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Heavy metal blood concentrations in association with sociocultural characteristics, anthropometry and anemia among Kenyan adolescents

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Abstract

Objectives: To measure heavy metal concentrations among Kenyan youth and quantify associations with sociocultural, demographic, and health factors as well as anthropometry.

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AUTHOR CONTRIBUTIONS

The first (J Ashley-Martin), second (L Iannotti), and final author (B Straight) all contributed equally to the development of this manuscript. J Ashley-Martin conceptualized and performed the statistical analysis and drafted the manuscript. L Iannotti conceptualized and performed statistical analyses of biomarkers and micronutrients with that contributed to conceptualizing the current study. Yuhan Cui provided additional statistical support. B Straight conceived the original 2017 study, interpreted data, and revised the manuscript. Data collection was undertaken by B Straight and C Hilton with support of C Olungah. T Zava and Genevieve Nyland were responsible for analysis of the metals; Eleanor Brindle was responsible for analysis of C-reactive protein. All authors reviewed and approved the manuscript for publication.

None of the authors declare any conflicts of interest.

Methods: Using data from a study of semi-nomadic pastoralists in Samburu County, Kenya, we measured blood concentrations of lead (Pb), mercury (Hg), and cadmium (Cd) in 161 adolescents. We identified sociocultural, demographic and health characteristics associated with each metal and quantified the association between metals and adolescent anthropometry.

Results: Median blood concentrations of Pb, Cd, and Hg were 1.82 μg/dL, 0.24 μg/L and 0.16 μg/L, respectively. Place of residence (highlands vs lowlands) was a determinant of metal concentrations. Hg was inversely related to anemia, and metals were not associated with anthropometry.

Conclusions: In this population of Samburu adolescents, median Pb and Cd blood concentrations were higher than other North American or European biomonitoring studies. These findings motivates further investigation into the environmental sources of metals in this community.

Keywords

lead; cadmium; mercury; adolescents; Kenya; anthropometry

INTRODUCTION

The public health ramifications of widespread exposure to heavy metals in Africa are largely unknown due to the limited evidence base (Fewtrell et al. 2004; Joubert et al. 2020). The legacies of land degradation, poverty and strife (Bornman et al. 2017; Anyanwu et al. 2018) create barriers to optimal health and may exacerbate the adverse effects of metal exposure. In addition, the lack of comprehensive biomonitoring programs impedes both clinical responses as well as scientific understanding of patterns, determinants and consequences of exposure (Bornman et al. 2017; Kordas et al. 2018). Authors of the Birth to Twenty cohort (BT20+), one of the few prospective African cohort studies (Johannesburg, South Africa) that measured blood lead levels, have noted the dearth of research on adolescent lead (Pb) exposure (Naicker et al. 2010).

Heavy metals such as Pb, mercury (Hg), and cadmium (Cd) persist in the environment and are toxic to human health. Lead is toxic to multiple organs with particularly well-established neurotoxicity (ATSDR 2007). Epidemiological research on Pb in countries of Sub-Saharan Africa has largely focused on mining communities that incur high exposure and subsequent poisonings (Bartrem et al. 2014; Bornman et al. 2017; WHO 2020a). Hg, another known neurotoxicant, is present in fish and industrial emissions (ATSDR 1999). Cd is an endocrine disruptor and toxic to the respiratory and renal systems. Ingestion of contaminated food (shellfish, leafy vegetables), cigarette smoking, and industrial emissions are primary sources of Cd exposure (ATSDR 2018). Knowledge of the patterns and determinants of exposure to each of these metals in rural African youth is lacking.

The potential effects of metal exposure on adolescent growth are also poorly understood. The US National Toxicology Program has reported an inverse relationship between blood Pb levels less than 10 μg/dL and growth (NTP 2012). One of the primary mechanisms underlying this association is the Pb-related impairment of growth plate morphology

(ATSDR 2007). Epidemiological studies have reported inverse associations between Pb and adolescent growth at both high (≥ 5μg/dL) (Vivoli et al. 1993; Burns et al. 2017) and low (< 5μg/dL) (Hauser et al. 2008) concentrations. Moreover, experimental (ATSDR 2020) and epidemiological (Cantoral et al. 2015) evidence suggest that these effects may be exacerbated in the presence of underlying malnutrition (ATSDR 2007; Cantoral et al. 2015; Wells et al. 2016). Exposure to Cd in utero has been inversely associated with birth weight and childhood growth (Zheng et al. 2016; Chatzi et al. 2019; Moynihan et al. 2019); effects of adolescent exposures are not well explored. Similarly, although Hg reduced birth weight in experimental models, epidemiological studies of growth related effects in adolescents are few and inconsistent (Wigle et al. 2008).

Kenyan pastoralist youth could be potentially susceptible to metal toxicity and adverse growth patterns due to malnutrition, changing livelihoods and recent history of drought and conflict (Iannotti & Lesorogol 2014). Our primary objective, therefore, was to characterize the heavy metal concentrations of Kenyan pastoralist youth and to understand individual, community and household level determinants of exposure. Our secondary objective was to determine the association of heavy metal status with anthropometry. We hypothesized higher levels of metal concentrations in the youth would be inversely associated with anthropometry.

METHODS

The present analysis builds upon two previous studies in the highland region of Samburu County, Kenya, both conducted to assess environmental and socioeconomic determinants of adolescent health (Iannotti & Lesorogol 2014; Pike et al. 2016). This study additionally includes the lowland region of Samburu, building on longitudinal sociocultural research (Straight 1997; Straight 2007). Samburu County is in the central Rift Valley of north-central Kenya. The population are semi-nomadic pastoralists who have been experiencing increasing changes in their livelihoods and lifestyle due to drought and conflict. All participants in the current study were exposed in early childhood to an extreme drought in 2008–2009 and a severe drought in 2017. The effects of intercommunity conflict have been exacerbated by widespread availability of military assault rifles, and, to varying degrees, by increased land pressure and resource scarcity.

All study participants, regardless of their region of residence, are linguistically, culturally, and self-identified as Samburu. All Samburu place a high cultural value on livestock rearing. The lowlands and highlands differ with respect to weather, livestock holdings, and infrastructure. In 2017, average rainfall in the lowlands and highlands was 421 mm and 639 mm respectively (FEWSNET 2021). Mean temperature in 2017 was 40 ° C in the lowlands and 35 ° C in the highlands. The study community in the highlands tends to have higher income and more infrastructure than the lowlands but fewer livestock (Lesorogol & Boone 2016). Highland children are more likely to attend school and have access to some degree of rural health services. Even if they attend school, highland boys and some girls engage in herding before and after school while girls (and some boys) engage in domestic labor. In contrast, lowland children have poor to non-existent access to regular health services, and access to even primary school is severely limited. For many girls, education beyond nursery school is not available because there are no schools nearby nor boarding facilities provided for girls at the nearest school. Lowland girls and boys engage in similar levels of daily livestock herding, often at moderate distances from home daily (≥ 5 km). Consistent with these observations, Samburu participants in the lowlands had significantly lower monthly incomes, higher expenditures, and higher livestock holdings than those in the highlands. Adolescents in the lowlands were also significantly less likely to be currently in school and those who did attend school had significantly less years of school than those in the highlands (Iannotti et al under review). While the objective of the Iannotti et al study was to compare adolescent nutritional vulnerability between the two sites, the objectives of this manuscript were to describe and compare metal concentrations in the entire population.

Study Population

Adolescents (10–19 years old) were recruited from both the highlands and lowlands study sites in December 2015 for a June 2016 pilot. After instrumentation and methods were refined, data collection took place in June – July, 2017. Adolescents were eligible for enrolment if they were between 10 to 19 years of age, resided in one of the two study sites and self-reported to be in good health. Exclusion criteria included pregnancy, severe malnutrition and age outside the defined range. None of the eligible adolescents refused to participate. Samburu do not routinely keep track of ages. Age was based on self-report or timing of events near the birth and confirmed by clinic record or birth certificate where possible; birth year documentation was available for 92 of the 161 participants.

The original study was approved by the Western Michigan University Human Subjects IRB (#14-05-27). Approval to conduct the research was granted by Kenya’s National Commission for Science, Technology and Innovation.

Blood levels of heavy metals

Pb, Cd, and total Hg were measured in whole blood collected from lancet finger pricks onto Whatman 903 filter paper, dried for four hours, and sent to ZRT Laboratory in Beaverton, Oregon. Blood metal concentrations were determined using inductively coupled mass spectrometry (Perkin Elmer NexIOM 300D ICP-MS with Dynamic Reaction Cell Technology). Intra- and inter-assay coefficients of variation were less than 8.3% and 15% respectively (details are provided in supplemental material). The limits of detection for Cd, Pb, and Hg were 0.22 μg/L, 0.64 μg/dL, and 0.11 μg/L respectively.

C-reactive protein

C-reactive protein (CRP), assessed as a biomarker of inflammatory response, was similarly measured in whole blood from finger pricks and analyzed at the Biodemography Lab at the University of Washington Center for Studies in Demography and Ecology using a microtiter plate-based sandwich enzyme immunoassay (Brindle et al. 2010). We adjusted for CRP in multivariable models to account for the potential effect of infection-induced inflammation on both metals concentrations and child growth (Lynch et al. 2018).

Sociocultural Factors

Detailed socioeconomic and demographic data including livestock ownership, family structure, child education, household income and spending were collected from each participant's parents, with children supplementing information concerning milk animals. This information was collected via study visits to each family's home, school, or a site convenient to participants. In addition to characteristics such as age, sex, education, income, and number of siblings, we assessed several characteristics unique to this population. Tropical livestock units (TLU) are a measure of livestock wealth with different types of livestock weighted according to their exchange value (1 TLU=0.7 camel, 1 cattle, 10 sheep, 11 goats). We also assessed the influence of family structure including polygynous households and the number of wives. We categorized continuous variables at the median to facilitate comparison of metal levels within each stratum of these characteristics.

Anthropometric and Biological Indices

Our primary outcomes were height, weight, and body mass index (BMI). Height and weight were measured using WHO (World Health Organization) protocols. Specifically, research personnel measured height twice using a stadiometer. If the two heights differed by more than 0.5 cm, a third measurement was taken. Similarly, weight was assessed twice using an electronic digital scale; a third measure was recorded if the first two differed by more than 0.5 kg. For children ages 5–19 years, WHO References are only available based on a reconstruction of data from the 1977 National Center for Health Statistics. These references are from a US population and not considered standards, similar to those available for children less than 5 years of age (WHO 2020b). Weight-for-age z-scores are not available after 10 years of age and weight without adjustment for height is difficult to interpret. We, therefore, used raw measures of height and calculated BMI, rather than z-scores, as the anthropometric variables in our analyses. For descriptive statistics, we categorized BMI at 16as a proxy for of thinness for both sexes and all ages. While we recognize that BMI changes with age, a BMI less than 16 is a reasonable cut-off to identify thinness status among adolescents (Cole et al. 2007).

Statistical Analysis:

We calculated descriptive statistics and Spearman Correlation coefficients for each of the metals using medians and interquartile ranges due to skewed distributions. We next developed a series of bivariate models to determine the association between each sociocultural characteristic and metal concentrations as an exploratory analysis of determinants of metal exposure. We used linear regression to model associations with log2 transformed Pb. We also calculated geometric mean Pb levels within each stratum of the characteristics. Due to the percent of samples below the limit of detection (LOD) for both Cd and Hg, we categorized these metals as binary variables by dichotomizing at the median. We then calculated the relative risk of exceeding the median metal concentration for each characteristicValues below the LOD were substituted as LOD/2 and included in this variable. We also calculated the percentage of participants with metal concentrations above the median for each stratum of the sociodemographic variables. By dichotomizing Hg and Cd rather than using the continuous variables, we were able to identify individuals with higher than median exposure without having to rely on a substitution or imputation method for the non-detects both of which can introduce measurement bias (Helsel 2006).

To assess the association between metal concentrations and anthropometric measures, we first calculated the mean level of each anthropometric outcome according to quantiles of each metal. Using multivariable linear regression, we next modeled the association between metals, as the independent variables, and adolescent anthropometric measurements (height, weight, BMI), as the dependent variables. Metals were categorized into quantiles to account for nonlinear relations and to avoid biased results due to the extent of undetectable concentrations of Cd and Hg. We categorized Pb into tertiles (33^{rd}, 66^{th} percentiles) and Cd and Hg into three groups with the referent group defined as values below the LOD and the top groups defined as medium and high exposure with cut points defined to create groups of roughly equal numbers of participants. For example, 33% of participants had Hg concentrations below the LOD of 0.11 μg/L. We, therefore, created three categories that represent < LOD, 0.12–0.26 μg/L, and >0.26 μg/L. Similarly for Cd, we created categories at < LOD (0.22), 0.23–0.35, and > 0.35 μg/L.

This approach was deemed preferable to categorizing at the LOD as it facilitates assessment of a dose-response trend. As there were no Pb measurement below the LOD, we also modelled associations between log2-transformed Pb and each anthropometric measure. We developed separate models for each metal and anthropometric measure. To account for age and sex variations in each anthropometric measure, we adjusted all models for age and sex (model 1). In model 2, we additionally adjusted for variables associated with elevated metal concentrations in the univariate analysis and variables known to differ between the highlands and lowlands. Prior to inclusion as a confounder, we evaluated whether each characteristic associated with the metals was plausibly associated with the anthropometric outcomes and unlikely to be a mediating variable. TLU and monthly spending were moderately correlated with each other (Pearsons's correlation coefficient = 0.41) and, therefore, not included in the same model. We additionally adjusted models for CRP to assess whether results differed in the presence of excess inflammation. To assess the presence of a dose-response relationship between the quintiles of metal concentrations and anthropometry, we calculated the p-value of the linear test for trend for each metal. We evaluated the presence of effect modification by sex by calculating the p-value of product term between sex and each metal and stratifying results by sex. Last, we assessed whether place of residence (lowlands vs highlands) was an effect modifier by calculating the p-value of the product term between residence and each metal and stratifying result by residence.

All analyses were done in R v.3.5.1 (R Core Team 2019).

RESULTS

Of the 164 adolescents who were recruited, three did not participate due to either pregnancy (n=1) or concerns regarding blood drop sampling and collection (n=2) resulting in a sample size of 161 with a mean age of 14 years. We additionally excluded one participant from the Cd analyses whose Cd concentration was in excess of 15 μg/L as this value was 100 fold greater than the interquartile range (0.14 μg/L) and deemed to be an outlier. Sixty percent of participants lived in the highlands, 48% were boys, and 73% were currently enrolled in school. Additionally, 48% of adolescents lived in a polygynous family structure (Iannotti et al. under review). The majority of adolescents (73%) had a BMI less than 16 kg/m^2. Further details on the study population according to place of residence are provided in Table 1.

Spearman correlations between the metals was −0.049 for Cd and Hg, 0.045 for Cd and Pb, and 0.273 for lead and mercury. All children had detectable concentrations of Pb. Cd and Hg were undetectable in 46% and 33% of blood samples respectively. Median and interquartile range (IQR) Pb concentrations were 1.82 (1.45–2.61) μg/dl. Four percent of children (n=6) had Pb concentrations above the US Center for Disease Control (CDC) guideline reference value of 5 μg/dL (3 in highlands and 3 in lowlands) (CDC 2020). Median concentrations for Cd and Hg were 0.24 μg/L and 0.16 μg/L (Table 2).

Sociocultural Characteristics and Metal Concentrations

Pb concentrations were statistically significantly higher in adolescents who were from a family with higher income, had more than five siblings, and were currently in school. Pb concentrations were lower in adolescents who lived in the lowlands (GM Pb=1.77 μg/dL) than the highlands (GM Pb=2.15 μg/dL) (Table 2, 3).

Adolescents who were older than 13 years of age, lived in a polygynous family structure, lived in the lowlands, were from a family with higher spending levels (>6000 Kenya Shillings monthly), or were anemic were significantly more likely to have Hg concentrations below the median. In contrast, adolescents who had higher income levels, were currently in school and had higher TLUs were significantly more likely to have Hg concentrations above the median (Table 4).

Characteristics significantly associated with Cd concentrations above the median included residence in the lowlands, being from a family with the highest spending category, and female sex. We also observed that adolescents who were currently enrolled in school and drank more than two cups of tea a day were significantly more likely to have Cd levels lower than the median (Table 5).

A binary variable of adolescent BMI categorized at 16 kg/m^2 was not associated with any of the metals (Tables 3–5).

Metals and Anthropometric Measures

Pb was inversely associated with each anthropometric measure but none of these associations were statistically significant. Compared to individuals with Pb concentrations in the lowest tertile (< 1.58 μg/dl), those in the highest tertile (> 2.25 ug/dl) had, on average, 0.31 lower BMI (95% CI: −1.03, 0.414) (Table 6). This effect size is 15% of the BMI standard deviation of 2.1. No statistically significant associations were observed between log2 transformed Pb and any of the anthropometric measures (data not shown). We observed that Hg was associated with lower height; individuals in the highest quintile (> 0.26 μg/l) were, on average, 3.7 cm (95% CI: −7.43, 0.04) shorter than those in the referent tertile (< 0.12 μg/l). We did not observe any statistically significant associations in the Cd analyses (Table 5). Adjustment for CRP did not materially alter any of the results (data not shown).

No statistically significant dose-response relationships were observed based on a p-value of the test for trend <0.05. We observed no effect modification by sex based on a p-value of the product term < 0.15 and no material differences in the sex specific models (data not shown). We similarly observed no statistically significant associations between metals and anthropometry when stratified by place of residence.

DISCUSSION

By characterizing heavy metal concentrations of Samburu adolescents, this study contributes to the limited biomonitoring data in African rural youth. Blood Pb and Cd concentrations in this population were, on average, higher than North American and European biomonitoring studies (Pb: 1.3 μg/dL higher, Cd: 0.11–0.13 μg/L higher). Hg concentrations tended to be between 0.10–0.29 μg/L lower in Samburu adolescents than reported in these biomonitoring studies (Schulz et al. 2009; Health Canada 2019; CDC 2019) (Table 6). The 97.5% percentile of Pb concentrations (7.3 μg/dL) in Samburu adolescents exceeds the CDC reference value of 5 μg/dl, but only 1% of Samburu adolescents had Pb concentrations in excess of the previous, long-standing CDC health-based guideline of 10 μg/dL (CDC 2020). We observed no statistically significant associations between any of the metals and anthropometric measures.

Other than the South African BT20+ cohort (Naicker et al. 2010) and a biomonitoring study in Kinshasa (Democratic Republic of Congo) (Tuakuila et al. 2015), population-based biomonitoring efforts in African adolescents are rare. Consistent with previous evidence that Pb exposure is lower in rural than urban populations (Fewtrell et al. 2004; Abdel Rasoul et al. 2012), blood Pb concentrations among the Samburu adolescents were lower than the Kinshasa (Tuakuila et al. 2015) and Johannesburg based populations (Naicker et al. 2010) (Table 6). Samburu adolescents are likely exposed to Pb via paint, pipes, and leaded gasoline from abandoned motorcycle and vehicle engines. Other sources of Pb exposure in Samburu include discarded bullets, bullet casings and other munitions found in nearby former and active military training grounds. Eating batteries (e.g., sizes AA, C, or D) and licking paint cans are known behaviors and sources of Pb exposure in younger children (Straight; Holtzman 2009; Development 2019), but these behaviors are not typical in adolescents.

Authors of the BT20+ study reported that male sex, low maternal education, and not owning a phone were determinants of elevated blood Pb (Nkomo et al. 2018). We similarly observed that males had higher lead concentrations than females. In contrast to the findings from BT20+ (Nkomo et al. 2018) that lower maternal education was associated with elevated blood Pb concentrations, we observed that higher socioeconomic status (income, schooling) were determinants of higher blood Pb concentrations in Samburu adolescents. This finding may be due, in part, to a correlation between higher socioeconomic status and exposure to Pb contaminated paint and pipes in homes and schools. Infrastructure and socioeconomic status are also likely contributors to the higher Pb concentrations in highlands residents who are more likely to live in modern vs traditional mud houses and go to school than residents of the lowlands.

Median blood Cd levels (0.24 μg/L) among Samburu adolescents were higher than reported in North American and European biomonitoring studies (Schulz et al. 2009; Health Canada 2019; CDC 2019) and also higher than the Kinshasa based study (Tuakuila et al. 2015) (Table 7). Soils in the Great Rift valley of Kenya contain relatively high concentrations of Cd and Hg due to urbanization, intensification of agricultural practices and subsequent release of metals into the atmosphere and soil (Mungai et al. 2016). Metals in soil can be absorbed by plants and, ultimately, contribute to an individual's body burden (ATSDR 2018). Local environmental sampling is necessary to elucidate whether soil metal concentrations differ between the highlands and lowlands. Use of smokeless tobacco, i.e., chewing tobacco and snuff, is another potential source of Cd exposure and is common in this population, particularly among lowlands residents (Straight 2007). Cd blood concentrations in individuals who use smokeless tobacco are lower than in cigarette smokers, (Marano et al. 2012; Rostron et al. 2015) but may still contribute to Cd body burden.

Our finding that females were more likely to have Cd concentrations above the median than males is consistent with sex specific results in Canadian and US biomonitoring studies where median concentrations in females were higher than males (Canada: females 0.27 μg/L males 0.19 μg/L; (Health Canada 2019) US: females 0.29 μg/dL males 0.23 μg/dl (CDC 2019)). Based on the available data, we are not able to elucidate completely these sex-specific differences, but boys in Samburu are more likely to attend school, participate in distance herding and, therefore, may have different dietary patterns and exposure profiles. Girls may be prone to higher Cd concentrations when menstruating due to the loss of iron (Lee & Yangho, Kim 2014). The inverse association between tea consumption and Cd concentrations may be explained by the presence of milk and phytates in tea that reduce Cd bioavailability (Daley et al. 2013; ATSDR 2018). Further research is necessary to explore the behavioral patterns and biological mechanisms underlying these associations.

Hg concentrations in Samburu adolescents were lower than other North American, European, or African populations (Table 7). Fish consumption, a major source of Hg exposure, has been prohibited according to Samburu traditions and is, therefore, not a common part of the Samburu diet with the rare exception being highland families of higher income and education. The observed inverse association between Hg concentrations and anemia is likely confounded by residence. Individuals who live in the highlands have lower rates of anemia (76% of highlands residents were not anemic vs 52% of lowlands residents) and are more likely to have Hg concentrations in excess of the median potentially due to their increased access to non-traditional foods or contaminated soil.

Experimental and epidemiological literature is suggestive of an inverse association between Pb and skeletal growth (ATSDR 2007; NTP 2012). Cross-sectional studies of US (Selevan et al. 2003), Polish (Ignasiak & Awin 2006), Italian (Vivoli et al. 1993), and Korean (Min et al. 2008) adolescents reported inverse associations between Pb and anthropometry with average blood Pb concentrations ranging from 2.4 μg/dL (Min et al. 2008) to 8.5 μg/dL (Vivoli et al. 1993). Prospective studies from the US and Russia with geometric mean and median lead concentrations of 1.0 μg/dL and 3.0 μg/dL similarly reported that Pb concentrations were inversely associated with reduced growth or height (Sergeyev et al. 2017; Deierlein et al. 2019). Authors of the BT20+ did not examine associations between metals and anthropometry; however, they did report that blood Pb levels greater than 5 μg/dL slowed pubertal timing (Nkomo et al. 2018). Although we did not observe any statistically significant associations between Pb and anthropometry, the direction of effect is consistent with this body of literature. Further, our results were likely underpowered to detect an association particularly in sex-specific analyses.

This study benefited from the extensive information on study participants' social, economic, and cultural characteristics. In addition, our ability to collect blood using a minimally invasive technique allowed us to measure metal concentrations in nearly all participants. Our findings are an important contribution to understanding heavy metal exposure in rural African youth.

Despite these strengths, our study is limited by the relatively small sample size and resulting imprecision in multivariable results. Due to the cross-sectional study design, we were not able to ensure temporality between metal exposure and adolescent anthropometric measures. As the half-lives of these metals in blood is on the order of several months (ATSDR 2007; Adams & Newcomb 2014; Environment and Climate Change Canada 2016), the observed concentrations are most reflective of recent exposure. On the other hand, authors of the BT20+ cohort noted a strong correlation between cord blood Pb and adolescent blood Pb concentrations suggesting that the determinants of youth blood levels are stable over time (Naicker et al. 2010). Understanding metal exposure-related etiology of adolescent growth patterns was not an objective of the original Samburu study. As such, the study did not collect information on early life metal exposures or other determinants of child growth (i.e., birth weight and gestational age at delivery).

Conclusions

We characterized blood metal concentrations in an understudied population of African youths. Blood Pb and Cd concentrations in this population were higher than North American and European biomonitoring studies. This research motivates further investigation into understanding the environmental sources of metals in this community and developing subsequent public health strategies aimed at reducing heavy metal exposure.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Table 1.

Individual, community and household characteristics of the Samburu adolescents stratified by place of residence[1]

	Highlands (n=97)	**Lowlands (n=64)**
	Mean (SD)	**Mean (SD)**
Age at time of study (years)	13.0 (2.3)	16.2 (3.0)
BMI (kg/m^2)	14.4 (1.9)	15.7 (2.2)
Number of siblings	5.6 (1.9)	5.3 (2.0)
Monthly Income (Kenya Shillings/month)	4,510 (3,259)	1, 828 (4,388)
Years in School	6.4 (2.8)	4.7 (4.1)
TLU values	11.3 (15.5)	36.1 (36.9)
Spending (Kenya Shillings/month)	5,623 (4,919)	13,562 (7,655)
	N (%)	N (%)
Anemia (yes)	23 (24)	31 (48)
Currently in school (yes)	87 (90)	31 (48)
Cups of tea		
≤1	74 (77)	63 (98)
>1	22 (22)	1 (2)
Number of wives in family[1]		
1	66 (71)	36 (59)
2	18 (19)	19 (31)
3	9 (9.7)	6 (9.8)

1. Subtotals do not sum to stratum total due to missingness: 1 missing tea consumption in highlands group, 4 missing number of wives in highlands group and 3 missing in lowlands group.

Table 2.

Descriptive statistics of metals in Samburu, Kenya adolescents (n=161)

Metal	% < LOD	25th percentile	50th percentile	75th percentile	95th percentile	Max
Cadmium (μg/L)	46	LOD	0.240	0.360	0.860	15.8
Lead (μg/dL)	0	1.45	1.82	2.61	4.62	10.3
Mercury (μg/L)	33	LOD	0.160	0.360	0.570	0.860

Abbreviations: LOD limit of detection

Table 3.

Univariate associations between sociodemographic/cultural characteristics and blood Pb concentrations (μg/dL) in Samburu, Kenya adolescents

	n	β[1]	95 % CI	Geometric Mean	95% CI
Age (yrs)					
< 13	74	ref		2.10	(1.89, 2.34)
≥ 13	87	−0.143	(−0.355, 0.068)	1.90	(1.72, 2.11)
Sex					
females	83	ref		1.86	(1.70, 2.04)
males	78	0.205	(−0.005, 0.415)	2.14	(1.91, 2.40)
BMI (kg/m ^{2})					
<16	117	ref		2.02	(1.86,2.19)
≥ 16	44	−0.068	(−0.305, 0.170)	1.93	(1.64,2.27)
Anemia [2]					
No	107	ref		1.99	(1.82,2.19)
Yes	54	−0.005	(−0.230, 0.219)	1.99	(1.75,2.25)
Education (yrs)					
< 7	96	ref		1.99	(1.82, 2.19)
≥ 7	62	−0. 013	(−0.231, 0.205)	1.98	(1.74, 2.24)
Income (Kenya Shillings/month)					
< 3000	**96**	**ref**		**1.84**	(**1.68, 2.00**)
≥ 3000	**65**	**0.291**	**(0.08, 0.502)**	**2.25**	(**1.98, 2.55**)
Polygyny					
no	67	ref		2.15	(1.90, 2.44)
yes	94	−0.192	(−0.405, 0.021)	1.89	(1.72, 2.06)
Residence					
highlands	**97**	**ref**		**2.15**	(**1.98, 2.34**)
lowlands	**64**	**-0.279**	**(−0.492, −0.067)**	**1.77**	(**1.56, 2.02**)
Number of siblings					
< 5	**83**	**ref**		**1.82**	(**1.66, 2.00**)
≥ 5	**74**	**0.259**	**(0.049, 0.469)**	**2.18**	(**1.94, 2.45**)
Spending category (Kenya Shillings/month)					
< 6000	88	ref		2.06	(1.88, 2.26)
≥ 6000	73	−0.106	(−0.318, 0.107)	1.91	(1.70, 2.15)
Currently in school					
no	**43**	**ref**		**1.67**	(**1.45, 1.92**)
yes	**118**	**0.348**	**(0.115, 0.581)**	**2.13**	(**1.95, 2.31**)
Tea consumption (cups)					
<2	137	ref		1.96	(1.81, 2.13)
≥2	23	0.136	(−0.167, 0.440)	2.16	(1.82, 2.56)
Number of wives					

	n	β[1]	95 % CI	Geometric Mean	95% CI
<2	139	ref		2.04	(1.89, 2.21)
≥ 2	15	−0.267	(−0.636, 0.102)	1.70	(1.27, 2.27)
Tropical Livestock Units					
<9	81	ref		2.05	(1.86, 2.25)
≥9	80	−0.079	(−0.290, 0.133)	1.94	(1.73, 2.17)

[1]These parameter estimates are calculated from individual univariate linear regression models examining the association between each characteristic and continuous log2 transformed Pb. For example, compared to children < 13 years of age, children ≥ 13 years of age have 0.143 lower Pb concentrations on the log 2 scale.

[2]Anemia was defined according to the World Health Organization cutoffs of hemoglobin < 12 g/dL for males and females less than 12–14 years of age, < 12 g/dL for females 15 years and older, and < 13 g/dL for males 15 years and older (WHO, 2011).

Abbreviations: Pb lead, GM geometric mean, yrs years

Missing: age n=0, anemia n=2, education n=3, income n=0, polygamous n=0, residence n=0, number of siblings n=4, spending n=0, school n=0, sex n= 0, tea n=1, number of wives n=7, tropical livestock units n=0, birth order n=4

Bolded = statistically significant at p<0.05

Table 4.

Univariate associations between sociodemographic characteristics and Hg levels greater than median (0.16 μg/L) n Samburu, Kenya adolescents

	N	% > median Hg	RR	95% CI
Age (yrs)				
<13	74	64	Ref	
≥13	87	38	**0.60**	**(0.43,0.82)**
Sex				
males	78	51	Ref	
females	83	48	0.94	(0.69,1.28)
BMI (kg/m^2)				
<16	117	53	Ref	
≥16	44	41	0.77	(0.52,1.14)
Anemia [1]				
No	107	32	Ref	
Yes	54	59	**0.53**	**(0.35,0.82)**
Education (yrs)				
< 7	95	47	Ref	
≥ 7	62	53	1.14	(0.83,1.56)
Income (Kenya Shillings/month)				
<3000	96	41	Ref	
≥3000	65	63	**1.55**	**(1.14,2.11)**
Polygyny				
No	67	60	Ref	
Yes	94	43	**0.71**	**(0.52,0.97)**
Residence				
highlands	97	90	Ref	
lowlands	64	10	**0.17**	**(0.09,0.33)**
Number of siblings				
< 5	83	51	Ref	
≥ 5	74	49	0.96	(0.70,1.32)
Spending category (Kenya Shillings/month)				
< 6000	88	67	Ref	
≥ 6000	73	29	**0.43**	**(0.29,0.63)**
Currently in school				
no	43	21	Ref	
yes	118	60	**2.87**	**(1.58,5.23)**
Tea consumption (cups)				
<2	137	44	Ref	
≥ 2	23	50	0.86	(0.53,1.42)
Number of wives				
< 2	139	53	Ref	

	N	% > median Hg	RR	95% CI
≥ 2	15	20	0.38	(0.13,1.05)
Tropical Livestock Units				
<9	81	42	Ref	
≥ 9	80	58	**1.40**	**(1.02,1.92)**

[1]Anemia was defined according to the World Health Organization cut-offs of hemoglobin < 12 g/dL for males and females less than 12–14 years of age, < 12 g/dL for females 15 years and older, and < 13 g/dL for males 15 years and older (WHO, 2011).

Abbreviations: Hg mercury, RR relative risk, yrs years, CI confidence interval,

Missing: age n=0, education n=3, income n=0, polygamous n=0, residence n=0, number of siblings n=4, spending n=0, school n=0, sex n= 0, tea n=1, number of wives n=7, tropical livestock units n=0, birth order n=4

Table 5.

Univariate associations between sociodemographic characteristics and Cd levels greater than median (0.24 μg/L) n Samburu, Kenya adolescents

	N	% > median Cd	RR	95% CI
Age (yrs)				
< 13	73	47	Ref	
≥ 13	87	51	1.11	(0.81,1.53)
Sex				
males	77	39	Ref	
females	83	59	**1.52**	(**1.09, 2.11**)
BMI (kg/m^2)				
<16	116	46	Ref	
≥16	44	59	1.29	(0.94,1.77)
Anemia [1]				
No	106	49	Ref	
Yes	54	50	1.02	(0.73,1.42)
Education (yrs)				
< 7	95	52	Ref	
≥ 7	62	47	0.91	(0.65,1.26)
Income (Kenya Shillings/month)				
< 3000	95	55	Ref	
≥ 3000	65	42	0.76	(0.54,1.04)
Polygyny				
no	67	46	Ref	
yes	93	52	1.12	(0.81,1.54)
Residence				
highlands	97	42	Ref	
lowlands	63	60	**1.43**	(**1.05,1.94**)
Number of siblings				
<4	82	49	Ref	
≥4	74	51	1.05	(0.77,1.44)
Spending category (Kenya Shillings/month)				
< 6000	88	39	Ref	
≥ 6000	72	63	**1.62**	(**1.18,2.22**)
Currently in school				
no	43	72	Ref	
yes	117	41	**0.57**	(**0.43,0.76**)
Tea consumption (cups)				
<2	136	54	Ref	
≥2	23	22	**0.40**	(**0.18,0.88**)
Number of wives				
<2	138	51	Ref	

	N	% > median Cd	RR	95% CI
≥2	15	40	0.79	(0.42,1.50)
Tropical Livestock Units				
<9	81	54	Ref	
≥9s	79	47	0.86	(0.63,1.17)

[1]Anemia was defined according to the World Health Organization cutoffs of hemoglobin < 12 g/dL for males and females less than 12–14 years of age, < 12 g/dL for females 15 years and older, and < 13 g/dL for males 15 years and older (WHO, 2011).

Abbreviations: Cd cadmium, RR relative risk, yrs years, CI confidence interval,

Missing: age n=0, education n=3, income n=0, polygamous n=0, residence n=0, number of siblings n=4, spending n=0, school n=0, sex n= 0, tea n=1, number of wives n=7, tropical livestock units n=0, birth order n=4

Table 6.

Parameter estimates from multivariable linear regression models estimating associations between quantiles[1] of metals and anthropometric measures in Samburu, Kenya adolescents

				Model 1[2]		Model 2[3]	
BMI		**n**	**Mean BMI**	**β**	**95% CI**	**β**	**95% CI**
Pb	Q1	54	15.4	Ref			Ref
	Q2	53	14.4	0.006	(−0.699, 0.711)	−0.050	(−0.769,0.669)
	Q3	54	14.5	−0.308	(−1.03, 0.414)	−0.374	(−1.13,0.383)
Cd	Q1	79	14.7	Ref			Ref
	Q2	37	14.7	−0.011	(−0.718, 0.695)	−0.117	(−0.865,0.631)
	Q3	44	15.6	0.636	(−0.042, 1.31)	0.537	(−0.185,1.26)
Hg	Q1	57	15.2	Ref			Ref
	Q2	51	15.2	0.255	(−0.436, 0.947)	0.467	(−0.337,1.27)
	Q3	53	14.3	−0.085	(−0.797, 0.628)	0.199	(−0.715,1.12)
Height			**Mean Height (cm)**	**β**	**95% CI**	**β**	**95% CI**
Pb	Q1	54	156	Ref		Ref	
	Q2	53	151	−0.304	(−4.05, 3.44)	−0.29	(−4.06,3.47)
	Q3	54	149	−2.15	(−5.99, 1.69)	−2.16	(−6.13,1.80)
Cd	Q1	79	152	Ref		Ref	
	Q2	37	150	−1.40	(−5.20, 2.40)	−1.52	(−5.49,2.44)
	Q3	44	154	0.284	(−3.36, 3.93)	0.171	(−3.65,3.99)
Hg	Q1	57	157	Ref		Ref	
	Q2	51	152	−2.09	(−5.72, 1.54)	−1.99	(−6.16,2.17)
	Q3	53	145	−3.70	(−7.43, 0.04)	−3.38	(−8.12,1.37)

[1]Metals were categorized as follows to account for the % < the LOD and account for potential non-linearity: Pb (μg/dL) Q1 <1.58, Q2 1.58–2.25, Q3 >2.25; Cd (μg/L): Q1 <0.23, Q2 0.23–0.35, Q3 >0.35, Hg (μg/L): Q1<0.12, Q2 0.12–0.26, Q3 >0.26

[2]Model 1: adjusted for age and sex. Parameter estimates represent the change in anthropometric outcome according to the quantiles of blood metal concentrations (ie compared to those in the referent group(Q1), individuals with blood metal concentrations in Q3 have, on average, a 0.308 lower BMI).

[3]Model 2: Pb models adjusted for age, sex, income school, residence, number of siblings; Cd models adjusted for age, sex, tea, school, residence, spending; Hg models adjusted for age, sex, income, school, residence, hemoglobin

Abbreviations: Pb lead, Cd cadmium Hg mercury, BMI body mass index, CI confidence interval

Table 7.

Median metal concentrations in Samburu and other biomonitoring studies

Study (Reference)	Age of Participants (years)	Sample Size	Cadmium (µg/L)	Lead (µg/dL)	Mercury (µg/L)
Samburu, Kenya 2015 s	10–19	161	0.24	1.8	0.16
CHMS Canada 2016–2017 (Health Canada 2019)	12–19	521	0.11	0.46	0.35
NHANES United States 2015–2016 (CDC 2019)	12–19	565	0.13	0.45	0.45
GerESIVs Germany 2003–2006 (Schulz et al. 2009)	12–14	460	<0.12	1.5	0.20
Birth to Twenty Cohort South Africa 2003 (Naicker et al. 2010)	13	618	--	5.7	--
Kinshasa biomonitoring Study Democratic Republic of Congo 2011 (Tuakuila et al. 2015)	1–14	125	0.15	5.4	1.6

Abbreviations: CHMS Canadian Health Measures Survey; NHANES National Health and Nutrition Examination Survey, GerESIVs German Environmental Survey on Children