

Original Article

Reducing Lead and Silica Dust Exposures in Small-Scale Mining in Northern Nigeria

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Abstract

Purpose: An ongoing health crisis across a large area of Northern Nigeria has resulted in hundreds of deaths and thousands of cases of lead poisoning from artisanal small-scale gold mining. Occupational Knowledge International (OK International) and Doctors Without Borders/Médecins Sans Frontières (MSF) have formed a partnership to conduct a pilot project to introduce safer mining practices in selected communities. The primary objective was to reduce lead exposures among artisanal small-scale miners and minimize take home exposures by reducing dust contamination on clothing and body surfaces.

Methods: Personal air samples were collected from miners and ore processors before and after the introduction of wet spray misting in mine processing activities to crush and grind gold ore. We measured reductions in total airborne lead and respirable silica dust levels. A total of 44 air samples were collected for airborne lead using NIOSH method 7082 and 29 air samples for respirable silica dust with NIOSH method 7500.

Results: Low-cost interventions to convert dry ore processing to wet methods with spray misting were effective at reducing arithmetic mean airborne lead levels by 95%. Mean airborne respirable silica (quartz) was reduced by 80% following the introduction of wet spray misting. Differences in geometric means between wet and dry ore processing methods were statistically significant for both airborne lead and respirable silica.

Conclusions: This pilot project has been successful in working cooperatively with miners to provide them with the necessary information and tools to reduce exposures in mining and processing, and minimize off-site contamination. As silica dust is a significant risk factor for silicosis and tuberculosis (TB), this intervention could provide public health benefits to small-scale mining communities even in areas without significant lead concentrations in the ore. Significant reductions in respirable silica and lead exposures are feasible in low-resource, small-scale mining communities.

Keywords: air sampling; lead poisoning; safer mining; silica exposure; wet spray misting

Introduction

Since 2010 Doctors Without Borders/Médecins Sans Frontières (MSF) responded to an observed increase in infant mortality in villages in Zamfara State, Nigeria that they investigated and linked to lead poisoning from gold mining activities. The gold ore in the area contains an average of 89 500 ppm lead and significant concentrations of other heavy metals (Bartrem *et al.*, 2014). After the lead contamination in these villages was remediated, chelation treatment was initiated for children meeting specific criteria. Since that time MSF has continued to monitor and treat thousands of poisoned children in several villages in Northern Nigeria (Tirima *et al.*, 2016).

In April 2015, severe lead poisoning cases were discovered in two villages in an area in Niger State ~250 km south of where the initial outbreak was identified. An investigation by the Federal Ministry of Health indicated that approximately 80% of the children tested had blood lead levels greater than 45 $\mu\text{g dl}^{-1}$ and 25% were above 100 $\mu\text{g dl}^{-1}$. In addition, at least 28 deaths among young children were reported (Nmodu, 2016). The majority of the homes and common areas were tested and found to be contaminated with lead and were remediated in 2016. MSF initiated treatment and health promotion programs for children in the area to reduce mortality.

Over time it had become apparent that the remediation of lead contamination and the treatment of lead poisoning among children were not sufficient to eliminate the lead poisoning hazard in these communities as long as mining continued. Plans were put in place to introduce the community in Niger State to safer mining practices to reduce exposures and minimize off-site contamination. Occupational Knowledge International partnered with MSF to pilot test these mining practices in this community starting in 2016.

Mining practices contributed to environmental contamination and childhood lead exposures (Dooyema *et al.*, 2012). The ground ore and contaminated soil generated from mining and processing are significant exposure sources for children in Northern Nigeria (Tirima *et al.*, 2016). Young children who are the most vulnerable get most of their exposure from contaminated dust and soil through hand to mouth contact (Dooyema *et al.*, 2012). In addition, before the launch of our pilot project miners routinely wore their dusty work clothing and footwear when entering residential areas and their

homes. Children of miners can get exposed from this take-home source of lead. In some cases miners would also transport ore to their homes for safe storage. These practices have been shown to result in significant lead contamination of common areas in these villages and the residential compounds.

Lead is present in the gold ore in substantial concentrations in several areas of Nigeria and processing this material results in significant exposures and environmental contamination (Akande *et al.*, 1988; Garba, 1996; Plumlee *et al.*, 2013). There is no ongoing blood lead surveillance in these areas nor in other communities where lead ore is being mined. Medical interventions and environmental remediation to remove contaminated soil and dust has been limited to select communities where significant numbers of lead poisoned children were identified. A survey of 70 villages in Zamfara State found that 77% had some ore processing activities and these were more likely to have children with lead poisoning and lead soil or dust contamination (Lo *et al.*, 2012).

Hazardous silica exposures have been documented in small-scale mining in other African countries (Gottesfeld *et al.*, 2015). Respirable silica is associated with silicosis, lung cancer, and other immune system disorders. In addition, silica dust is a known risk factor for TB and miners are responsible for a substantial proportion of TB incidence rates in sub-Saharan Africa (Stuckler *et al.*, 2011).

To date, most international aid targeted to artisanal small-scale mining has focused on mercury exposures from the amalgam process used to separate gold from the ore (IGF, 2017). This safer mining pilot project tested the efficacy of improved practices to meet our primary objective of reducing lead exposures to miners in this community. In reducing airborne exposures, we also intended to minimize lead contamination taken home by workers on clothing and skin. At the same time, this intervention was designed to reduce exposures to respirable silica, and to mitigate other hazards through increased education and awareness.

Previously others have reported on the efficacy of reducing respirable dust with water spray misting (Beamer *et al.*, 2005, Ren *et al.*, 2011). However, our pilot was the first to assess the application of this technology to reduce airborne lead and silica exposures in small-scale informal gold mining.

Materials and methods

Site assessment

This study was conducted in the Shikhira community in Niger State following the reported lead poisoning outbreak and after two villages in the area underwent extensive soil remediation. As part of the remediation efforts, the mechanical ore processing machines that had operated in these villages were consolidated and relocated to a site removed from residential areas. The new site contained approximately eight stone crushing and grinding machines. A seasonal water spring in this area was used for sluicing ore, but no other water supply was present.

Mining activities take place in various locations in the area mostly in hand dug pits and small mine shafts extending down ~20 m below the surface. Manual labor is used to remove the ore which is then broken up at the surface with hammer and chisel into smaller fist sized rocks. The ore is then loaded into large bags and transported on motorcycles to the mechanical processing equipment generally operated by other independent miners. The processing equipment included diesel powered rock crushing machines and ore grinding machines that were designed to grind food staples such as corn. The crushing and grinding machines were processing dry ore and created extremely high levels of visible dust (Fig. 1). No dust control measures or personal protective equipment were used.

In the study area, there was one mechanical processing machine that combined ore crushing and grinding tasks and operated with a steady stream of water pumped from a local surface water source. The liquid effluent from the machine was discharged over a sluicing ramp lined with

rough rags or carpet that is used to trap gold particles. This processing equipment did not generate visible airborne dust, although it required a large continuous flow of water to operate. Due to the lack of availability of surface water, this equipment was used only intermittently during the wet season.

Community engagement

Residents of the area, including men, women, and children, were engaged in both hard rock mining and in panning soil or alluvial deposits. Miners were generally not taking any measures to control or reduce dust during work activities.

Training programs were held with groups of miners and processors to inform them of the hazards of lead and silica dust. Methods were also suggested to minimize exposures and improve work practices. These sessions included information on the health effects of lead to both adults and children. The training covered the principles of reducing dust exposures during mining and processing activities with an emphasis on using wet methods.

Additional less formal training was conducted at mining and processing sites and regular meetings were held with mining leaders. A safety committee was established that included representatives from the miners and processors to monitor compliance with recommended practices and report back on implementation challenges.

Site improvements

To reduce exposures in the processing site, a bore well and elevated storage tank were installed to provide water. To



Pre-intervention



Post-intervention

Figure 1. Visible dust from ore crushing machines before and after implementing wet spray misting.

provide sufficient water pressure for wet spray misting nozzles, a concrete tower was constructed to a height of 4 m and a 1000-l water tank was placed on top. The grinding and crushing machines were then relocated along two lines meeting at the water tower. The spacing distance between the processing machines was maintained at approximately the same distance. Plumbing lines were installed to provide water to spray mist nozzles at the input and output of each processing machine. Nozzles that generate a fine mist in a cone shape pattern were installed directly over the area with the greatest dust release. As each machine is generally owned by separate individuals and operate intermittently, each nozzle was provided a shut-off valve to independently control the flow of water.

The misting was created with commercially available 0.25 inch brass nozzles (Spraying Systems Co. Glendale Heights, IL) with a nominal flow rate capacity between 0.86 and 1.4 l per minute at an estimated water pressure of 0.4 bar (5.8 PSI). Two nozzle sizes were tested to ensure that adequate water pressure was maintained to provide a full spray cone misting pattern. The median droplet size for these nozzles ranged from 495 to 614 microns at our estimated operating pressure according to information supplied by the manufacturer.

Two nozzles were installed at each crushing and grinding machine with one directly over the bulk ore inlet and another over the outlet. Nozzles were installed ~40–60 cm from the source to allow for sufficient space for loading and unloading ore. Processed ore generated from this process is taken to another location for sluicing.

Air sampling

We collected 18 personal air samples for lead exposure from miners and ore processors before introducing wet dust control methods and 26 lead air samples after introducing wet methods. We also collected 18 air samples for respirable silica dust before these interventions and 11 samples after installing wet spray misting. Air samples were collected using the National Institute for Occupational Safety and Health (NIOSH) method 7500 for respirable silica dust and NIOSH method 7082 for lead. Method blanks were prepared in the field as specified and transported with the air samples to the analytical laboratory. Silica samples were analyzed by X-ray diffraction (XRD) and lead samples were analyzed by atomic absorption spectroscopy (AAS).

Battery operated low-volume air pumps were used to collect samples from the breathing zone of representative miners and ore processors. Silica samples were collected with an aluminum cyclone (SKC) designed for a 4 μm 50% cut-point and pumps calibrated to draw 2.5 l per

minute with a primary standard flow meter (Mesa Labs Biodefender 510). The silica samples were collected with closed face, preweighed, 37 mm sample cassettes with PVC filters with 0.8 μm pore size. Sampling times for silica ranged from 144 to 423 min depending on individual work schedules. Both pre and post air samples were collected during periods when one to eight machines were operating. Two bulk samples were collected from processed ore (one taken during the preintervention and one collected during the postintervention air sampling) and tested for silica content with XRD.

Air sampling pumps used for the lead samples were calibrated in the field with a primary standard flow meter (Mesa Labs Biodefender 510). Standard 37 mm sample cassettes operated at 2.0 to 2.1 l per minute with closed face MCE filters were placed in a downward position in the breathing zone of participating miners. Sampling times were generally of a full shift or full work day which varied considerably in the study population. Sample durations ranged from 76 to 430 min for lead exposure monitoring.

Samples were shipped by air freight carrier to an accredited laboratory in the United States. Samples were analyzed by Maxxam Analytics/Bureau Veritas with EPA Method 6010C for lead and NIOSH 7500 with XRD for silica content. Results were reported in mg m^{-3} . The limit of detection (LOD) for lead is 0.001 mg filter^{-1} and the LOD for silica (quartz) is 0.005 mg filter^{-1} .

In summarizing air sample results for lead that were below the LOD, we adjusted the reported result as the LOD divided by 2 in providing summary statistics. We calculated and reported the arithmetic mean and geometric mean (GM) of the censored data utilizing these adjusted values. Statistical comparisons of the GM were done with the Welch's *t*-test on the log-transformed data for (i) dry mechanical ore processing versus wet stream ore processing, (ii) dry mechanical ore processing versus wet spray ore processing, and (iii) wet stream ore processing versus wet spray ore processing for both lead and respirable silica.

Results

A total of 44 samples were collected for airborne lead with personal air sampling from select volunteers working in mining and processing activities (see [Supplementary Tables S1 and S2](#), available at *Annals of Work Exposures and Health* online). Six air samples were collected for airborne lead before wet practices were introduced in the ore processing area and results showed an arithmetic mean exposure of 0.96 mg m^{-3} . These levels were approximately 19-fold higher than the US Occupational Safety and Health Administration (OSHA) Permissible Exposure Level (PEL) for lead of 0.05 mg m^{-3} .

Table 1 summarizes the lead air sampling results from ore processing with dry mechanical methods, wet spray misting, wet stream, and manual processing. A total of 12 air samples for lead were collected during mining activities including two conducted during manual ore processing (e.g. rock breaking) conducted with a hammer and chisel at the surface at the mining site. The arithmetic mean exposures without dust controls among miners were 0.004 mg m^{-3} . No postintervention sampling was conducted in mining operations.

Wet spray misting postintervention reduced arithmetic mean lead exposure among processors to 0.048 mg m^{-3} representing a 95% reduction. Mean lead exposures with a wet stream ore processing machine that combined crushing, milling, and sluicing were 0.0056 mg m^{-3} .

We performed a Welch's *t*-test of the lead air sampling results for dry mechanical ore processing exposure versus, respectively, the wet stream ore processing and the wet spray ore processing. Assuming a normal distribution of the log-transformed values, the GMs for wet spray ore processing (0.008 mg m^{-3}) versus dry ore processing (0.88 mg m^{-3}) are significantly different with *t*-test statistic = -9.38 with 22 degrees of freedom and $P = 3.8 \times 10^{-9}$. The GMs for wet stream ore processing (0.0034 mg m^{-3}) versus dry ore processing (0.88 mg m^{-3}) are significantly different with *t*-test statistic = -12.2 with 8 degrees of freedom and $P = 1.67 \times 10^{-6}$.

A total of 29 air samples were collected and tested for respirable silica content from the breathing zone of representative miners and ore processors (see [Supplementary Tables S3 and S4](#), available at *Annals of Work Exposures and Health* online). **Table 2** provides the results of silica air samples including air samples from mining activities, dry mechanical processing before the implementation of dust controls, and processing with wet methods. The arithmetic mean exposures without dust controls were 0.20 mg m^{-3} for mining and 0.81 mg m^{-3} for mechanical processing. A single sample was conducted for respirable silica during manual rock breaking at the mine site with a result of 0.26 mg m^{-3} .

XRD results for the silica air samples only detected the presence of quartz as none of the samples contained cristobalite or tridymite above reporting limits. Ore samples collected during air monitoring at the processing site contained quartz ranging from 64 to 68% by weight.

The air sample data indicates that spray misting at the processing site reduced arithmetic mean respirable silica exposures by 80% to 0.164 mg m^{-3} following this intervention. In addition, air samples collected for silica during mechanical processing with a wet stream machine that combines grinding and sluicing were 0.062 mg m^{-3} . This machine takes dry ore and applies a stream of water from a hose during crushing and grinding and discharges the resulting material onto a sluice.

We performed a Welch's *t*-test of the dry mechanical ore processing silica exposure data versus the combined data for wet stream ore and wet spray ore processing. We combined the two wet processes because the range of silica exposures are similar. Assuming a normal distribution of the log-transformed values, the GMs for wet ore processing (0.091 mg m^{-3}) versus dry ore processing (0.526 mg m^{-3}) are significantly different with *t*-test statistic = 4.12 for 17 degrees of freedom and $P < 0.00064$.

Discussion

This intervention demonstrated that artisanal small-scale miners are interested and motivated to take measures to reduce exposures to lead and silica dust to protect themselves and their communities. Miners contributed to these efforts by constructing changing and eating areas, and hand washing stations adjacent to work areas. In addition to contributing labor, the miners and processors provided equipment and collected funds to contribute to these efforts. The processors worked cooperatively to develop and install a water distribution system to reach every machine in the processing area.

Average lead exposures in the processing area were reduced to just below the US PEL of $50 \text{ } \mu\text{g m}^{-3}$ following the introduction of wet spray misting. It is important to

Table 1. Lead personal air sample results.

Activity	<i>n</i>	<LOD	Arithmetic mean lead (mg m^{-3})	Geometric mean lead (mg m^{-3})	Range (min–max) lead (mg m^{-3})	Standard deviation	Range of sample times (min)
Dry mechanical processing	6	0	0.96	0.88	0.57–1.6	0.4	265–376
Wet spray mechanical processing	19	3	0.048	0.008	<0.0012–0.42	0.097	352–430
Wet stream processing	7	4	0.0056	0.0034	<0.0013–0.0038	0.005	109–380
Manual processing	2	0	0.13	0.13	0.12–0.14	0.01	76–255
Mining	10	7	0.004	0.0007	<0.0012–0.029	0.008	333–393

Table 2. Respirable silica (quartz) personal air sample results.

Activity	<i>n</i>	<LOD	Arithmetic mean silica (mg m ⁻³)	Geometric mean silica (mg m ⁻³)	Range (min–max) silica (mg m ⁻³)	Standard deviation	Range of sample times (min)
Dry mechanical processing	10	0	0.81	0.526	0.11–2.3	0.7	144–237
Wet spray mechanical processing	7	0	0.164	0.138	0.076–0.35	0.1	375–423
Wet stream processing	4	0	0.062	0.044	0.02–0.16	0.057	346–422
Mining	8	0	0.20	0.151	0.05–0.43	0.135	316–356

note that the PEL is not a health based standard and this exposure level would still result in worker blood lead levels that are many times higher than are considered acceptable for adults (Kosnett *et al.*, 2007).

There is no occupational exposure limit for silica dust in Nigeria. Respirable silica dust exposures with wet spray misting decreased from ~16-fold higher than the US OSHA PEL to 3-fold higher than the PEL. However, the US PEL is based on an 8-h time-weighted average (TWA) whereas we report results that are unadjusted for the sampling duration. The nature of the ore processing is that this work is sporadic based on the delivery of rock from the miners in the area. In addition, processors spend considerable portions of a work day on machine maintenance. Given the irregular working hours and variable workloads, the air sample results should be considered as TWA exposures for ore processing activities. In addition, the reported exposure levels were so elevated that if one credits zero exposure for the unsampled portion of the day, most values will still exceed the regulatory PEL. We observed airborne respirable silica levels with wet spray misting generally greater than the US regulatory standard of 0.05 mg m⁻³.

To our knowledge, this is the first intervention to reduce lead or silica dust exposures in artisanal small-scale mining. Previously, we have demonstrated that exposures to respirable dust and silica are generally higher in these operations than in large-scale mining (Gottesfeld *et al.*, 2015). Reductions in respirable silica of 80% with the use of water spray misting is consistent with laboratory study of brick cutting that demonstrated a similar reduction (Beamer *et al.* 2005). In that study misting nozzles with various flow rates were used and shown to reduce the respirable mass fraction of the airborne dust from 63% to 79%.

In an earlier study, we demonstrated that wet spray misting in stone crusher mills in India was responsible for an 82% reduction in respirable silica quartz (Gottesfeld *et al.*, 2008). This is very consistent with our current findings presented here.

Personal air samples from operators processing ore with the wet stream machine had respirable silica exposures that were 92% less than the average level observed during dry processing. Similarly, freely flowing water reduced the respirable mass fraction of the dust by 93% in the laboratory study during brick cutting (Beamer *et al.*, 2005). Despite the success of the wet stream machine in reducing lead and respirable silica dust, there is a concern about the applicability of this technology in Northern Nigeria due to the very dry conditions during most of the year. These machines were only used in the wet season in this area. The flow rate measured at these machines is ~30 l per minute. By contrast the spray nozzles we employed in our pilot were rated to consume between 0.8 and 1.4 l per minute at the operating pressure.

Water spray atomizers with pressurized systems could be employed to further reduce water consumption and potentially improve the dust collection efficiency. However, these systems generally require a reliable source of electricity which is not available in our study area.

The costs of these improvements to reduce these exposures as piloted, will vary considerably depending on the availability of a sufficient water supply. In our case of working in a semi-arid region, it was most cost effective to provide a well and water storage facility. The capital cost for providing the bore well, water storage, plumbing, and spray nozzles was ~\$5000 USD. In addition to providing water for processing activities, this water is used by both miners and processors for washing at the end of the day before returning to their villages.

There are an estimated 40.5 million informal small-scale miners that are estimated to contribute 20% of the world's gold supply in addition to other minerals and metals (IGF, 2017). In addition to providing a certain economic boost to local economies, the recent growth of this endeavor around the world has also brought increased risks to human health from exposures to mercury, silica dust, lead, and other toxic metals.

Although mercury exposures have brought the most scrutiny to ASGM, particularly since the Minamata

Convention was adopted in 2013, it is likely that the lead and silica hazards characterized in this study pose a far greater risk to human health and contribute significantly more mortality to exposed populations (Steckling *et al.*, 2017). Nevertheless, the Convention encourages governments to develop comprehensive health strategies to address these hazards with data collection, training, and awareness-raising (WHO, 2017). These national action plans required under the treaty offer an important opportunity to holistically address health risks in ASGM beyond the mercury hazard. Programs that arise from this effort may also benefit from the experience described in this pilot program.

Outside of Nigeria, there have been very few areas where ore from small-scale mining operations has been tested for lead or other metals. It is possible that other mining communities may be suffering from acute and chronic effects of heavy metals present in the ore without recognizing its presence. A study of metal exposures among a group of small-scale gold miners in Ghana indicated that they are heavily exposed to metals including chromium and arsenic (Basu *et al.*, 2011). It is well established that all such mining operations involve silica dust exposures. These communities are likely suffering from a high prevalence of TB, silicosis, and other silica-related diseases.

The background air sampling conducted before introducing wet processing quantified exposures and determined that mechanical ore processing poses a significantly higher risk than mining. After overcoming hurdles including the lack of water availability, we demonstrated substantial airborne lead and silica dust reductions with low-cost wet spray misting.

Although there have been more than 100 published reports on mercury exposures in ASGM, few have reported on other hazards in small-scale mining (Gibb and O'Leary, 2014). We are not aware of any other published reports of airborne lead levels in small-scale mining operations.

Previously, we had collected air samples for respirable silica dust in similar gold mining operations in Tanzania (Gottesfeld *et al.*, 2015). In Tanzania, respirable silica exposures exceeded occupational limits for all tasks monitored with an average exposure of 16.85 mg m^{-3} for underground mining with power drilling that was 337-fold greater than the US exposure limit (PEL) and 0.19 mg m^{-3} for dry processing operations or 4-fold greater than the PEL. One additional study had measured respirable silica during small-scale underground mining in Tanzania and reported a median level of 1.4 mg m^{-3} (Bratveit *et al.*, 2003). In both of these Tanzania-based studies, pneumatic drills were employed during mining operations. It is likely that use of this equipment contributed to the higher respirable silica exposures than we observed in Nigeria.

It is important to note that the introduction of wet mining and processing does not interfere with the yield of the gold from the ore. Of course, one advantage to the miners is that the wet spray misting will trap and retain ore that would normally be lost to the wind. In addition, this method reduces the dust that settles on crops in the area and can therefore help maintain crop yields that could suffer from dust deposition.

With the results of this pilot, we have demonstrated that there are simple, low-cost interventions to reduce these hazards in resource constrained environments in low-income countries. This approach can be a significant intervention to prevent lead poisoning and TB in these high-risk environments particularly in countries with high prevalence rates.

Conclusions

We have obtained excellent cooperation from mining communities and built successful partnerships. We achieved statistically significant reductions in airborne lead and silica dust levels. With low-cost interventions to convert dry ore processing to wet methods, we demonstrated the feasibility of reducing lead and respirable silica dust.

There is little data indicating how widespread the presence of lead and other heavy metals is in gold ore beyond this region of northern Nigeria. However, it is likely that other mining areas beyond the few locations that have been surveyed are facing similar lead hazards without knowing it. In addition, extremely high exposures to silica dust have been measured in small-scale mining and the presence of silica in ore is certainly not confined to any geographic area. Similar interventions are needed to work cooperatively with artisanal mining communities in all regions to assess and reduce these hazards.

Supplementary Material

Supplementary data are available at *Annals of Work Exposures and Health* online.

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Declarations of interest

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