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ORIGINAL RESEARCH

Global Burden of Disease of Mercury Used in Artisanal Small-Scale Gold Mining

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Abstract

BACKGROUND Artisanal small-scale gold mining (ASGM) is the world's largest anthropogenic source of mercury emission. Gold miners are highly exposed to metallic mercury and suffer occupational mercury intoxication. The global disease burden as a result of this exposure is largely unknown because the informal character of ASGM restricts the availability of reliable data.

OBJECTIVE To estimate the prevalence of occupational mercury intoxication and the disability-adjusted life years (DALYs) attributable to chronic metallic mercury vapor intoxication (CMMVI) among ASGM gold miners globally and in selected countries.

METHODS Estimates of the number of artisanal small-scale gold (ASG) miners were extracted from reviews supplemented by a literature search. Prevalence of moderate CMMVI among miners was determined by compiling a dataset of available studies that assessed frequency of intoxication in gold miners using a standardized diagnostic tool and biomonitoring data on mercury in urine. Severe cases of CMMVI were not included because it was assumed that these persons can no longer be employed as miners. Cases in workers' families and communities were not considered. Years lived with disability as a result of CMMVI among ASG miners were quantified by multiplying the number of prevalent cases of CMMVI by the appropriate disability weight. No deaths are expected to result from CMMVI and therefore years of life lost were not calculated. Disease burden was calculated by multiplying the prevalence rate with the number of miners for each country and the disability weight. Sensitivity analyses were performed using different assumptions on the number of miners and the intoxication prevalence rate.

FINDINGS Globally, 14-19 million workers are employed as ASG miners. Based on human biomonitoring data, between 25% and 33% of these miners—3.3-6.5 million miners globally—suffer from moderate CMMVI. The resulting global burden of disease is estimated to range from 1.22 (uncertainty interval [UI] 0.87-1.61) to 2.39 (UI 1.69-3.14) million DALYs.

CONCLUSIONS This study presents the first global and country-based estimates of disease burden caused by mercury intoxication in ASGM. Data availability and quality limit the results, and the total disease burden is likely undercounted. Despite these limitations, the data clearly indicate that mercury intoxication in ASG miners is a major, largely neglected global health problem.

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KEY WORDS artisanal small-scale gold mining, burden of disease, disability-adjusted life year, global, DALY, mercury, mercury intoxication

INTRODUCTION

Artisanal small-scale gold mining (ASGM) is the largest consumer of mercury worldwide and the largest anthropogenic source of mercury emissions in the environment.[1] In ASGM, gold is extracted using rudimentary techniques, including the use of mercury to bind the gold contained in the ore.[2] Smelting the amalgam releases mercury and leaves gold.[3] The occurring mercury vapor contaminates the environment and affects miners as well as residents living nearby.[4] In these groups, large quantities of mercury are measurable in human specimens and various health problems, such as neurological disorders (eg, tremor) and kidney effects, occur.[5,6]

Because the amount of gold produced in ASGM is still increasing worldwide,[7,8] a rising health burden can be assumed. However, data scarcity restricts the quantification of this disease burden. ASGM is mostly not regulated[9,10] and it is an informal or even illegal activity. Thus, data collection on the health situation at mining sites is difficult, which probably leads to an underestimation of the corresponding disease burden.[11-13]

Some preliminary work has been done to show the extent of this public health issue. Recent reviews summarize studies presenting mercury concentrations in human specimens of miners and residents as well as their related health effects.[5,6] A combination of both human biomonitoring (HBM) and health data was used in a diagnostic algorithm to identify cases of chronic mercury intoxication.[14] This diagnostic tool was applied in several field studies[14-18] and used to calculate preliminary estimates of the burden of disease (BoD) as a result of the use of mercury in ASGM in Zimbabwe. The burden was estimated at about 95,400 disability-adjusted life years (DALYs) using an incidence-based approach and a approximative disability weight (DW).[18] Pure Earth and Green Cross Switzerland[19] assumed a global ASGM BoD of 1.5 million DALYs as a rough estimate. Besides the generally limited database, a missing DW, a factor needed for DALY quantification, hampered the calculation of more valid estimates. Recently, DWs for chronic mercury intoxication as a result of metallic mercury vapor were derived to improve the input data for DALY quantifications.[20] The DWs were based on detailed case descriptions of moderate and severe chronic metallic mercury vapor intoxication (CMMVI),[21] which is assumed to be the main health outcome resulting from exposure to mercury in ASGM.

There is an urgent need to quantify the health burden of mercury used in ASGM to raise awareness and to foster actions targeting a reduction of disease burden. An established method should therefore be used to quantify the burden, so that it can be compared with other risk factors and health conditions. The objective of this project is a rough estimate of the number of DALYs attributable to chronic metallic mercury vapor intoxication in gold miners caused by the use of mercury in ASGM on a global level and for a set of selected countries.

METHODS

DALYs are the sum of years of life lost (YLLs) and years lived with disability (YLDs).[22] YLLs are the product of disease-specific death cases multiplied by a remaining life expectancy at age of death. Prevalence-based YLDs are the product of the number of prevalent cases of a given disease multiplied by its corresponding DW.[23] The DW represents the severity of a disease anchored on a scale between 0 (perfect health) and 1 (a health state comparable to death). The DW is the key element to be able to sum up the time lost due to premature death and time lived in a state of reduced health.[24] DALY quantifications were performed without age weighting and time discounting.[25] Assuming no fatal effects of CMMVI, the DALYs in our estimates only represent the morbidity component YLDs.

Available data on key parameters were used to calculate DALYs resulting from the use of mercury in ASGM. All model components, underlying concepts, and assumptions are described below and summarized in Table 1.

Subgroup of Interest. The estimation focuses on artisanal small-scale gold miners. This includes all

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Table 1. Summary of Assumptions and Methodological Decisions

DALY quantification	• DALYs = YLLs + YLDs
	• YLDs = prevalent cases * DW
	• As no mortality is assumed (see row "mortality"), the DALYs consist of 100% YLDs
	• Prevalence-based approach
	• No age weighting and time discounting
Subgroups included	• Artisanal small-scale gold miners, of all ages, male and female, were included.
	• No stratifications by sex and age were intended because of a scarcity of data.
	• Subgroups other than miners (eg, family members, other residents in ASGM areas) were not included in the analyses because of data restrictions.
Health outcome	• The outcome considered was moderate CMMVI as defined by Steckling et al.[20]
	• Severe CMMVI as defined by Steckling et al[20] was excluded from the analyses because it cannot be assumed that a gold miner with such a severe intoxication is still able to work.
	• It was assumed that the miners had not received medical treatment for their condition.
	• Mercury-related and non–mercury-related health effects other than moderate CMMVI caused by ASGM were excluded from this analysis.
Prevalence	• The prevalence estimates were based on a pooled analyses of primary data from 5 countries (Ecuador, Indonesia, Philippines, Tanzania, Zimbabwe) applying the rapid diagnostic algorithm developed by Doering et al,[30] on the basis of Drasch et al.[14] Diagnosis included urine samples (no blood or hair samples).
	• Prevalence was then applied to published HBM data by adapting the analyses to the data structure of every single HBM study.
	• It was assumed that the estimated prevalence rates reflected the approximate range of prevalence globally.
	• Stratifications regarding involvement in ASGM (panners vs smelters), sex, and gender were not intended because of a scarcity of data.
Disability weight (DW)	• DW for moderate CMMVI was 0.368 (uncertainty interval [UI]: 0.261-0.484).[20]
	• It was assumed that the DW reflects the severity of CMMVI on a scale between 0 (perfect health) and 1 (status equal to death)
Mortality	• Based on published research, mortality as a consequence of CMMVI was excluded.[18]
	• YLLs therefore are assumed to be zero.

ASGM, artisinal small-scale gold mining; CMMVI, chronic metallic mercury vapor intoxication; DALY, disability-adjusted life year; DW, disability weight; HBM, human biomonitoring; UI, uncertainty interval; YLDs, years lived with disability; YLLs, years of life lost.

workers involved in any step of the gold mining process, with direct or indirect contact to mercury: workers and millers mixing the ore with mercury, smelters conducting the amalgam smelting process, as well as refiners, also called gold dealers or gold shop workers. Environmentally exposed residents and family members of miners are not included.

Number of Miners. There are no registers or official numbers of artisanal small-scale gold (ASG) miners worldwide available. Telmer and Veiga[26] created a list of countries with ASGM activity. Seccatore et al[27] summarized estimates of country-specific numbers of miners and supplemented them with modeled estimates and thus this review was the most complete source for numbers on miners working in ASGM per country. These estimates were supplemented by information from a structured literature search performed in PubMed, Google, and Google Scholar (search terms: "*country name*" AND "artisanal small-scale gold mining"). To consider alternative estimates, different scenarios were formulated: one with the highest estimates of miners (maximum scenario), one with the lowest estimates of miners (minimum scenario), and one restricted to the numbers estimated by Seccatore et al.[27]

Health Outcome. The quantification focuses on the health effects of chronic exposure to metallic mercury vapor, which is the main exposure in ASGM.[4] There is no standardized and internationally agreed upon definition or diagnosis for chronic mercury intoxication. In a separate project,[21] 85 distinguishable health symptoms related to this type of mercury exposure were identified. The most common symptoms were used to develop disease descriptions of moderate and severe CMMVI.

Drasch et al[14] developed a practical diagnostic tool for chronic mercury intoxication. The tool includes information about mercury in human specimens (blood, hair, urine) in combination with health data summarized in a medical score. This diagnostic tool, recommended by the United Nations Environmental Programme (UNEP) and the World Health Organization (WHO)[4] as well as Veiga and Baker,[28] was used in studies examining health outcomes in ASG miners.[14,15,17,29] Recently, the tool was reevaluated by Doering et al[30] to develop a set of essential indicators to simplify data collection. For the current analysis, the condensed version[20] of the detailed disease description of moderate CMMVI[21] was used to define the health outcome of interest. The health outcome was assessed applying the diagnostic tool called "essential indicators"[30] but limited to the single information on elemental mercury in urine. Elemental mercury vapor is the primary form to which ASG miners are exposed, and this can be accurately measured in urine.[31] A detailed description of the diagnostic tool applied in the current project is given in Table 2, in which differences with the previous diagnostic tools[14,30] are also described.

Although exposures to other forms of mercury (eg, methylmercury from contaminated food or water) are also common in some ASGM areas, this project focuses on the main occupational exposure pathway. Because of the hazards of gold mining, gold miners are additionally affected by a great number of other health outcomes and risk factors such as infectious diseases, accidents, and dust-related health effects.[32] The disease burden of these other risk factors was not considered in the current analysis.

Prevalence. The diagnostic tool developed by Drasch et al[14] has previously been applied to samples of gold miners in Indonesia,[16,17] Tanzania,[29] Philippines,[14] and Zimbabwe.[18] For the current analysis, raw data from these studies were pooled and reanalyzed in the new built primary dataset. The analysis was based on urine samples, and the essential indicators of the diagnostic tool[30] were applied (Table 2). Additionally, it was possible to supplement this dataset with raw data containing health and HBM data from a sample of 36 gold miners in Ecuador[33] which had not yet been assessed to diagnose intoxication.

This primary dataset was analyzed using crosstabs in SPSS version 23 (SPSS Inc., Armonk, NY). The resulting prevalence of chronic mercury

Table 2. Diagnostic Tool (based on Drasch et al[14] and Doering et al[30]) Used to Identify Cases of Moderate Chronic Metallic Mercury Vapor Intoxication (CMMVI) Applied to Analyze the Primary Dataset

Diagnosis Tool Applied in the Recent Quantification	Medical Score Sum		
	0-2 points	3-4 points	5-10 points
Mercury concentration in urine*			
<7 µg/L or 5 µg/g cr	Not intoxicated	Not intoxicated	Not intoxicated
Between 7 and <25 µg/L or 5 and <20 µg/g cr	Not intoxicated	Not intoxicated	Intoxicated
>25 µg/L or 20 µg/L cr	Not intoxicated	Intoxicated	Intoxicated

Health Indicators Included in the Medical Score Sum†	Evaluation	
1. Ataxia of gait‡	0 = no symptom	1 = symptom
2. Dysdiadochokinesia‡	0 = no symptom	1 = symptom
3. Excessive salivation§	0 = no symptom	1 = symptom
4. Gray to bluish discoloration of the oral cavity‡	0 = no symptom	1 = symptom
5. Heel to shin ataxia‡	0 = no symptom	1 = symptom
6. Matchbox test‖,¶	0 = good performance	1 = restricted performance
7. Pencil tapping test‖,**	0 = good performance	1 = restricted performance
8. Proteinuria‡	0 = no symptom	1 = symptom
9. Sleeping problems at night§	0 = no symptom	1 = symptom
10. Tremor at work§	0 = no symptom	1 = symptom

cr, creatinine.
* In Drasch et al[14] and Doering et al,[30] hair and blood samples were additionally included.
† In Drasch et al.[14] the following health indicator were additionally included: metallic taste,§ health problems worsened since Hg exposed,§ finger to nose tremor.‖
§ Surveyed by a questionnaire.
‡ Surveyed by clinical examination.
‖ Surveyed by neuropsychological tests.
¶ Matchbox test was developed by Zimmer and Volkamer.[63] The test was evaluated as good performed if 17 seconds or less were needed to put 20 matches into the matchbox (15 cm away) by using alternating hands.
** Pencil tapping test was developed by Zimmer and Volkamer.[63] The test was evaluated as good performed if more than 45 dots were made within 10 seconds.

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Table 3. Prevalence of Chronic Mercury Intoxication as Determined in the Primary Dataset Based on 677 Gold Miners

Unit	n	Subgroup	Concentration Steps Used for Data Analysis	Proportion of Sample per Concentration Step	Prevalence of Moderate CMMVI in Concentration Steps	Estimated Summary Prevalence
Mercury in μg/L	663	Gold miners from Ecuador (n = 36), Indonesia (n = 235), Philippines (n = 87), Tanzania (n = 128), Zimbabwe (n = 177)	0.1-6.9 μg/L	34.7%	0.0%	29.6%
			7-24.9 μg/L	31.2%	19.8%	
			25.0-99.9 μg/L	22.0%	68.5%	
			100-199.9 μg/L	6.0%	67.5%	
			200-299.9 μg/L	2.3%	80.0%	
			300.0-399.9 μg/L	1.5%	70.0%	
			400.0-5249 μg/L	2.3%	60.0%	
Mercury in μg/g cr	603	Gold miners from Indonesia (n = 221), Philippines (n = 87), Tanzania (n = 129), Zimbabwe (n = 166)	0.08-4.9 μg/g cr	40.0%	0.0%	24.2%
			5.0-19.9 μg/g cr	29.9%	17.8%	
			20.0-99.9 μg/g cr	21.1%	63.0%	
			100.0-199.9 μg/g cr	6.0%	58.3%	
			200.0-299.9 μg/g cr	1.5%	77.8%	
			300.0-1697.39 μg/g cr	1.5%	66.7%	

Parts of the data were analyzed previously by applying different analysis methods.[14-18,29,33,64,65]

intoxication was applied to available samples of urine data using the following method: First, publications containing data on mercury in human urine samples from ASG miners were identified using 2 current reviews.[5,6] The original publications were obtained and useful data on mercury in urine were extracted. An ideal dataset would have been a complete list of the individual mercury concentrations in the urine of each miner. If not available, the range (minimum value, maximum value), median, percentiles, quartiles of mercury in human specimens of miners or percentages of individuals exceeding a defined value (eg, more than 25 μg/L) were used. Mercury concentrations in urine measured in micrograms per liter (μg/L) were preferred. If not available, mercury concentrations in micrograms per gram creatinine (μg/g cr) were extracted and used.

Then the primary dataset was reanalyzed according to the respective structure of the data given in the publications (exemplary data structure: 2-25 μg/L: 35% of the sample; 25.1-99.9 μg/L: 55%; 100-120 μg/L: 10%). The prevalence of moderate CMMVI for the sample in the original publication was determined in the primary dataset per concentration category given in the original HBM publication. A detailed list is included in Supplemental Material 1. One overall prevalence estimate for all studies included was derived. This was done by weighting the prevalence estimates by the number of individuals in the respective category. One resulting overall prevalence rate was applied to the gold mining population of each country with ASGM activity included in this quantification (minimum scenario). Using a country-specific prevalence based on the data available was not intended, because it cannot be assumed that the HBM studies available are representative for the mercury exposure of miners in the entire country. Furthermore, for most countries no HBM studies were available.

In a second scenario, an alternative prevalence estimate was derived based on the exclusion of studies with a specific focus on subgroups (eg, children, women, gold miners using retorts) or that included specific subgroups besides miners (eg, exposed residents in ASGM or former miner). Consequently, the second scenario had a narrowed focus on gold miners and gold shop workers (maximum scenario).

Disability Weight. To calculate YLDs, a disease-specific DW is necessary. Steckling et al[20] derived DWs for moderate (DW: 0.368; uncertainty interval

[UI]: 0.261-0.484) and severe CMMVI (DW: 0.588, UI: 0.193-0.907). The DW of moderate CMMVI, which is used in this analysis, is based on the same disease description used in this study and described earlier. Severe cases of CMMVI were excluded because it is assumed that gold miners suffering from such severe health effects are no longer able to work and thus not included in the prevalence numbers. YLDs are presented with UIs basically indicating the impact of the uncertainty of the DW.

Mortality. Mortality as a consequence of chronic mercury intoxication is ruled out. This assumption was made based on the published research as summarized previously.[18] Therefore, only the morbidity part—the YLDs—is calculated and added to zero YLLs to express DALYs.

RESULTS

Sixty-two countries were considered in the analysis, with most countries from the WHO African Region (34) and the least from the WHO South-East Asia Region (2). No data on miners or prevalence data on mercury intoxication were found for the WHO European Region, which therefore was excluded. Other countries had to be excluded because no information on the number of miners could be found through the review by Seccatore et al[27] and the new literature search. However, for some of these excluded countries, the UNEP report stated the use of mercury in ASGM, such as Gambia, Guatemala, Honduras, Lesotho, and Malaysia. The literature search turned up new information on the number of miners for 6 further countries (Burkina Faso, Cambodia, Dominican Republic, Ghana, Mongolia, Nigeria) not listed by Seccatore et al.[27]

Of these 62 countries, the estimated number of miners in the minimum scenario is 14.0 million, 2 million less than Seccatore et al[27] have estimated. The maximum scenario comprises 18.9 million miners (34% more miners). With a number above 2.7 million miners, most of the miners live in China. The greatest difference between the assumed minimum and maximum was seen for the Democratic Republic of Congo (difference: 2,310,000), Sudan (709,000), Ghana (594,000), and Ethiopia (428,000). Table 4 contains the numbers of miners by country and the reporting references.

The primary dataset was based on 677 miners from Ecuador, Indonesia, Tanzania, Philippines, and Zimbabwe. Overall prevalence of moderate CMMVI in the primary dataset was estimated at 24.2%-29.6%, depending on whether mercury concentrations were measured in micrograms per liter or micrograms per gram creatinine (Table 3).

Twenty-five HBM studies including mercury concentrations in urine were analyzed in addition to the 5 studies whose data were included in the primary dataset. The analysis covers 15 countries (see Supplementary Material 1). One HBM study contained no useful information for this project (study conducted in Thailand[34]). This reduced the number to 29 studies from 14 countries. The most HBM studies were found for Brazil (7 studies).

The sample size of the studies varies considerably from 11[35] to 865 individuals.[34] A total of 3194 individuals were analyzed, including 677 from the primary dataset and 2517 from 24 additional HBM studies. The mean weighted prevalence rate of chronic mercury intoxication over the pooled studies was estimated at 23.7%, resulting in a total number of 3.3-4.5 million intoxicated miners (depending on the total numbers of miners assumed). Because some studies have a focus on subgroups, such as female miners,[36] children,[37,38] or a sample of the subgroup with the greatest exposure,[37,38] these studies were excluded for a second scenario to determine the overall prevalence. The remaining studies with a total number of 1590 individuals include only active miners and gold shop workers. The mean weighted prevalence rate is much higher with 34.3%. The underlying quantification of study-specific prevalence is shown in the Supplementary Material 1.

The burden ranges from 1.22 (UI 0.87-1.61, minimum number of miners, lower prevalence) to 2.39 (UI 1.69-3.14, maximum number of miners, higher prevalence) million DALYs lost as a result of chronic mercury intoxication (Table 4). The scenario based only on the lower estimates of miners from Seccatore et al[27] yielded 1.42 (UI 1.0-1.87) million DALYs if using the lower prevalence rate of 23.7% and 2.05 (UI 1.46-2.70) million DALYs if using the higher prevalence rate of 34.3%. The resulting disease burden is between the minimum and maximum estimate shown earlier.

The burden is not equally distributed throughout the WHO regions (Figure 1). Although the same mean prevalence was assumed for all countries, the burden varies based on the number of miners per country. The burden per 100,000 inhabitants[39] is highest in the African region and lowest in the South-East Asian region (Fig 2). However, only India and Indonesia were included in the South-East Asian region, compared with 34 African countries.

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Table 4. Numbers of Miners per Country and Years Lived With Disability (YLDs, corresponding to Disability-Adjusted Life Years [DALYs]), Minimum and Maximum Scenarios With Uncertainty Intervals (UI) Based on Disability Weights (DWs)

WHO Regions	Countries Where ASGM Is in Practice	No. of miners				YLDs (corresponding to DALYs)	
		Minimum Estimate	Reference	Maximum Estimate	Reference	Minimum Scenario* (UI)	Maximum Scenario† (UI)
African Region	Algeria	7000	27	7000	27	610 (433-803)	882 (626-1161)
	Angola	218,000	27	218,000	27	19,010 (13,482-25,002)	27,482 (19,491-36,144)
	Benin	15,000	27	15,000	27	1308 (928-1720)	1891 (1341-2487)
	Botswana	15,000	27	15,000	27	1308 (928-1720)	1891 (1341-2487)
	Burkina Faso	400,000	66	400,000	66	34,880 (24,738-45,875)	50,425 (35,763-66,320)
	Burundi	91,000	27	91,000	27	7935 (5628-10,436)	11,472 (8136-15,088)
	Cameroon	44,000	27	44,000	27	3837 (2721-5046)	5547 (3934-7295)
	Central African Republic	291,000	27	291,000	27	25,375 (17,997-33,374)	36,684 (26,018-48,248)
	Chad	146,000	27	146,000	27	12,731 (9029-16,744)	18,405 (13,054-24,207)
	Democratic Republic of Congo	600,000	66	2,910,000	27	52,320 (37,107-68,812)	366,841 (260,178-482,476)
	Equatorial Guinea	15,000	27	15,000	27	1308 (928-1,720)	1891 (1341-2487)
	Ethiopia	300,000	1	728,000	27	26,160 (18,554-34,406)	91,773 (65,089-120,702)
	French Guiana	7000	27	7000	27	610 (433-803)	882 (626-1161)
	Gabon	36,000	27	36,000	27	3139 (2226-4129)	4538 (3219-5969)
	Ghana	200,000	67	1,000,000	66	17,440 (12,369-22,937)	126,062 (89,408-165,799)
	Guinea	200,000	27	300,000	27	17,440 (12,369-22,937)	37,819 (26,823-49,740)
	Guinea Bissau	7000	27	7000	27	610 (433-803)	882 (626-1161)
	Kenya	146,000	27	146,000	27	12,731 (9029-16,744)	18,405 (13,054-24,207)
	Liberia	147,000	27	147,000	27	12,818 (9091-16,859)	18,531 (13,143-24,373)
	Madagascar	437,000	27	437,000	27	38,106 (27,026-50,118)	55,089 (39,071-72,454)
	Mali	361,000	27	400,000	66	31,479 (22,326-41,402)	50,425 (35,763-66,320)
	Mozambique	291,000	27	291,000	27	25,375 (17,997-33,374)	36,684 (26,018-48,248)
	Namibia	29,000	27	29,000	27	2,529 (1794-3326)	3,656 (2593-4808)
	Niger	291,000	27	291,000	27	25,375 (17,997-33,374)	36,684 (26,018-48,248)
	Nigeria	500,000	68	500,000	68	43,600 (30,923-57,343)	63,031 (44,704-82,900)
	Rwanda	73,000	27	73,000	27	6366 (4515-83,729	9203 (6527-12,103)
	Senegal	15,000	27	70,000	66	1308 (928-1,720)	8824 (6259-11,606)
	Sierra Leone	437,000	27	437,000	27	38,106 (27,026-50,118)	55,089 (39,071-72,454)
	South Africa	37,000	27	37,000	27	3226 (2288-4243)	4664 (3308-6135)
	Tanzania	800,000	66	994,000	27	69,760 (49,476-91,749)	125,306 (88,872-164,805)
	Togo	20,000	27	20,000	27	1744 (1237-2294)	2521 (1788-3316)
	Uganda	218,000	27	218,000	27	19,010 (13,482-25,002)	27,482 (19,491-36,144)
	Zambia	87,000	27	87,000	27	7586 (5381-9978)	10,967 (7779-14,425)
	Zimbabwe	509,000	27	509,000	27	44,385 (31,479-58,375)	64,166 (45,509-84,392)
Eastern Mediterranean Region	Libya	7000	27	7000	27	610 (433-803)	882 (626-1161)
	Morocco	73,000	27	73,000	27	6366 (4515-8372)	9203 (6527-12,103)
	Pakistan	515,000	27	515,000	27	44,908 (31,850-59,064)	64,922 (46,045-85,387)
	Somalia	15,000	27	15,000	27	1308 (928-1720)	1891 (1341-2487)
	Sudan	291,000	27	1,000,000	66	25,375 (17,997-33,374)	126,062 (89,408-165,799)
Region of the Americas	Bolivia	130,000	27	130,000	27	11,336 (8040-14,909)	16,388 (11,623-21,554)
	Brazil	861,000	27	861,000	27	75,079 (53,249-98,745)	108,540 (76,981-142,753)
	Chile	17,000	27	17,000	27	1482 (1051-1950)	2143 (1520-2819)
	Colombia	268,000	27	418,000	27	23,370 (16,575-30,736)	52,694 (37,373-69,304)

(continued)

Table 4. continued

WHO Regions	Countries Where ASGM Is in Practice	No. of miners				YLDs (corresponding to DALYs)	
		Minimum Estimate	Reference	Maximum Estimate	Reference	Minimum Scenario* (UI)	Maximum Scenario† (UI)
	Cuba	7000	27	7000	27	610 (433-803)	882 (626-1161)
	Dominican Republic	2000	69	3000	69	174 (124-229)	378 (268-497)
	Ecuador	90,000	70	128,000	27	7848 (5566-10,322)	16,136 (11,444-21,222)
	Guyana	28,000	27	28,000	27	2442 (1732-3211)	3530 (2503-46,429)
	Mexico	56,000	27	56,000	27	4883 (3463-6422)	7059 (5007-9285)
	Nicaragua	20,000	27	30,000	27	1744 (1237-2294)	3782 (2682-4974)
	Panama	63,000	27	63,000	27	5494 (3896-7225)	7942 (5633-10,445)
	Peru	70,000	27	70,000	27	6104 (4329-8028)	8824 (6259-11,606)
	Suriname	28,000	27	28,000	27	2442 (1732-3211)	3530 (2503-4642)
	Venezuela	25,000	27	70,000	27	2180 (1546-2867)	8824 (6259-11,606)
South-East Asia Region	India	915,000	27	915,000	27	79,788 (56,589-104,938)	115,347 (81,809-151,706)
	Indonesia	250,000	27	250,000	27	21,800 (15,461-28,672)	31,516 (22,352-41,450)
Western Pacific Region	Cambodia	5000	1	6000	1	436 (309-573)	756 (536-995)
	China	2,746,000	27	2,746,000	27	239,450 (169,828-314,929)	346,167 (245,515-455,285)
	Laos	3000	71	3000	71	262 (186-344)	378 (268-497)
	Mongolia	30,000	1	30,000	1	2616 (1855-3441)	3782 (2682-4974)
	Papua New Guinea	108,000	27	108,000	27	9418 (6679-12,386)	13,615 (9656-17,906)
	Philippines	366,000	27	366,000	27	31,915 (22,635-41,9759)	46,139 (32,723-60,683)
	Vietnam	63,000	27	63,000	27	5494 (3896-72,259)	7942 (5633-10,445)
Sum		**14,042,000**		**18,922,000**		**1,224,458 (868,433-1,610,4289**	**2,385,352 (1,691,785-3,137,256)**

ASGM, artisanal small-scale gold mining; DALYs, disability-adjusted life years; UI, uncertainty interval; WHO, World Health Organization; YLDs, years lived with disability.
For the UI, the UI of DWs was applied as presented in Steckling et al.[20]
* Minimum scenario: lowest number of miners, lower prevalence rate of 23.7% intoxication.
† Maximum scenario: highest number of miners, higher prevalence rate of 34.3% intoxication.

DISCUSSION

To our knowledge, this is the first country-specific estimation of the burden of disease caused by chronic mercury intoxication resulting from mercury exposure in ASGM. A range of 1.22 (UI 0.87-1.61) to 2.39 (UI 1.69-3.14) million DALYs was estimated. According to the high number of miners, the burden is highest in the WHO African Region and lowest in the South-East Asian Region. There was no burden quantifiable for the WHO European Region.

For comparison, the estimated disease burden according to the Global Burden of Disease (GBD) 2015 study yielded 2.45 million DALYs as a result of hepatitis B and 2.06 million DALYs for Parkinson's disease,[23] which are close to our maximum scenario. However, both diseases globally get much more attention and financial support compared with CMMVI. Truly, the comparison is limited because the GBD studies use more sophisticated methods to estimate disease burden. However, to give a rough valuation of our estimates and to show the relevance of the burden caused by CMMVI in a broader context, the numbers can be used as a start to indicate the non-negligible health impact of CMMVI.

ASGM is a nonformalized sector, often even an illegal activity,[26] which results in little reliable data. Therefore, data available are discussed in the following section, and options for data improvement are proposed.

Subgroup of Interest. The quantification focused on workers involved in ASGM and excluded other subgroups, although non–occupationally involved residents and family members at mining areas might also be adversely affected by the exposure to mercury.[5] Thus, the current quantification of the BoD underestimates the burden from mercury pollution at ASGM sites. In Indonesia, for example, ore amalgamation commonly takes place inside housing

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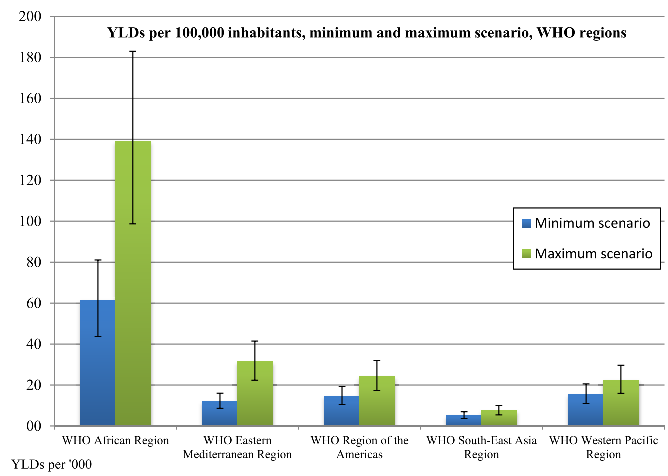

Figure 1. Years lived with disability (YLDs) per 100,000 inhabitants by World Health Organization (WHO) regions (minimum scenario: lowest number of miners, lower prevalence rate of 23.7% intoxication; and maximum scenario: highest number of miners, higher prevalence rate of 34.3% intoxication (YLDs correspond to disability-adjusted life years, DALYs). Numbers of inhabitants were taken from WHO[39]; the vertical lines show the uncertainty intervals (UI) based on the UIs of the disability weights).

areas.[40] Large quantities of semivolatile elemental mercury are released into the air in crowded neighborhoods without emission controls, thereby exposing people of all ages. Similarly, in Peru gold shops regularly burn off mercury vapors into residential streets in towns and cities.[41] For future research, it is recommended to focus specifically on children, because mercury is particularly toxic to brain development.[42]

Some HBM studies distinguished between groups of occupationally exposed individuals such as miners, smelters, and gold shop workers. This is reasonable because the exposure to mercury differs significantly between these occupational groups.[43] Consequently, variations in the disease burdens can be assumed. Having data on how many people work in the different areas would allow a stratified BoD quantification and may shed further light on the most vulnerable groups.

Gold dealers were not excluded from the analyses, although no focused search for gold dealers was done. Eight HBM studies included gold shop workers (6 in Brazil,[35,43–47] 1 in Ecuador,[10] and another 1 in Peru[48]). This subgroup involved in gold refinement is strongly exposed. Some studies analyzed miners and gold shop workers separately, and all[10,43,47] but one[48] identified a much higher mercury concentration in human specimens from gold shop workers compared with gold miners. It could be beneficial to survey this subgroup in more detail and develop specific intervention strategies to reduce their burden.

We did not include people suffering from severe mercury intoxication in the DALY estimate. Besides the DW of a moderate CMMVI, a different DW for severe CMMVI is available.[21] However, the available data do not allow a stratified estimate on the prevalence distinguishing between moderate and severe cases. Because of its severe effects on the human body, such as severe coordination problems and difficulties in concentrating, and its restrictions on the quality of life, such as not being able to perform usual activities,[21] it is likely that this health condition would restrict mining work. Hence, severe cases are to be expected in the subgroup of former miners. Estimating their burden is important in detecting the entire burden from exposure to mercury in ASGM. However, so far, comprehensive data about former miner are not available.

Number of Miners. An exact number of individuals exposed to mercury from ASGM belongs to the most crucial input for a valid BoD estimate. Comprehensive official registers and numbers are needed. For some countries, the presence of ASGM was reported but there were no estimates about the number of miners available. Consequently, these countries could not be included in this analysis, which might have resulted in an underestimate of the disease burden. For the countries with available estimates on the number of miners, this information was included without further verification. Here, it is necessary to foster research activities that focus on the estimation of

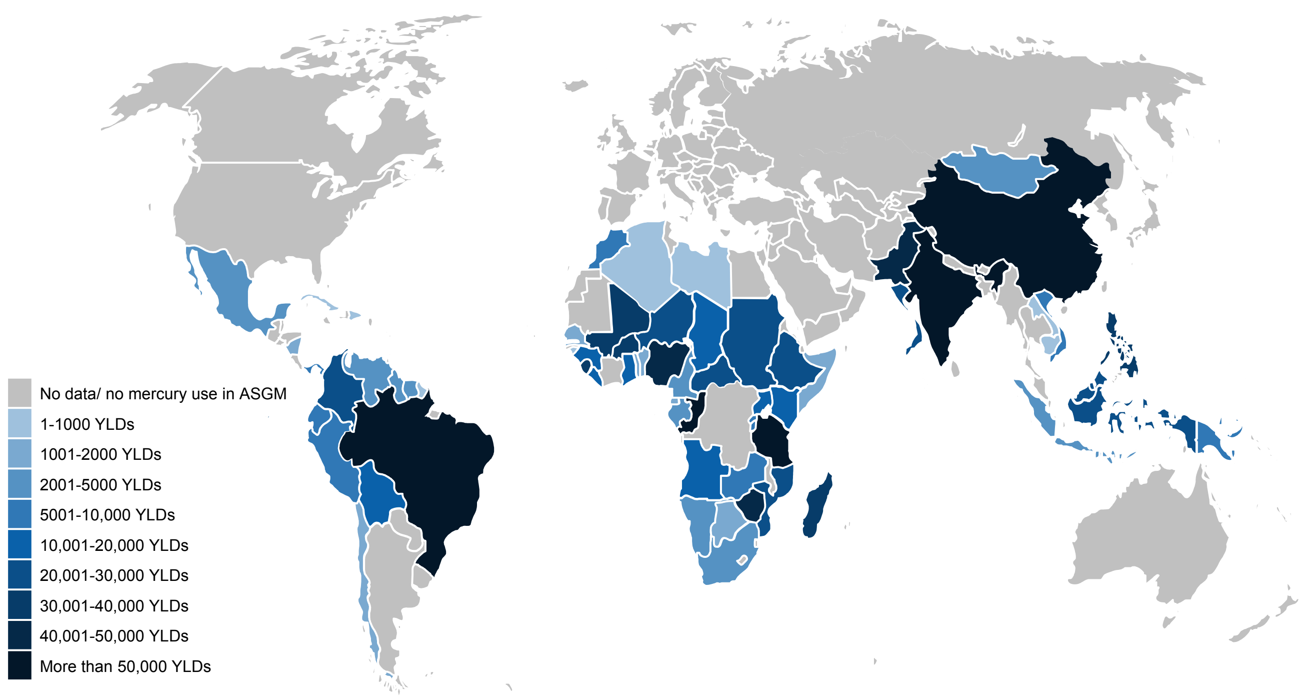

Figure 2. Number of total years lived with disability (YLDs; corresponding to total disability-adjusted life years, DALYs) per country with artisanal small-scale gold mining (ASGM) activity, estimated in the minimum scenario (lower number of miners and lower prevalence rate).

reliable numbers of miners working in ASGM. Formalization and regulation of ASGM could improve official reports of the number of miners involved.

Health Outcome. Mercury is one of many health issues related to ASGM. Several other health effects are common in gold mining communities, such as infectious diseases, accidents, and lung diseases caused by dust.[32] Exposure to other chemicals such as lead[49] or cyanide[26] is also possible. ASGM-related health restrictions other than chronic exposures to elemental mercury vapor were not considered in this assessment. Also excluded were exposures to other kinds of mercury (eg, methylmercury) and other mercury-related health outcomes like acute intoxications, acrodynia, and mild mental retardation.[50]

Prevalence. Earlier analyses of the primary data[14,15,17,18,29] yielded diverging prevalence estimates, because an extensive diagnostic tool[14] was used rather than the essential indicators[30] and combined with mercury concentrations in blood, hair and urine rather than, as was done in this analysis, focusing on urine samples. It was decided to focus on urine data to only consider exposures to mercury vapor.

An overall prevalence rate (in 2 scenarios) was calculated through a data analysis of 24 HBM studies in addition to the primary dataset. This summary prevalence was applied to all countries according to the estimated number of gold miners involved. This decision was made because of the large range of the mercury exposure ($<$1-5240 µg/L[17]) reported in the individual studies—which is mostly the result of different techniques to separate gold from ore[27]—and the fact that these studies are not representative of the miners of the entire country. Also, most studies are based on very small samples (14 of 24 studies had fewer than 50 participants).[35,44-46,48,51-57] To improve the reliability of the prevalence estimates, the study-specific prevalence estimates were pooled to one estimate due to weighting by the sample size. This pragmatic approach was used because of the missing representativeness, the small sample sizes, and the lack of comprehensive data.

The studies on mercury concentrations in human specimens from gold miners were found through literature reviews.[5,6] In the future, a comprehensive dataset should be generated, including all available HBM data for gold miners and other relevant subgroups. The database should be further expanded by conducting representative HBM studies in ASGM regions.

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Furthermore, there are several studies available that report health symptoms possibly associated with the exposure to mercury. These data were not included in the current analysis. It would be beneficial to develop a strategy to use these data for identifying cases of chronic mercury intoxication. So far, the essential indicators of the available diagnostic tool were—limited to urine samples—applied to the primary dataset. Including further individual health data, which were differently collected, was not addressed in this first rough estimate. Beyond that, the collection of representative health data from gold miners needs to be further intensified. A generally accepted and standardized tool to collect these data would also help. The available diagnostic tools[14,30] are a good starting point to ensure comparability.

Disability Weights. DWs are one of the most critical parts of the DALY concept. However, DWs enable the comparison of life years lost as a result of mortality and years lived with disability.[24] For the GBD study, 255 DWs were derived in 2 large population studies including more than 30,000 respondents each.[58-60] However, DWs for chronic mercury intoxication were not derived in the GBD study. Thus, Steckling et al estimated DWs for moderate and severe CMMVI to calculate YLDs as a result of the use of mercury in ASGM.[20] The validly of these DWs is limited because only a small sample of respondents (n = 105) was used to evaluate the severity of a selected set of different diseases. Moreover, comparability with GBD is limited because similar but not exactly the same methods were used to derive DWs.

Mortality. Underestimation could also result from the assumption that chronic inorganic mercury intoxication is not fatal. This assumption was based on a study comparing the mortality of workers exposed to elemental mercury vapor and nonexposed workers. No difference was found and so it was concluded that chronic exposures to metallic mercury vapor do not result in an increased mortality.[61]

Interpretation of the Results. Besides these limitations, this work presents the first burden of disease estimates for mercury exposure in ASGM on a global scale and thus offers important insights. Our analysis indicates that the use of mercury is a considerable health threat in the developing world. Therefore, it should gain more attention by politics. More funds for research are urgently needed to fill data gaps on the numbers of affected miners and their health effects. The development of affordable mercury-free technologies should be enforced. Also, the treatment of already intoxicated miners needs to be addressed.

To allow a comparison of mercury intoxication with other diseases, we recommend including mercury intoxication in the GBD study to reach the study's goal of giving "a comprehensive picture of what disables and kills people."[62]

CONCLUSIONS

These preliminary and rough estimates of the global burden of disease as a result of inorganic mercury exposure in ASGM underline the use of mercury for gold extraction as a serious health hazard. Because of diverging data, a broad range of 1.22 (UI 0.87-1.61) to 2.39 (UI 1.69-3.14) million YLDs was estimated. Nonetheless, even the lower estimate indicates the worrying public health dimension. It is further of major importance because the effects mostly hit the poor segments of the society. Technical and health interventions are needed to reduce this specific environmental burden. Mercury use in ASGM is principally avoidable by other techniques than mercury amalgamation. These estimates should raise awareness of this global health problem.

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SUPPLEMENTARY DATA

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