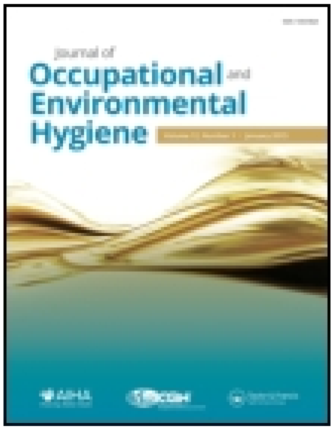

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Silica Exposures in Artisanal Small-Scale Gold Mining in Tanzania and Implications for Tuberculosis Prevention

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Gold miners exposed to crystalline silica are at risk of silicosis, lung cancer, and experience higher incidence rates of pulmonary tuberculosis (TB). Although the hazards associated with mercury exposure in artisanal small-scale gold mining (ASGM) have been well documented, no published data was available on crystalline silica exposures in this population. Air sampling was conducted in the breathing zone of workers in five villages in Tanzania with battery-operated sampling pumps and bulk samples were collected to measure the type and concentration of crystalline silica in the ore. Samples were analyzed at an accredited laboratory with X-ray diffraction. Airborne crystalline silica exposures exceeded recommended limits for all tasks monitored with an average exposure of 16.85 mg/m^3 for underground drilling that was 337 fold greater than the recommended exposure limit (REL) published by the U.S. National Institute for Occupational Safety and Health (NIOSH) and 0.19 mg/m^3 for aboveground operations or 4-fold greater than the REL. The exposures measured raise concern for possible acute and chronic silicosis and are known to significantly contribute to TB incidence rates in mining communities. The use of wet methods could greatly reduce exposures and the risk of TB and silicosis in ASGM. Ongoing efforts to address mercury and other hazards in ASGM should incorporate crystalline silica dust controls.

Keywords airborne silica, gold mining, silica, silicosis, tuberculosis, TB

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/uoeh.

INTRODUCTION

A major occupational health hazard associated with mining is exposure to respirable crystalline silica dust which is known to cause silicosis, cancer and other disease.(1) Mining in Sub-Saharan Africa is also associated with higher incidence rates of pulmonary TB and these rates are typically 5–6 times higher among miners than in the general population.(2) Infected miners also contribute to secondary TB infections in the general population due to migration and therefore have a much greater impact than their numbers alone suggest. (3)

Crystalline silica in the form of quartz is the most common component of soil, sand, and rocks. Exposures to respirable crystalline silica from large-scale gold mining operations have been documented in the past.(4,5) However, we were unable to locate any published exposure data from small-scale mining operations despite the growth in ASGM over the past decade fueled in part by rising gold prices.(6)

Tanzania is a country with significant mineral resources, including gold. ASGM accounted for an estimated 10% (5 tons) of the country's total gold extraction in 2010.(7) It is estimated that between 500,000 and 1.5 million people in Tanzania work in ASGM operations and are representative of the 15 million artisanal miners around the world. (8)

ASGM is estimated to produce approximately 13% of the world's gold.(9) In many areas with ASGM, the ore-processing operations are carried out directly in the communities where people live and often employ women and children. In recent years, small-scale gold mining in Zamfara State in northern Nigeria was responsible for poisoning thousands of children and contaminating entire villages as lead-containing ore was processed and stored in and around residential structures. (10) In such environments that are typical in ASGM, there are no clear distinctions between occupational and environmental exposures.

Miners used pneumatic jackleg drills powered by diesel generators at the surface while working in underground mines. The jacklegs are used to loosen ore, which was then gathered in bags and brought to the surface using a manual or powered winch. The ore on the surface was transported by laborers to other sites to be manually hammered into smaller sizes and then mechanically ground using ball mills. Many of the mining and milling sites were located near residential dwellings. Figure 1 shows a typical ball mill operation.

Crystalline silica dust is released into the air when miners drill, transport, and crush ore in the effort to extract and process minerals. While some attention is paid to reducing crystalline silica exposures in some large-scale mines in developing countries, ASGM is generally unregulated or illegal

FIGURE 1. Worker processing gold ore with a ball mill while wearing an air sampling device

and conducted without regards to health and safety considerations.

Occupational exposure to respirable crystalline silica causes silicosis and lung cancer, chronic renal disease, and autoimmune diseases such as rheumatoid arthritis.[1] Crystalline silica has been classified as carcinogenic to humans by the International Agency for Research on Cancer. [11] It is also a significant risk factor for TB even in the absence of silicosis.[12] Tanzania ranks among the top 20 countries with the highest incidence rates of TB and therefore it is important to investigate prevention strategies.[13]

Mining communities in Africa are known to have significant prevalence rates of HIV, which is also a strong risk factor for TB. In mining communities with high exposures to crystalline silica these factors work together in a multiplicative interaction to greatly increase incidence of TB. This interaction has resulted in a measurable increase in active TB among miners in South Africa observed since the 1970s. Increased prevalence of TB has even been noted in longitudinal studies among HIV-negative miners.[3] An increased prevalence of TB has also been noted in studies of granite workers exposed to crystalline silica and among other workers diagnosed with silicosis in the U.S.[1]

The primary factors determining the pathogenicity of crystalline silica exposures are particle size and airborne concentration.[1] Occupational exposure regulations, including the U.S. Occupational Safety and Health Administration (OSHA), require sampling respirable crystalline silica particulates ($< 10\ \mu$m in diameter) and studies with human subjects have shown the most fibrogenic particle size to be about 1 μm in diameter (range 0.5–3 μm).[14]

Silicosis is normally not apparent until 20 years or more after the first exposure to crystalline silica. However, with exposure to extremely high concentrations of crystalline silica an acute or accelerated form of silicosis can occur in 1–3 years. The rate at which silicosis progresses is related to the duration and concentration of crystalline silica exposure. Accelerated silicosis has been reported among gold miners in China, Scottish stonemasons, and garment industry workers sandblasting denim jeans in Turkey. [15,16,17]

U.S. OSHA established a permissible exposure limit (PEL) for respirable crystalline silica proportional to the concentration of quartz and cristobalite forms of silica present in the dust. However, this standard is understood not to be protective against silicosis and the agency recently proposed a lower PEL.[18] The proposed regulatory limit would bring the agency in line with the recommended exposure limit (REL) published by the U.S. National Institute for Occupational Safety and Health (NIOSH) which uses a single respirable crystalline silica limit of 0.05 mg/m^3 as a time-weighted average (TWA). The American Conference of Governmental Industrial Hygienists (ACGIH) has recommended an even lower threshold limit value (TLV) of 0.025 mg/m^3. [19] Tanzania has no regulatory level for crystalline silica exposures.

PURPOSE

The purpose of this investigation was to measure respirable crystalline silica exposures among workers in ASGM in Tanzania. Because small-scale gold miners lack basic personal protective equipment and generally operate without any dust controls, it is important to assess their exposures separately from workers in medium and large-scale mines operated by mining companies. This investigation was also performed to evaluate potential interventions to reduce airborne respirable dust in these operations to better protect workers and surrounding communities.

METHODS

Air monitoring was conducted in July 2014 during five distinct operations, including drilling, manual hammering, loading, crushing, and miscellaneous processing operations in five villages. Samples were collected by drawing air through pre-weighed three-stage 37-mm polyvinyl chloride (PVC) filters (5 μm pore size) with battery operated air sampling pumps at a flow rate of 2.5 L per minute. The filters were downstream from SKC, Inc. aluminum cyclones (with a 50% aerodynamic diameter cut-point at 4 μm) to collect the respirable portion of the dust. Air sampling pumps (SKC, Inc. and Gilian) were calibrated using a primary standard (BIOS dry calibrator) before and after each sampling period.

Personal samples were collected with battery-operated pumps in the breathing zone of workers clipped to the lapel area with the cyclones hanging vertically downward (see Figure 1). Sample durations ranged from 85 min to 7 hr. All personal samples were collected on unique individuals except when two consecutive samples were collected to complete sampling within a single day work shift (samples 297610 and 297623 and Samples 297636 and 297648). In some cases area air samples were collected from stationary worksite locations approximately 1–2 m above the ground near crushing, hammering, and loading operations. A field blank sample was collected on each of the four monitoring days as per method requirements.

TABLE I. Exposure Levels of Respirable Dust at Aboveground Gold Mining Sites, Tanzania

Sample ID	Village/ Sample Type	Work Activity	Sampling Time (min)	Respirable Particulate Mass (mg/m3)	Quartz (mg/m3)	Quartz/REL
297627	A (Personal)	Crushing	90	0.78	0.16	3
297647	A (Personal)	Hammering	208	1.56	0.71	14
297610	B (Personal)	Crushing	283	1.20	0.22	4
297623	B (Personal)	Crushing	137	1.57	0.09	2
297612	A (Personal)	Loading	248	0.23	0.03	1
297636	C (Personal)	Crushing/Loading	183	0.93	0.08	2
297648	C (Personal)	Crushing/Loading	85	1.41	0.10	2
297618	C (Area)	Crushing/Hammering	360	0.87	0.09	2
297601	C (Area))	Crushing/Hammering	88	0.60	NA	NA
297620	A (Personal)	Loading	225	2.69	0.66	13
297630	A (Personal)	Loading	251	0.41	0.05	1
297625	B (Area)	Crushing/Loading	278	0.95	0.20	4
297642	B (Area)	Crushing/Loading	134	0.52	0.09	2
297640	D (Personal)	Crushing	231	0.34	0.07	1
297604	D (Personal)	Crushing	224	0.75	0.15	3
297646	D (Personal)	Loading	138	0.35	0.11	2
297609	D (Personal)	Loading	139	0.15	0.08	2
297617	D (Area)	Crushing	223	2.09	0.57	11
297632	D (Personal)	Hammering	121	2.77	0.23	5
297607	D (Personal)	Crushing	118	0.38	0.05	1
297628	D (Personal)	Crushing	226	0.37	0.07	1
			Mean:	1.00	0.19	4
			Standard Deviation:	0.75	0.20	

TABLE II. Exposure Levels of Respirable Dust from Personal Air Monitoring in Underground Gold Mining Sites, Tanzania

Sample ID	Village/ Sample Type	Work Activity	Sampling Time (min)	Respirable Particulate Mass (mg/m3)	Quartz (mg/m3)	Quartz/REL
297622	D (Personal)	Drilling	137	28.79	14.83	297
297619	D (Personal)	Drilling	134	35.39	17.64	353
297633	D (Personal)	Drilling	132	28.70	12.28	246
297641	E (Personal)	Drilling	122	31.91	2.34	47
297613	E (Personal)	Drilling	428	112.98	17.81	356
297603	E (Personal)	Drilling	365	266.08	36.61	732
297643	E (Personal)	Drilling	436	92.46	12.80	256
297639	E (Personal)	Drilling	429	89.97	12.74	255
297624	E (Personal)	Drilling	413	154.93	29.44	589
297631	E (Personal)	Drilling	412	76.54	12.22	244
297634	E (Personal)	Drilling	418	113.82	16.69	334
			Mean:	93.78	16.85	337
			Standard Deviation:	67.56	8.74	

TABLE III. Analysis of Bulk Material Samples for Silica Content by X-Ray Diffraction (XRD) Reported in Percent by Weight

Sample ID	Village	Quartz	Cristobalite	Tridymite
0037	C	28.7	<0.8	<0.8
0038	A	67.0	<0.8	<0.8
0039	D	67.9	<0.8	<0.8

Note: Reporting limit for Quartz = 0.2% and the reporting limit for Cristobalite and Tridymite = 0.8%.

Air sample durations included a mix of full and partial work days for representative miners. However, because of the defined division of labor observed, we considered partial shift sample durations to be representative of full shift exposures. As individual exposures appeared to be generally consistent throughout the workday, we did not calculate time-weighted averages (TWA) for partial shift sampling. TWA calculations would underestimate actual exposures in cases where sampling periods were less than full shift.

Three bulk samples of processed ore were collected from mining or processing sites in different villages to determine the type of crystalline silica present and its concentration. The bulk material and 36 air sample filters (including blank samples) were analyzed by EMSL, Inc. (Cinnaminson, NJ) with NIOSH Method 7500 using X-ray diffraction. The limit of detection for gravimetric respirable dust with this NIOSH method is 0.05 mg and the limit of detection for silica dust as quartz is 0.005 mg.[20]

This study did not attempt to measure TB incidence rates among this group of miners as that was outside of the scope due to the limited resources available. Nor did we assess any symptoms of crystalline silica exposure among the exposed workers.

RESULTS

Results indicate that 31 (97%) of the 32 air samples (excluding blank samples) exceeded the NIOSH REL. Average exposures for aboveground ore processing tasks were 4-fold greater than the NIOSH REL. The mean concentration of respirable crystalline silica during aboveground operations was 0.19 mg/m^3. See Table I for results of air samples from aboveground operations. All method blank samples were below the limit of detection.

For below-ground drilling operations, sample results showed the mean exposure was 16.85 mg/m^3 or 337-fold greater than the NIOSH REL. See Table II for results of air samples from underground operations.

The predominant form of crystalline silica observed in bulk samples of ore collected around various operations was quartz. Quartz concentration ranged from 28.7% for a sample collected below crusher machinery to 67.9% for a sample from the bottom of a mining pit. No cristobalite or tridymite was detected in these samples. See Table III for results of bulk samples.

DISCUSSION

Although the hazards of mercury use in ASGM have been characterized in over 70 studies, no reports quantifying respirable crystalline silica exposures in these communities could be located in the published literature.[21] One previous study conducted in Tanzania reported respirable dust and crystalline silica exposures in a Tanzanite gemstone mine employing approximately 50 workers underground.[22] They reported a median crystalline silica dust exposure of 1.4 mg/m^3 (with a range from 0.9–2.7).

One study reported on the prevalence of acute or accelerated silicosis among small-scale gold miners in China operating without dust controls.[15] This study did not include any air sampling but the authors estimated that mean exposures for total crystalline silica dust based on an extrapolation from government records of exposure monitoring data to be 89.5 mg/m^3. They found that the prevalence of accelerated silicosis was 29.1% among 597 workers with an average employment duration in the mine of 5.6 years.

In contrast to the respirable crystalline silica exposures observed in our study, the reported mean from air sampling conducted in large-scale gold mining in Ontario, Canada was 0.08 mg/m^3 for quartz during the period 1978–1979.[4] Another study of respirable quartz in a large gold mine in South Africa conducted in 2000 reported a mean concentration of 0.051 mg/m^3.[5]

The results reported here for crystalline silica exposures in above ground rock crushing and processing are similar to the levels reported in small-scale stone crushing operations in India.[23] However, levels observed in underground operations were considerably higher than what were reported in underground mining elsewhere in Tanzania but in the same range as estimated exposure levels in China where accelerated silicosis was reported.[15,22]

Implications for Tuberculosis Prevention

ASGM is a growing endeavour in over 70 countries primarily in Asia, Africa, and South America and is concentrated in countries with a higher incidence of TB.[24] Previous studies of health endpoints among workers in ASGM focused on biological exposure markers and neurological effects associated with mercury exposure.

Estimates of mercury consumption for ASGM are the best available surrogate measure for the ASGM production in a country. Tanzania is one of the 11 countries with the highest consumption of mercury use for ASGM.[25] In fact, of the 11 countries with the highest estimated consumption of mercury use for this purpose, 5 are considered high-burden countries (HBCs) for TB that have been prioritized since 2000 by the World Health Organization (WHO) as shown in Table IV.

These 22 priority countries are a focus of TB response efforts as they account for more than 80% of the world's

TABLE IV. Countries With the Highest Estimated Mercury Use (t) per Year for ASGM

Country	Mean Estimated Mercury Use (t)/year
China	444.5
Columbia	180.0
Indonesia	175.0
Bolivia	120.0
Peru	70.0
Philippines	70.0
Ghana	70.0
Sudan	60.0
Ecuador	50.0
Brazil	45.0
Tanzania	45.0
Burkina Faso	35.1
Zimbabwe	25.0
Nigeria	20.0
Mali	20.0
Guyana	15.0
Venezuela	15.0
DR Congo	15.0
Russia	11.0
French Guiana	7.5
Kenya	7.5
Cambodia	7.5
South Africa	7.5
Vietnam	7.5
Mozambique	4.0
Thailand	1.5
Congo	1.5
Uganda	0.8
Ethiopia	0.3

Note: Countries in **BOLD** are classified as high-burden TB countries by WHO. Sources: AMAP/UNEP [13] and WHO.[25]

incident TB cases. WHO estimates incident rates based on notifications of smear positive test results and other survey data. As indicated in Table IV, ASGM is known to be a significant activity in 17 of the 22 countries.[13] These 17 countries account for 54% of mercury use in ASGM and therefore we estimate that collectively they account for more than half of small-scale gold mining operations. These same countries account for approximately 46% of the global incident TB cases.

The information in Table IV is not intended to suggest that there is necessarily a statistical correlation between ASGM and TB incidence rates in these countries. Certainly there are many factors that account for the reported TB incidence in these countries in addition to crystalline silica exposures. However, this table is presented to help policy makers consider strategies to prioritize programs to reduce crystalline silica exposure as part of a TB prevention strategy.

Large-scale mining communities in Africa are known to have significant prevalence rates of HIV, which is also a strong risk factor for TB.[3] In mining communities with high exposures to crystalline silica these factors work together in a multiplicative interaction to greatly increase incidence of TB. This interaction has resulted in a measurable increase in active TB among miners in South Africa since the 1970s. Increased prevalence of TB has been noted in longitudinal studies among HIV-negative miners.[2]

As the location of ASGM operations are concentrated in countries that have the highest TB burden, we recommend that public health prevention efforts initially focus on a relatively small group of countries. As exposure to crystalline silica and HIV infection combine synergistically to greatly enhance TB incidence, background rates of HIV should also be taken into consideration in prioritizing interventions.[26] Africa hosts the largest percentage of people co-infected with TB and HIV and it is estimated that 34% of Africans with TB are co-infected.[13] The greatest public health benefit from investments in crystalline silica exposure reduction can be expected in communities with the highest rates of TB and HIV. Therefore, any response to this crisis should prioritize ASGM mining areas in countries with a high-burden of TB and in communities with readily available water supplies for dust control applications.

Although surveys have been conducted among large-scale gold mines, there is no data on TB incidence rates among small-scale miners. The lack of information on TB in communities of small-scale miners precludes establishing a firm link between small-scale gold mining and TB. In addition, we know that other risk factors for TB transmission including socioeconomic status, late diagnosis, and insufficient access to health care, contribute to the TB incidence in this population of miners.[2]

Opportunities for Crystalline silica Dust Reduction

Due to the recently completed Minamata Convention which has a large focus on the use of mercury in ASGM, a significant increase in outreach efforts to reduce the use of mercury is currently underway. The Global Environment Facility (GEF) has allocated $141 million dollars for these efforts and other international aid programs are also independently targeting funds for this purpose.[27] Governments have also been charged with preparing national strategic plans to reduce mercury consumption in ASGM and to include such elements as educating healthcare workers on mercury hazards, but they are not explicitly required to incorporate any health risks from crystalline silica dust exposures in their planning.[28] To date, mercury reduction efforts in ASGM have concentrated efforts on a single exposure and have not focused on the potentially larger public health risks associated with crystalline silica exposures documented in this investigation. These programs could incorporate crystalline silica dust controls along with mercury reduction strategies to provide a more comprehensive public health response to this ongoing crisis.

Even programs to certify gold and other metals from artisanal mines for social and environmental aspects have failed to address the hazards posed by crystalline silica dust. For example the "Fairtrade Standard for Gold and other Precious Metals for Artisanal and Small Scale Mining" (2013) fails to require dust controls or other provisions to reduce crystalline silica emissions.[29] Specific requirements for reducing respirable dust should be included in future updates and in other comprehensive environmental standards.

Simple dust controls including the use of wet methods with plumbed water directed to specialized spray misting nozzles has been shown to be effective in significantly lowering respirable crystalline silica and fine particulate matter in similar small-scale rock crushing operations. [23,30] With additional investment in equipment and extending water supplies, dust exposures can be reduced along with associated incidence of silicosis and TB among small-scale miners. Some of the miners in the study area were observed using Jackleg drills which are equipped to be connected to a water hose but were used without a water connection. Even wetting the rock face before drilling will help reduce dust. Both underground drilling and aboveground ore processing can be modified to use wet methods to at least alleviate the highest exposures.

Dry dust collection systems may also be employed to reduce airborne crystalline silica but require larger capital investments and a reliable source of electricity. Such methods may involve enclosing above-ground rock crushing operations and/or providing local exhaust ventilation from crushing machines to cyclone dust collectors. A study from Iran demonstrated the efficiency of a cyclone used in rock crushing varied by particle size with efficiencies ranging from 60– 90% with the upper range representing larger particle sizes.[31] Employee exposures to respirable quartz during stone crushing operations following the installation of these dust collection systems still exceeded the current NIOSH REL (0.05 mg/m^3) by up to 8-fold. [32] Similar results for airborne respirable quartz were obtained in areas of a stone crushing mill in a pilot project in India after the installation of a dust collection system.[33] Dry dust collection systems if adequately designed may be feasible where mining cooperatives have been formed or where centralized ore processing can be organized by the miners.

Respiratory protection also helps to lower exposures but should be used only in combination with other means to reduce the dust. However, it is important to consider the appropriate protection factor in the selection of respirators as most inexpensive models would provide insufficient protection for the exposures observed.

As in the case of mercury reduction efforts, the adoption of dust controls will require significant outreach and education among miners to encourage the use of wet methods. Unlike the elimination of mercury, the addition of water in mining and ore processing does not reduce the yield of gold and therefore may be more readily accepted by mining communities.

CONCLUSION

Respirable crystalline silica dust exposures in gold mining are known to greatly increase the morbidity and mortality of workers due to silicosis and other silica-related disease. In addition, previous studies conducted in large-scale gold mines have demonstrated that even lower levels of respirable crystalline silica than those reported here are associated with an increased prevalence of TB among miners. Given the high background incidence rates of TB in Tanzania and in other countries with extensive ASGM, workers engaged in ASGM are at much greater risk of TB. In addition, the exposures noted in underground drilling operations will place workers at risk for developing acute silicosis within five years of initial employment unless measures are taken to reduce these exposures.

In light of these results, there is an urgent need to introduce dust control measures to help prevent TB in ASGM communities around the world. Ongoing efforts by WHO, the UN Environment Programme (UNEP), and the Global Environment Facility (GEF), and other bilateral and multilateral aid agencies should immediately incorporate dust controls into mercury reduction efforts in ASGM. Such efforts have the potential to do more to reduce morbidity and mortality among miners than the introduction of mercury capture technology and mercury-free alternatives. However, as most airborne crystalline silica is generated during the mining and processing conducted before the application of mercury at the end stage, a combined approach would have the greatest public health impact.

Given the expense and challenges of conducting outreach to encourage the implementation of improved work practices in remote and widely dispersed ASGM sites in many countries, the incremental effort to include crystalline silica dust controls is proportionally small. There are significant public health benefits to an integrated approach to introduce wet methods for reducing respirable crystalline silica dust while demonstrating safer mercury use or alternative technologies.

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