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Artisanal and small-scale gold mining: A cross-sectional assessment of occupational mercury exposure and exposure risk factors in Kadoma and Shurugwi, Zimbabwe

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ABSTRACT

In artisanal and small-scale gold mining (ASGM) the toxic metal mercury is used for gold extraction. The objective of this cross-sectional study was to assess mercury concentrations in urine and blood and mercury-related symptoms of participants identifying themselves as miners from Kadoma and Shurugwi, Zimbabwe. Moreover, we aimed to explore possible risk factors influencing mercury body burden. In 2019, urine and blood samples of 207 participants were collected and analyzed for mercury using atomic absorption spectroscopy. All participants answered questions regarding their exposure risks. The median urine mercury value was 4.75 μg/L with a maximum of 612 μg/L. Median mercury concentration in creatinine corrected urine values was 3.98 μg/g with a maximum value of 478 μg/g. The median blood mercury value was 2.70 μg/L with a maximum of 167 μg/L. Correlations between exposure risks factors such as the lack of retort use and elevated mercury values were demonstrated. ASGM is very common in Zimbabwe. Thus, mercury exposure is a major occupational health risk for miners. Moreover, this study emphasizes the impact of exposure risk factors on the mercury body burden.

1. Background

Mercury (Hg) is neurotoxic and chronic exposure can lead to severe health impairments (UNEP, 2013a). In artisanal and small-scale gold mining (ASGM), Hg based gold extraction is a common practice. With 37%, ASGM represents the greatest source of anthropogenic Hg pollution (Gibb and O'Leary, 2014; Telmer and Stapper, 2012). Worldwide, around 14 to 19 million people work in ASGM (Seccatore et al., 2014; Steckling et al., 2017).

Despite Hg's toxic character, amalgamation is a method widely used in ASGM, primarily because of its simple, fast and highly cost effective handling process (Telmer and Veiga, 2009). In the first step of the gold mining process, miners dig the ore from underground or open pits. The ore is crushed and elemental Hg is added to the pulp where it forms an

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amalgam with the gold. Amalgam smelters use blowtorches or burning coal to obtain the gold after Hg has evaporated. During the whole process, most of the workers do not use or wear protective devices and clothing (e.g. retorts, masks or glasses). ASGM comprises various tasks, whereas the smelters are exposed to toxic Hg in the form of vapor (Baeuml et al., 2011b; Bose-O'Reilly et al., 2010a; Kristensen et al., 2014;; Steckling et al., 2011; UNEP, 2013b). Hg can be assessed in various human specimen e.g. blood and urine, providing information about Hg exposure (Basu et al., 2018).

In Zimbabwe an estimated 500,000 people are directly engaged in ASGM and several million people depend on it (Seccatore et al., 2014). High unemployment rates and economic hardships in Zimbabwe accompanied by high commodity prices have resulted in an increase in ASGM activities. On the one hand, it makes ASGM an important source of livelihood, and on the other, mining practices are widespread with a growing number of intermittent miners (Chan, 2019; Chenjerai, 2017; Kristensen et al., 2014). Kadoma and Shurugwi are old gold mining towns. Kadoma has the largest gold deposits and the highest density of miners in Zimbabwe (Billaud et al., 2004; Bose-O'Reilly et al., 2004). In Shurugwi, there is a growing trend for ASGM activities. However, almost nothing is known about the situation in Shurugwi.

In 2013, Zimbabwe signed the treaty of the *Minamata Convention on Mercury*, declaring to take action intended to reduce and, where feasible, eliminate the use of Hg in the mining industry (UNEP, 2019, 2013c). According to the convention, each party is requested to develop appropriate strategies for the identification and assessment of contaminated sites (UNEP, 2013b, 2013c). In Kadoma, the most recent Hg exposure data dates back to 2006 (Baeuml et al., 2011b). Little is known about the current situation and we wanted to provide relevant information on Hg exposure and body burden in Zimbabwe.

The main objective of this study was the collection of current data on Hg exposure of participants identifying themselves as miners from Kadoma and Shurugwi Districts, Zimbabwe. This included the assessment of Hg-related symptoms and Hg concentrations in urine and blood samples. Additionally, an analysis of the correlation between exposure to risk factors and Hg concentrations in human specimens was performed.

2. Materials and methods

This study had a cross-sectional design. Hg concentrations in urine and blood were assessed. Exposure risk factors influencing the Hg concentrations were determined for participants who identified themselves as miners working in Kadoma and Shurugwi District, Zimbabwe.

2.1. Study setting and study population

The study was conducted during two weeks (March 18, 2019 to the March 29, 2019) in two hospitals in the Kadoma and Shurugwi District (Zimbabwe), respectively.

Permission to conduct the study was obtained from the relevant health authorities at regional and district level and the ministry of health. The study was carried out in accordance with the Code of Ethics of the Declaration of Helsinki for experiments involving human subjects. The protocol was approved by the ethics committee of the Medical Research Council and the Research Council of Zimbabwe (MRCZ/A/2367, September 26, 2018 and February 25, 2019) and of the Ludwig Maximilians University of Munich, Germany (18–421, October 15, 2018).

The minimum age of participation was 18 years. All females and males that identified themselves as miners and worked for at least 1 month as miners were included. There was no preselection regarding the participants' state of physical health. To avoid contamination of the human biomonitoring samples, the study centers were located at the hospitals in Kadoma and Shurugwi. Due to the distance between the mining sites and the study centers as well as a hard-to-reach target population, snowball sampling was used to recruit participants. For this sampling technique participants recruited further participants among their colleagues. Local partners established the initial contact with miners, promoted the study and organized transport from the workplace to the study sites for the participants. To compensate for their loss of income on the study day the participants received a per diem of US $ 5 for participation. Prior to the data and sample collection, each participant signed an informed consent form and material transfer agreement, available in three languages: English, Shona and Ndebele. Of the 207 eligible participants all consented to participate: 131 and 76 from Kadoma and Shurugwi respectively. A sub-sample of 93 randomly selected participants were handed an additional questionnaire regarding their handling of Hg. In case of low literacy of the participants, the participant information and informed consent form was read to the participants and fully explained by a research assistant. Participation in the study was voluntary. All samples were analyzed using a code to ensure a confidential analysis.

2.2. Urine and blood collection

All sample containers were labelled with the participant's code for future allocation. Spot urine samples were collected using disposable urine collection cups. For transport and analysis, aliquots of the urine samples were transferred into a urine monovette (Sarstedt®). To prevent bacteria growth and degradation the samples were acidified with nitric acid to a pH of approximately 2, which was tested with a pH strip. Trained health professionals took blood samples in 7 ml Lithium-Heparin-coated tubes for trace metal analyses (Sarstedt®) from all participants. All samples were continuously stored at 4 °C. Once located in the laboratory, samples were stored at – 18 °C. For further details on methodology see Baeuml et al. (2011a).

2.3. Mercury determination

Urine and blood specimens were analyzed without any pre-processing by direct Hg analysis using a DMA80-evo® instrument (MLS GmbH, Leutkirch, Germany). 100 µL of each sample was directly pipetted into quartz tubes for analysis. All of the steps were part of the automated Hg analysis. Hg was detected by atomic absorption at 253.5 nm. The quantification was based on an external calibration. The detection limit for total Hg in urine and blood using DMA80-evo was 0.05 µg/L. For quality control ClinChek® -Control (Recipe, Munich, Germany) reference material for whole blood and urine was used. Reference material was analyzed approximately every 40–50 samples and at least once every day of analysis. All samples were measured twice. Once standard deviation of the duplicate was more than 20%, a third measurement was performed for precision. In terms of external quality assurance, the laboratory participated and successfully passed the G-EQUAS ring trial (German External Quality Assesment Scheme For Analyses in Biological Materials) for mercury analyses in blood and urine.

Additionally, creatinine in urine samples was determined for creatinine corrected Hg levels. Creatinine corrected urine values were considered, in order to remove the influence of the effect of urine dilution on the exposure indicator. Urine samples were sent to the central laboratory of University hospital of LMU and analyzed with Cobas C702 using the Jaffé-method. Creatinine adjusted Hg urine values (HgCr) with creatinine levels < 0.3 g/l and > 3.0 g/l were excluded from analysis.

2.4. Threshold values

To summarize the results in terms of exposure level, threshold values were used. There are no internationally approved threshold values for elemental Hg exposure of gold miners (Lettmeier et al., 2010). Therefore recommendations for threshold values for total Hg in urine,

Table 1
Toxicologically established threshold limits, for Hg in urine (HgUr), creatinine-corrected (HgCr) and blood (HgBl); HBM = Human Bio- Monitoring (Commission Human-Biomonitoring of the German Environmental Agency, 1999).

Exposure limit values of mercury	HgUr [μg/L]	HgCr [μg/g creatinine]	HgBl [μg/L]	Classification
Below HBM I	≤7	≤5	≤5	Low level
HBM I - HBM II	> 7 to ≤ 25	> 5 to ≤ 20	> 5 to ≤ 15	Alert level
Above HBM II	> 25	> 20	> 15	High level

creatinine – corrected urine and blood from the German Human Biomonitoring Commission were applied (Schulz et al., 2007). The classification is based on two threshold levels with a detailed classification of Hg concentration for each specimen (Table 1). All values below the threshold of human biomonitoring (HBM) I are considered "normal/low" level. Values between HBM-I and HBM-II indicate the "alert" level, where adverse health effects cannot be excluded. Therefore, it is recommended to identify possible sources and reduce or eliminate the exposure (Ewers et al., 1999). Concentrations above HBM II are classified as "high/action" levels, where the risk for negative health effects is increased and the reduction of the exposure is necessary (Ewers et al., 1999; Schulz et al., 2007).

2.5. Outcome variables

Hg levels in urine [(HgUr) in μg/L], creatinine corrected urine values [(HgCr) in μg Hg/g creatinine] and blood [(HgBl) in μg/L] are classified into their respective HBM threshold categories and further merged into combined HBM threshold values, respecting all specimens (*combined HBM values*). Assessment and evaluation of Hg related symptoms and Hg intoxication are explained in Appendix A.1 and A.2.

2.6. Explanatory variables

Regarding possible influencing factors on Hg intoxication, the following variables were evaluated:

- Last time of contact with mercury [*Last time Hg* (1–2 days/3–7 days/1–4 weeks/ > 4 weeks)]
- How many years did you work in mining [*years mining* (in years)]
- Use of a retort [*retort use* (yes/no)]. A retort is a simple device capturing the Hg vapor and condensing it to liquid Hg (Telmer and Stapper, 2012)
- Whether working clothes were worn at home or not [*work clothes at home* (yes/no)]
- If Hg is not stored at all or at work as opposed to at home [*Hg storage* (no/at work/at home)]

Additionally, to analyze a possible correlation between binary coded exposure risk factors and Hg concentrations in the sample an exposure risk score was established. It links the exposure risk of each participant to his or her respective Hg concentration. A score point was added to the exposure risk score for each variable if the higher Hg exposure was likely [*retort use* (no); *work clothes at home* (yes); *Hg storage* (at home)]. Therefore, the exposure risk score ranges from 0 to 3. Fish consumption (< once a week/ > once a week) was considered as a potential bias, because fish accumulates Hg in the form of methyl-Hg (Steckling et al., 2014a).

2.7. Statistical analysis

Statistical analyses were performed using the statistical software IBM SPSS®, Version 25. Continuous variables were summarized using median and interquartile range (25th percentile – 75th percentile) due to non-parametric distribution of most variables. Categorical and nominal variables were summarized using frequencies and percentages. All continuous variables were tested for normality using the *Shapiro-Wilk* test and graphical methods (e.g. histograms). All analyses were stratified by location. For detailed analysis in terms of study location, see Appendix B.

Chi-square tests were used to test differences between nominal and categorical variables by area of residence. *Mann-Whitney-U* tests were conducted to examine differences between the medians of continuous variables by area of residence. Due to non-parametric distribution robust *Spearman's correlation coefficients* were used to examine the correlations between variables.

The following tests were performed to identify possible exposure risk factors for elevated Hg concentrations. The variables *retort use*, *work clothes at home* and *Hg storage* were tested for differences regarding the Hg levels employing *Mann-Whitney-U* test. *Jonckheere-Terpstra* test was used to examine a trend towards increased Hg levels across the exposure risk score and *last time Hg*. *Kruskal-Wallis* test examined difference of *years mining* across the *combined HBM values*. Reference groups were determined based on the group category with the lowest Hg exposure.

Mann-Whitney-U test was applied to test for differences of fish consumption across the Hg levels.

3. Results

From 207 participants, 131 (63.3%) were from Kadoma and 76 (36.7%) from Shurugwi (Table 2). In the study sample, men accounted for 81.2%, which corresponds with the gender distribution among miners. The exposure risk factors include the following variables; *retort use* (no: 69.1%), *work clothes at home* (yes: 31.9%), *Hg storage* (at home: 33.8%).

Moreover, *last time Hg* was assessed with the majority of participants having used Hg in the last one to two days (38.7%). There was no significant difference in mercury concentrations of HgUr, HgCr and HgBl between the groups of fish consumption. There was a significant difference between the two study locations in terms of the median of *years mining* with 10 years in Kadoma and 7 years in Shurugwi ($p = 0.035$).

3.1. Human biomonitoring results

In Table 3 the HgUr, HgCr and HgBl concentrations are shown stratified by study setting. In urine samples the median value of total Hg concentration was 4.75 μg/L ranging from 0.08 to 612 μg/L. The overall median HgCr value was 3.98 μg/g creatinine with a maximum of 478 μg/g creatinine. Mean urine creatinine level was 1.44 g/l with a minimum of 0.32 g/l and a maximum of 2.90 g/l (Appendix B.1). The minimum and maximum total HgBl concentration were 0.20 μg/L and 167 μg/L, respectively, with a median of 2.70 μg/L for the overall sample. Overall, 26% of the participants had Hg concentrations for *combined HBM values* between HBM I and HBM II and 26% above HBM II.

3.2. Exposure risk factors and their influence on Hg values

3.2.1. Exposure risk score

For the human specimens, there was an almost 5- fold higher

Table 2
Demographic details of the study population according to location of mining.

		Kadoma		Shurugwi		*Mann-Whitney-U* test	Overall	
		N		N			N	
Age	Median (Min. - Max.)	39	(18–77)	37	(18–62)	p = 0.06	38	(18–77)
Years mining	Median (Min. - Max.)	10.0	(0.5–48)	7.0	(0.1–30)	p = 0.035*	10	(0.1–48)
		N	(%)	N	(%)	***Chi square* test**	N	(%)
Gender	Males	109	(83.2)	60	(78.9)	p = 0.45	169	(81.6)
	Females	22	(16.8)	16	(21.1)		38	(18.4)
Retort use	Yes	23	(17.5)	12	(15.8)	p = 0.26	35	(16.9)
	No	79	(60.3)	64	(84.2)		143	(69.1)
	Missings	29	(22.1)				29	(14.0)
Work clothes at home	No	67	(51.1)	45	(59.2)	p = 0.38	112	(54.1)
	Yes	35	(26.7)	31	(40.8)		66	(31.9)
	Missings	29	(22.1)				29	(14.0)
Hg storage	No/at work	64	(48.9)	44	(57.9)	p = 0.51	108	(52.2)
	At home	38	(29.0)	32	(42.1)		70	(33.8)
	Missings	29	(22.1)				29	(14.0)
Last time Hg	> 4 weeks	10	(7.6)	7	(9.2)	p = 0.72	17	(8.2)
	1–4 weeks	8	(6.1)	6	(7.9)		14	(6.8)
	3–7 days	14	(10.6)	12	(15.8)		26	(12.6)
	1–2 days	16	(12.2)	20	(26.3)		36	(17.4)
	Missings	83	(63.4)	31	(40.8)		114	(55.1)
Fish consumption	< once a week	23	(17.6)	19	(25.0)	0.20	42	(20.3)
	> once a week	108	(82.4)	57	(75.0)		165	(79.7)

Mann-Whitney-U test to analyze possible significant difference in median between the two study locations.
Significant * = $p < 0.05$; Min.: Minimum; Max.: Maximum.
Chi square test (*Pearson*) to show significant differences between the two study locations for all parameter.
All test were performed using available case analysis. Missing values are presented and percentage given for all available cases in the respective variable.

median for HgCr those who are not *using a retort* when handling Hg. The exposed group who stores Hg at home had a 2.5 fold higher median HgCr concentrations compared to the non-exposed group (Table 4). A 1.8-fold, 1.5-fold and 1.6-fold higher HgBl median concentration was discernible for the exposed groups of the variables *retort use, work clothes at home and Hg storage*, respectively. In all variables the exposed group showed a strong tendency towards higher Hg values compared to the reference. The combined exposure risk score (*retort use*, *work clothes at home* and *Hg storage*) showed a trend towards increased HgBl and HgCr median concentrations with increasing risk score (*Jonckheere – Terpstra Trend* test both $p < 0.01$). Fig. 1 pictures the boxplot of the logarithmized Hg concentrations for HgCr and HgBl showing increasing Hg levels with the existence of one or more exposure risk factors.

3.2.2. Exposure risk of last time Hg use

The highest median of *last time Hg* use for the biomonitoring parameters could be found in the category *1–2 days* (Table 4). The following two categories of *last time Hg* did not show a clear time trend regarding median Hg values. The last category *> 4 weeks* showed the smallest median Hg values across all categories.

3.2.3. Exposure risk of years mining

The violin plot in combination with the *Kruskal-Wallis* test showed that along the categories of *combined HBM values* for *all specimens below HBM I* participants have significant lower years of mining (Fig. 2).

4. Discussion

This cross-sectional study identified increased Hg levels in urine and blood in participants identifying themselves as miners from Kadoma and Shurugwi. Moreover, a correlation between increased Hg concentrations in human specimens and selected exposure risk factors was established.

Table 3
Human biomonitoring results stratified by study location and for the overall sample.

		Kadoma		Shurugwi		*Mann Whitney < U test*	Overall
HgUr [µg/L]	N (%)	131	(63.3)	76	(36.7)		207
	25th Percentile	0.77		1.43			0.92
	Median	3.53		6.48		p = 0.030*	4.75
	75th percentile	14.0		29.2			20.7
HgCr [µg/g crea.]	N (%)	122	(63.2)	71	(36.8)		193+
	25th Percentile	0.51		1.15			0.64
	Median	3.25		5.31		p = 0.053	3.98
	75th percentile	12.7		23.0			16.5
HgBl [µg/L]	N (%)	131	(63.3)	76	(36.7)		207
	25th Percentile	0.90		1.53			1.2
	Median	2.10		3.25		p = 0.108	2.70
	75th percentile	6.30		5.90			6.3

Mann-Whitney-U test testing median of variables for significant differences between the two study locations:* significant = $p < 0.05$. N = Number of samples. + HgCr number of samples different due to exclusion of thirteen samples due to creatinine values < 0.3 g/L and > 3.0 g/L. HgBl: Mercury concentration in blood, HgCr: Mercury concentration in urine which is corrected for creatinine, HgUr: Mercury concentration in urine. No Hg level was below detection limit of 0.05 µg/L.

Table 4
Hg concentrations for all specimens stratified by exposure risk factors.

Overall		HgBl [µg/L] Median (IQR)		N	HgCr [µg/g crea.] Median (IQR)		N
Retort use	Yes	1.40	(4.75)	35	0.86	(9.30)	34
	No	2.50	(4.70)	143	4.25	(16.7)	132
Mann - Whitney - U		p = 0.096			p = 0.021*		
Work clothes at home	No	2.10	(4.27)	112	2.86	(12.1)	104
	Yes	3.25	(7.38)	66	4.25	(22.9)	62
Mann - Whitney - U		p = 0.025*			p = 0.068		
Hg storage	No/at work	1.95	(4.30)	108	2.09	(12.6)	99
	At home	3.20	(6.60)	70	5.3	(17.5)	67
Mann - Whitney - U		p = 0.008**			p = 0.046*		
Exposure risk score	0	0.90	(3.20)	21	0.60	(7.16)	21
	1	2.10	(4.30)	65	3.98	(16.7)	57
	2	2.50	(5.10)	62	3.98	(15.1)	60
	3	4.15	(8.43)	30	6.10	(29.8)	28
Jonckheere-Terpstra		p = 0.001++			p = 0.003++		
Last time Hg	> 4 weeks	2.10	(3.38)	17	1.45	(5.05)	16
	2–4 weeks	3.20	(6.95)	14	4.38	(21.8)	13
	3–7 days	2.35	(8.05)	26	3.55	(12.0)	24
	1–2 days	4.60	(20.8)	36	13.85	(48.4)	35
Jonckheere-Terpstra		p = 0.094			p = 0.025+		

Mann-Whitney-U test testing for significant differences between the reference and the exposure: * = significant with p values < 0.05,: ** = significant with p values < 0.01.
Jonckheere-Terpstra trend test to test for significant differences between the subgroups with an a priori ordering of the respective variable: + = significant with p values < 0.05, + + = significant with p values < 0.01. HgBl: Mercury concentration in blood, HgCr: Mercury concentration in creatinine corrected urine values. Exposure risk score: combines individual exposure risk regarding retort use, work clothes at home and Hg storage. N for HgCr different due to exclusion of samples with creatinine values < 0.03 g/L and > 3.0 g/L. IQR: Interquartile range.

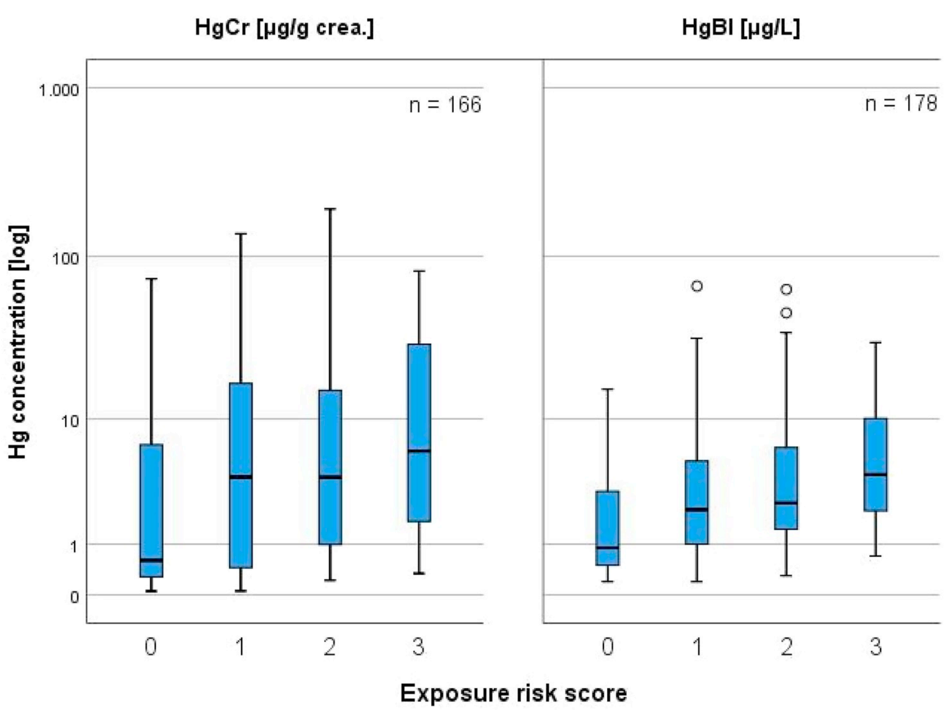

Fig. 1. Boxplot with logarithmized Hg concentrations for HgCr and HgBl by exposure risk score. HgBl: Mercury concentration in blood, HgCr: Mercury concentration in creatinine corrected urine values, Exposure risk score: combined individual exposure risk regarding retort use, work clothes at home and Hg storage. N for HgCr different due to exclusion of samples with creatinine values < 0.03 g/L and > 3.0 g/L.

4.1. Differences between study locations: Kadoma vs. Shurugwi

Higher Hg concentrations in all specimens in Shurugwi compared to Kadoma may be attributed to several factors including use of protective devices, variations in the method of gold extraction, extent of Hg use and awareness of the toxic nature of Hg (Kristensen et al., 2014). As the exposure risk factors indicate, the participants from Shurugwi were more exposed to Hg in all relevant variables compared to the participants from Kadoma (Table 2). Lower uptake of retort use in Shurugwi could partly explain this difference. Moreover, Kadoma was subject to earlier interventions (e.g. safety and Hg free mining trainings) (Steckling et al., 2014b). The analyses stratified by location showed that significant differences for the outcome variables of the overall sample are largely deriving from the analyses of the sample from Kadoma (Table 3, Appendix B, Table B.6 and B.7).

4.2. Human biomonitoring

Fifty-two percent of the sample had Hg concentrations exceeding HBM-I or HBM-II threshold values (Appendix B, Table B3). This indicates that individuals are exposed via occupational and environmental routes to high levels of Hg in Kadoma and Shurugwi, Zimbabwe.

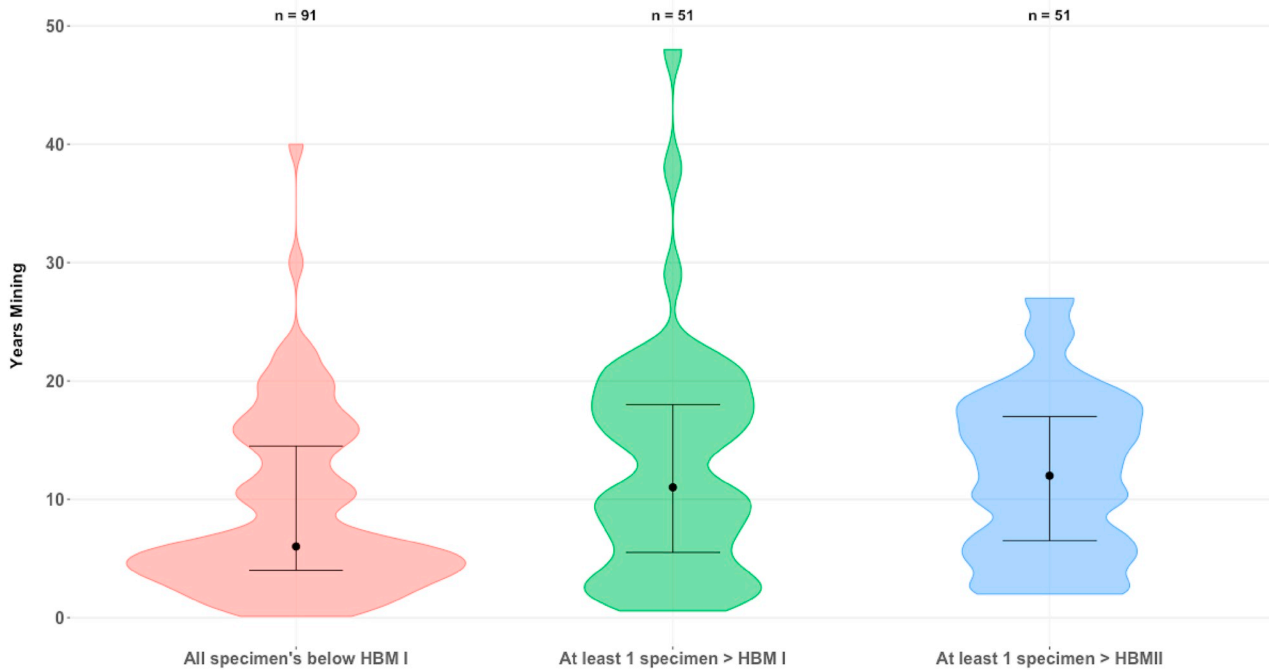

Fig. 2. Violin plot of years mining across the combined HBM value categories. Kruskal-Wallis test $p - value < 0.01$. Combined HBM value categories: Hg biomarkers classified into their respective HBM threshold categories and further merged into combined HBM threshold values. •: Median; All specimens below HBM I: 6 years mining. At least one specimen above HBM I: 11 years mining. At least one specimen above HBM II: 12 years mining. Lower whisker: 25th percentile. Upper whisker: 75th percentile.

Given the economic circumstances (Chan, 2019) and the growing popularity of ASGM in Zimbabwe (Chenjerai, 2017), we expected generally higher Hg concentrations.

In 2004, Hg concentrations of miners in Kadoma, Zimbabwe were assessed. The exposed group median HgUr was seven times the median of our findings. HgCr values were approximately a quarter lower than HgUr concentrations (Baeuml et al., 2011b), indicating hot temperatures and lower fluid intake (Nemery and Nkulu, 2018). The median HgBl in the exposed group by Baeuml et al. (2011b) was three times higher than in our sample. Basu et al. (2018) included 17 studies in a pooled analysis concerning Hg concentration of the ASGM population worldwide. The pooled analysis revealed a central median urine concentration of 5.9 μg/L and an upper median urine concentration of 188 μg/L. Central median HgBl concentration was 10.9 μg/L which is approximately fourfold the median of our findings. Relative to results presented by Basu et al. (2018) and Baeuml et al. (2011b) our sample included low to medium Hg concentrations. This supports the assumption that our study sample consists of regular miners as well as intermittent miners. Alternatively, most workers in ASGM work in ore extraction and crushing operations, and only a minority actually handle Hg during the amalgamation process with less still involved in the final burning of the amalgam. Kristensen et al. (2014) emphasize the difficulty of stratification by work tasks, and similarly in this study most miners were multi-tasking and as such, allocation of responses to task groups was not straightforward. Therefore, the stratified analysis, which might have given more differentiated and higher Hg values for certain exposure groups, was not possible. It should be pointed out that certain individuals have atypical mercury metabolism for various reasons (e.g. genetics, nutrition) which could result in low Hg values (Andreoli and Sprovieri, 2017).

4.3. Exposure risk factors

The main factors that determine Hg exposure levels and whether health effects occur are the exposure duration and the exposure route (Sakakibara and Sera, 2017; WHO, 2016). Kwaansa-Ansah et al. (2019) showed a strong correlation between increased Hg values in urine and the duration of stay at the mining site of miners in Ghana. The same effect was shown for a group of indirectly and directly exposed workers from Indonesia (Sakakibara and Sera, 2017). Our results confirm this positive correlation between *years mining* and steadily increasing HgUr, HgCr and HgBl values as a combined variable (see Fig. 2 and Appendix B, Table B.4 and B.5). Participants who work almost daily with Hg (*1–2 days last time Hg use*) have comparably higher Hg values than the other subgroups (Table 4) (Berlin et al., 2015). This decline of the Hg burden in the body over time was already presented by Roels et al. (1991) for an occupationally exposed group (Berlin et al., 2015). The results from our study show the same effect for ASGM populations. The incongruity between the subgroups *3–7 days* and *2–4 weeks* in terms of Hg median values could be explained by recall bias. Moreover, it indicates that these participants might work more on an irregular basis, whereas people who responded working with Hg in the last *1–2 days* can be considered as full time miners. This underlines our hypothesis, that due to the economic crisis, there is a high number of intermittent miners in Zimbabwe. Both results emphasize the risk of long-term (*years mining*) and chronic (*last time Hg*) exposure especially in regard to the long-term adverse neurological health effects of Hg (WHO, 2016). A detailed analysis and evaluation on Hg related symptoms in this study population can be found in Appendix A.1 and A.2.

There is a direct positive correlation between exposure risk factors, including *retort use*, *work clothes at home* and *Hg storage* and corresponding Hg concentrations in human specimens (Table 4). Many studies emphasize the risk of Hg exposure and mention a corresponding increase in Hg concentration in human specimens (Gibb and O'Leary, 2014; Kristensen et al., 2014; Kwaansa-Ansah et al., 2019; Paruchuri et al., 2010; Sakakibara and Sera, 2017; Steckling et al., 2014a).

In ASGM, the use of retorts is generally rare as well as the use of other protective devices or precautions against Hg exposure (Kristensen et al., 2014; Steckling et al., 2014a). The results of the exposure risk score accentuate the impact simple risk reduction measure can have on the individual's body burden. Nonetheless, it should be kept in mind that miners often have few options in regard to their choice of employment (UNEP, 2013a). As Hg -related symptoms develop over a long time exposure risks and their influence are not obvious to all miners (WHO, 2016). In addition, Hg intoxication has a negative influence on the health-related quality of life among people living in ASGM areas (Butscher et al., 2019).

4.4. Limitation and strength

Our initial intention to attract miners to participate in the study with a per diem of US $ 5 underestimated the current economic hardship in Zimbabwe. It is very apparent that the economic and climatic vicissitudes in the country are pushing more and more people into ASGM as an alternative income strategy (Kuyedzwa, 2020). This leads to high fluctuations in the number of people who intermittently work in mining resulting in widespread knowledge in mining practices. As a result, differentiation between regular miners and intermittent miners became difficult. Moreover, the reluctance of informal or illegal miners to avail themselves for research studies like the current one, e.g. due to their fear of coming into contact with government mining officials (Bose-O'Reilly et al., 2010a) was underestimated. Future studies should address this problem by assessing data directly at the ASGM sites. Moreover, data from a matching control group would have helped to show differences in characteristics.

The objective of the *Minamata Convention* is to protect human health and the environment from anthropogenic emissions and releases of Hg. Therefore, a strength of this study is that we were able to show that Kadoma and Shurugwi are established ASGM areas with Hg exposure. Studies such as this one provide necessary support for the Minamata Convention's assessment of baseline data on Hg use in ASGM, particularly filling a knowledge gap in southern Zimbabwe (Shurugwi).

5. Conclusion

This study presents current data on Hg exposure of people identifying themselves as miners from Kadoma and Shurugwi, Zimbabwe. We found that miners have low to high concentration of Hg. Moreover, a correlation between exposure risk factors such as not using a retort as well as storing Hg at home and elevated Hg concentrations was demonstrated. This study highlights the impact of exposure risk factors on the Hg body burden in the ASGM sector. The results showed increased levels of mercury in urine and blood in two ASGM areas in Zimbabwe. ASGM is very common in Zimbabwe. Thus, mercury exposure is a major occupational health risk for miners. Further research is needed to identify exposure risk factors more in depth and to develop tailored interventions that actively address the use of Hg in ASGM.

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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Ethical approval

Permission to conduct the study was obtained from the relevant health authorities at regional and district level and the ministry of health. The study was carried out in accordance with the Code of Ethics of the Declaration of Helsinki for experiments involving human subjects. The protocol was approved by the ethics committee of the Medical Research Council and the Research Council of Zimbabwe (MRCZ/A/2367, September 26, 2018 and February 25, 2019) and of the Ludwig Maximilians - University Munich, Germany (18–421, October 15, 2018).

CRediT authorship contribution statement

Viola Mambrey: Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Stefan Rakete:** Formal analysis, Funding acquisition, Methodology, Writing - review & editing. **Myriam Tobollik:** Investigation, Writing - review & editing. **Dennis Shoko:** Investigation, Writing - review & editing. **Dingani Moyo:** Investigation, Project administration, Supervision, Writing - review & editing. **Paul Schutzmeier:** Funding acquisition, Writing - review & editing. **Nadine Steckling-Muschack:** Conceptualization, Funding acquisition, Project administration, Writing - review & editing. **Shamiso Muteti-Fana:** Writing - review & editing. **Stephan Bose-O'Reilly:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Writing - review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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List of abbreviations

ASGM Artisanal and small-scale gold mining
Hg Mercury
HgBl Mercury concentration in blood
HgCr Mercury concentration in urine which is corrected for creatinine
Hg storage (no/at work/at home) If Hg is not stored at all or at work opposed to at home
HgUr Mercury concentration in urine
Last time Hg The last time mercury was used for work purposes
Miners Artisanal and small-scale gold miners
Retort use (yes/no) If a retort was used or not. A retort is a simple device capturing the Hg vapor and condensing it to liquid Hg
Work clothes at home (yes/no) Whether working clothes were worn at home or not
Years mining How many years does/did the miner work in mining

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.109379.

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