary function

The recent increase in ASGM in Ghana has elicited a number of public health concerns for miners and mining communities, including respiratory health concerns. There are two primary inhalational concerns for adverse respiratory health to ASGM communities: respirable crystalline silica expected to be present in gold ore and biomass fuels used in cooking.

Percent predicted FEV_1, FVC and FEV_1/FVC, which were lower than expected for healthy U.S. African American adults, were not significantly different between Kejetia and Gorogo or by mining status in Kejetia (Table 4.2). We observed higher rates of abnormal percent predicted FEV_1 (15.0%) and FEV_1/FVC (22.0%) measures than the lower fifth percentile of normal performance based on healthy adults (Pelegrino et al., 2005). These rates of abnormality suggest higher obstructive disease to be apparent in both communities. History of mining involvement, as a proxy for respirable silica exposure, was not significantly associated with pulmonary function measures and were in the counter-intuitive, protective direction for percent predicted FEV_1 and FEV_1/FVC. Kejetia participants that had engaged in mining activities generally had minimally higher percent predicted FEV_1, FVC, and FEV_1/FVC measures than those with no mining involvement. The latency period necessary for silicosis to develop 20-40 years after exposures may explain why significant decrements in pulmonary function were not observed (Mason & Thompson, 2010), as Kejetia miners were young and more transient, suggesting that the Healthy Worker Effect may have biased our results.

Some respiratory symptoms were more prevalent in Kejetia and Gorogo than in healthy populations (Table 4.3). The prevalence of usual cough, phlegm production, phlegm production for longer than three months, chest tightness, and shortness of breath were elevated in Kejetia. Usual cough and chest tightness were elevated in Gorogo.

Main wood fuel use was associated with a significant decrease in the percent predicted FEV_1/FVC ratio in Gorogo, where cooking was primarily done indoors.

Biomass cooking fuels were not significantly associated with pulmonary function measures in Kejetia, where cooking was primarily done outdoors. Female participants had higher rates of abnormal pulmonary function than males, which may be due to differential sex roles in food preparation and cooking. Early life exposures to biomass fuel smoke for all participants may partially explain the decreased respiratory health but lack of significant associations with biomass fuel use.

This study is the first to investigate pulmonary function and respiratory symptoms with small-scale miners, to our knowledge. In a setting where there are multiple stressors from occupational and household activities, it is difficult to isolate causes of respiratory dysfunction. However, our study demonstrates that pulmonary obstruction is elevated in both Kejetia and Gorogo. This may be due to mining or biomass fuel smoke exposures, but also may result from inadequate pulmonary function prediction equations for the Upper East Ghanaian population.

5.3 Future work

The global escalation of ASGM and Hg use necessitate better assessments of exposure pathways and contamination, and the health outcomes associated with direct and indirect mining involvement. This research applies to the 500,000 Ghanaians employed through small-scale gold mining formally, the estimated one million Ghanaians involved with illegal small-scale mining, and the people involved or dependent indirectly on ASGM for their livelihood (Bawa, 2010; Banchirigah, 2008; UNEP, 2010).

This work fills a particular knowledge gap of Hg assessment in northern Ghana, as all other Hg assessments have focused exclusively on ASGM in southern Ghana.

Given higher urinary Hg levels among Upper East Region miners in Kejetia than southern ASGM miners, this prompts a need to assess the different practices that may be resulting in higher Hg exposures and develop initiatives to reduce these exposures. The results of this exposure and health assessment inform a national-level integrated assessment project examining water sustainability, infrastructural integrity, and health in small-scale gold mining communities in Ghana (ASGM Research Group, 2015). This integrated assessment can serve as a model and resource for other low and middle-income countries (LMICs) with ASGM.

As a signatory to the Minamata Convention on Mercury, Ghana will be required to develop a National Action Plan that includes a baseline assessment of Hg use and emissions, submit progress reviews every three years assessing measures to reduce and eliminate Hg use ASGM, and educate miners on Hg risks (Minamata Convention on Mercury, 2015; UNEP, 2013b). The Hg exposure assessment, as it informs the integrated assessment of ASGM nationally, will help to form the baseline Hg assessment and develop initiatives for ASGM formalization and Hg reduction.

Soil has not been considered a significant source of Hg exposure in the past, but given extremely high contamination levels, it is important to consider it as a potential exposure pathway. To assess this potential exposure pathway, a relevant and applicable soil and dust ingestion estimation is needed for rural West Africa to account for the regional climate, environment, housing, dietary and cooking practices, hygiene, and lifestyle. Many studies of soil contamination have measured Hg contamination at specific ASGM sites, but our research highlights the importance of measuring soil in common dwelling areas to better capture personal exposures.

The blood pressure assessment of ASGM miners and residents are a first look at a more highly elemental Hg exposed group, but there is a need for more research. Future studies of cardiovascular health outcomes and Hg exposure would benefit from larger cohorts of ASG miners that use Hg (>100) to increase statistical power to detect significant relationships to BP at higher Hg exposures. Assessments of quantities of Hg used, time spent using Hg, or personal mining practices are difficult to measure in these resource-limited settings, but an exposure assessment would benefit from understanding what practices may lead to higher Hg exposures among miners using Hg.

There are significant challenges with assessing pulmonary function at ASGM sites. ASG miners are likely healthier, younger, and more transient, making it difficult to see latency-dependent pulmonary dysfunctions in current miners (Greenberg et al., 2007). A study exclusively of ex-ASG miners would combat these problems in latency and transience. There is clear evidence that higher exposure to respirable silica is associated with decrements in pulmonary function and silicosis, so while he respirable silica content of gold ore in Ghana is unknown, an assessment of crystalline silica content at different ASGM sites would provide insight onto whether the hazard is present.

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