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Mercury Exposure and Health Problems in Urban Artisanal Gold Mining (UAGM) in Makassar, South Sulawesi, Indonesia

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Abstract: Urban artisanal gold mining (UAGM) in Makassar, South Sulawesi, Indonesia, has been run by a number of urban gold workers with gold jewelry manufacture as its core activity. The wastes generated from goldsmiths' activities were further processed by the gold smelters to recover fine gold particles. Smelting gold doré, amalgamation, and burning out the amalgam were the mercury-based gold process usually applied in their work. While working the gold workers are, therefore, potentially exposed to a source of mercury pollution that may cause health problems because of working without proper protection. The aims of this research are to characterize the process of urban artisanal gold mining with the potential mercury exposures during the process, and to assess the health of the gold workers. The results showed that the gold workers had a low educational background, but a relatively high income. The total mercury concentration of gold workers was higher than the control group. They were exposed to intoxicatingly high levels of mercury with the average total mercury concentrations of 6.6 and 10.8 μg/g in the hair of indirect and direct exposed workers, respectively. The health assessment showed that 85% of the gold workers suffered neurological symptoms, such as tremors, and 44%–56% of them experienced restricted fields of vision, slow reflexes, sensory disturbances, unbalanced rigidity, and ataxia. The results also showed that the working years have reasonable correlation with the sum of the positive findings in the 10 neurological symptoms.

Keywords: urban artisanal gold mining (UAGM); mercury exposure; health assessment

1. Introduction

Mercury is one of the highly toxic pollutants posing a serious threat to public health and the environment. Mercury takes three chemical forms in the environment, namely, elemental mercury, inorganic mercury, and organic mercury or methylmercury. Humans are mainly exposed to organic mercury through consumption of fish, while inorganic mercury exposure occurs mostly through the inhalation of mercury vapor. Mercury exposure in urban areas are generally from anthropogenic sources, such as industrial pollution, transportation, waste incineration, and fossil fuel combustion,

while ore processing, such as artisanal small-scale gold mining (ASGM) was always associated as the source of mercury exposure in rural areas or mining towns.

The contribution of mercury to environmental pollution worldwide has grown as it is widely used in artisanal and small-scale gold mining (ASGM). ASGM often uses simple mercury-based technologies to extract gold, then mercury is released and evaporated during the amalgamation and burning processes. Despite the fact that it is illegal, ASGM is increasing in Indonesia [1]. Mining has expanded into the rural countryside of Sulawesi and Kalimantan. Several studies have examined the environment and health of miners engaged in various ASGM activities in rural areas of Sulawesi and Kalimantan. In the Tatelu (North Sulawesi) and Galangan regions (Central Kalimantan), mercury accumulation in the water, local fish, and bottom sediments of the rivers that receive drainage from ASGM activities has reached levels that pose risks for human health [2,3]. Health assessments of gold workers in mining towns showed that 55% and 62% of gold shop workers engaged in smelting amalgam in the Tatelu and Kereng Pangi regions (Central Kalimantan), respectively [3]. Their health report recorded the symptoms of mercury vapor intoxication, which includes ataxic gait, tremors of the eyelid, heel-to-shin ataxia, and hypomimia [3]. There may also be health risks to urban dwellers who live a long distance from gold-mining areas because mercury vapor released to the atmosphere in rural areas was dispersed by the wind to urban areas, as has occurred, for example, in Palu, the capital of Central Sulawesi [4]. Mercury exposure can also extend to the urban environment through the trade of gold doré, a type of gold that still contains mercury. A previous study reported that the burning of gold doré that was sold to gold shop workers in urban areas of Segovia, Columbia, and Andacollo, Chile, causing elevated levels of mercury vapor in the urban atmosphere of those cities [5].

Urban artisanal gold mining (UAGM) in Makassar can be categorized into two groups: goldsmiths and gold smelters. The goldsmiths design and manufacture gold jewelry, while the gold smelters recover the fine gold particles incorporated in the waste generated during the goldsmiths' work. With the exception of the ore excavation stage, the recovery process in UAGM is similar to the gold extraction stage in ASGM, but rather than excavating gold deposits or secondary ores, the gold smelters collect the waste from the goldsmiths and then apply a waste recovery process in the urban core of Makassar. An amalgamation method is applied during this recovery process to separate incorporated gold particles. Used mercury is released from the pond or trommel into the drainage system of the building, from where it flows to the main city drains, finally ending in the river. Doré, the gold resulting from the amalgamation process, usually still contains about 2%–5% mercury [6]. Therefore, when a goldsmith refines the gold doré by burning, he or she is directly exposed to mercury vapor. Moreover, the smelting operation is carried out in small buildings with insufficient ventilation, and there is no use of retorts or any type of condenser to capture the mercury fumes. Furthermore, they have used mercury for a long time, thereby potentially having health-related mercury intoxication problems. In this present study, we observed artisanal gold mining like the processes conducted in urban areas of Makassar.

Mercury concentration in hair generally reflects environmental exposures to methylmercury, though there about 20% of mercury in hair may be derived from inorganic mercury [7]. However, many studies have shown that hair can record long-term mercury exposure of methylmercury, as well as inorganic mercury. In a situation of low inorganic mercury exposure, almost all mercury in the hair is in methylmercury speciation, for example general population with high fish consumption. In the other hand, in cases of people engaged in gold mining and gold refining that have a high possibility of being exposed to mercury vapor, almost all mercury in the hair is in inorganic mercury speciation. As an example, total mercury concentration in the hair of workers involved in panning and smelting of artisanal gold mining in Sulawesi and Kalimantan, Indonesia were dominated by inorganic mercury [3]. Similar results were shown among gold miners, people in Seweya and Mwanza, Tanzania [8] and the Kedougou region, Senegal [9]. In addition, mercury, when incorporated into the hair, will not have any active metabolism, so the hair can provide long-term information of mercury

exposure. The importance of hair as a bioindicator has been discussed elsewhere [10–14]. UAGM may occur in many urban areas, yet there were no published paper dealing with these activities.

The present study characterized UAGM to recognize the process and the potential mercury exposures, and analyzed head hair of the gold workers to reveal mercury exposure levels. Exposure to mercury is known to have potentially damaging neurological effects on the human body by various mechanisms [7]. Therefore, health status was assessed by evaluating a number of neurological symptoms indicating mercury intoxication. The gold workers may occur in many urban areas of Indonesia, yet there were no official reports of these activities. Therefore, we used the mercury exposure issues related to ASGM activities in developing countries as comparative references.

2. Materials and Methods

2.1. Study Area

Makassar city, located in the southern part of Sulawesi, is the fifth largest city in Indonesia, in terms of population. The Makassar economy is built mainly on trade, processing industries, services, transportation, and communication, banking, and finance. One of the trade commodities is gold jewelry. The gold workers in this city fabricate gold bars to produce gold jewelry and then are sold to gold stores. Gold mining companies and ASGM in neighboring provinces (Minahasang utara [2], Gorontalo [15], Palu [16], and Kendari [17]) make significant contributions to the supply of gold bars to the city.

Since the 1970s, when a gold market was formally established, Makassar has become one of the main gold trading centers in Indonesia. From that time, urban residents in Makassar have been engaged in gold-related work. However, few technological improvements over traditional methods have been employed. The urban gold workers' activities are mainly concentrated in Tallo and Wajo sub-districts, as shown in Figure 1. The majority of urban residents in Makassar are fish consumers. As urban residents living in Makassar, gold workers have a high possibility of being exposed to methylmercury through fish consumption. On the other hand, they are also exposed to inorganic mercury through inhalation of mercury vapor. General urban residents who consume fish were selected for the control group. They are living in other sub-districts of Makassar, such as Mariso, Rappocini, Panakkukang, Tamalanrea, and Biringkanaya.

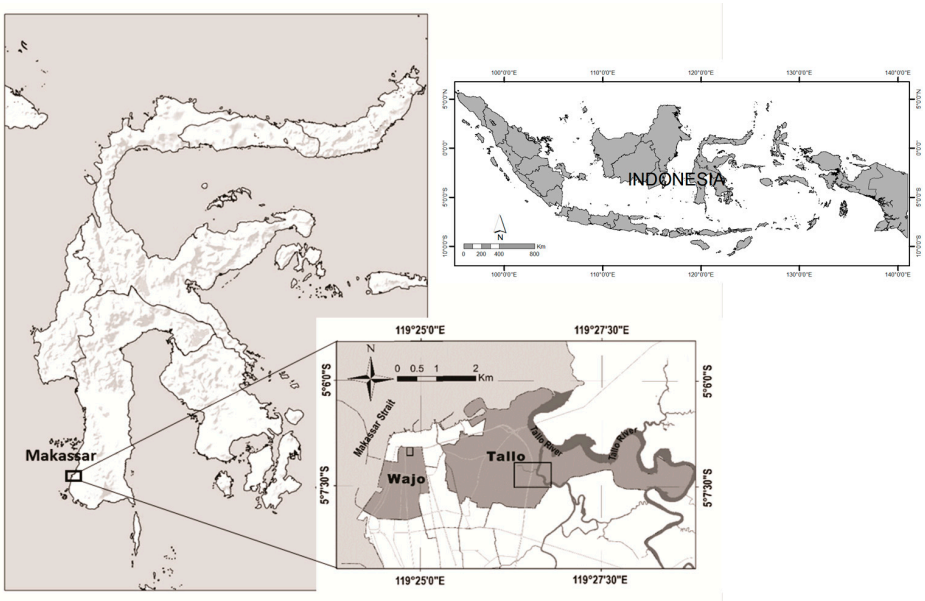

Figure 1. Sulawesi island, Indonesia, the locations of urban gold workers (two square boxes) in Tallo and Wajo sub-districts, Makassar.

2.2. Sample Colletion

Sample collection was conducted in March 2016 in the two sub-districts (Kecamatan) of Makassar, namely Tallo and Wajo. The subject was observed to study the process and the features of the job of every worker. The study was approved by the local government of Makassar district and Ethical Committee of the author's institution in Indonesia. An explanation was given to ensure they know the purpose of the sampling. Then, before the head hair was taken and an interview was performed, they signed an informed consent form.

Based on the observation, the UAGM workers were grouped into goldsmiths and gold smelters. Based on the relationship between their job and mercury exposure, the workers can be categorized as directly exposed and indirectly exposed to mercury. The gold workers conducting amalgamation, burning amalgam, and refining gold doré were categorized as being directly exposed to mercury, while those who conducted forming, decoration, or fashioning gold jewelry, and collecting the goldsmiths' waste, were categorized as indirectly exposed. An interview composed of relevant questions about the participants, such as age, gender, education, income, task in gold work, working year, and rate of fish consumption was implemented.

There were 95 gold workers that participated in donating their head hair and only 40 out of the 95-gold workers agreed to be involved in a health assessment. From the 40 gold workers, six gold workers who were under medical treatment were excluded because their disease might have biased the result of their neurological examination.

Since the background of hair mercury levels across the general urban populationin Makassar is unknown, head hair mercury levels of the gold workers was compared to the control group with the same rate of fish consumption. Through this comparison, the dominant route of the exposures would be known. A group of 80 urban residents served as a control group, which have no direct contact to mercury, with an age range and rate of fish consumption nearly the same as the gold workers. They also agreed to be involve in the hair sampling and only 17 out of the 80 participants agreed to be involved in the health assessment.

Participants, both gold workers and the control group, using dental amalgam fillings and cosmetics with positive mercury content were excluded. All of the participants were interviewed to record the socio-demographic factors, such as age, sex, education, income, and working years.

2.3. Analytical Procedure

To investigate the level of mercury exposure in the gold worker and the control group, we analyzed the total mercury concentrations in hair samples taken from all participants. Approximately 50–100 mg strands of hair were cut close to the skin from the occipital region on the right back side of the head and then labeled and sealed in a plastic sample bag before sending them to the laboratory for analysis.

The scalp hair samples were analyzed using particle-induced X-ray emission (PIXE) spectrometry at the Cyclotron Research Center, Iwate Medical University, Japan. The PIXE method has been used by many researchers [15,17,18]. Hair samples were washed in an ultrasonic bath by Milli-Q water and acetone for 5 min. The samples were dried at room temperature. The hair samples were affixed to a target holder. A 2.9 MeV proton beam hit the target after passing through a graphite beam collimator 6 mm in diameter. X-rays of energy higher than that of the K-Kα line were detected by a Si(Li) detector (25.4-μm thick Be window; 6 μm active diameter) with a 300-μm thick Mylar absorber. For the measurement of X-rays emitted at energies lower than the K-Kα line, a Si(Li) detector (80 mm Be; 4 mm active diameter), which has a high detection efficiency for low-energy X-rays, was used. The typical beam current and integrated beam charge were 100 nA and 40 mC, respectively. The procedure of the standard-free method for hairs without grinding and acid treatment was almost the same as that reported in previous studies [19,20].

The mercury level associated with the total mercury concentrations in hair samples were assessed by comparison with reference values. The reference values were obtained from benchmark limits of the

US EPA [21], and derived in analogy [22] were compared to the toxicology threshold limit established by the Human Bio Monitoring Commission of the German Federal Environment Agency [23]. Based on that comparable values, the threshold limits can be put into three categories: mercury concentrations of 0–1 μg/g are normal, of 1–5 μg/g represent the alert level, and of >5 μg/g represent high level risk.

2.4. Neurological Assessment

Neurological symptoms were clinically examined on the 34 gold workers and 17 control group participants. There were 10 objective symptoms [22] diagnosed by a physician following the protocols for environmental and health assessment of mercury suggested by UNIDO [24]. The 10 neurological symptoms consist of: (a) signs of bluish discoloration of gums; (b) rigidity and ataxia (walking or standing); (c) alternating movements or dysdiadochokinesia; (d) irregular eye movements or nystagmus; (e) field of vision; (f) knee jerk reflex and biceps reflex; (g) Babinski reflex and labial reflex; (h) salivation and dysarthria; (i) sensory examination; and (j) tremor: tongue, eyelids, finger to nose, pouring, posture holding, and the Romberg test. To determine the prevalent symptoms, we scored 1 for positively-observed symptoms and 0 for negatively-observed symptoms. Then, we calculated the occurrences of every symptom and the sum of symptoms that was found positive for every individual in the samples.

2.5. Statistical Analysis

Statistical analysis of total mercury concentrations in the hair samples was conducted using SPSS software (version 16.0, SPSS Inc., Chicago, IL, USA). An unpaired (two-tailed) non-parametric *t*-test with a 95% confidence level was used to determine the difference between the total mercury concentrations in the gold workers and the control group. Correlations between the total mercury concentration and working years of the gold workers were determined using Spearman correlation analysis. Correlations between the neurological findings and total mercury concentration and working years of the gold workers were determined with Pearson correlation analysis. A p value of less than 0.05 was considered significant.

3. Results

The activities of gold workers in Makassar city have operated for over 40 years. The activities of the urban artisanal gold mining can be divided into two groups, goldsmiths and gold smelters, as shown in Figure 2. Edible vegetables and fruits are planted in the yard. In addition to tap water from the domestic water system, artesian wells and open wells are used for daily life, such as drinking water and food preparation. Local fishes are produced in brackish water ponds located in the Tallo river bank.

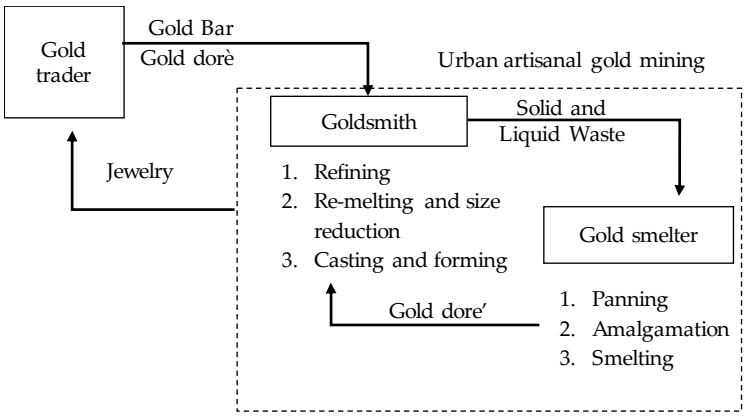

Figure 2. The urban artisanal gold mining process. Relationships between gold traders, goldsmiths, and gold smelters.

3.1. Goldsmiths' Activities

The goldsmiths in Makassar design, fashion, and artistically decorate jewelry made from gold. Gold bar or doré is obtained from either a gold trader or an artisanal gold mining worker. They design and fashion the gold to the desired shapes and sizes, and decorate it artistically using traditional tools and manufacturing processes. They also repair or remodel jewelry and sell it to gold stores. The gold bar/doré is refined by a torch flame in an open clay bowl, and then alloyed with Ag and Cu until it has a malleable composition (e.g., gold alloy composed of 65 wt% Au and 35 wt% Cu). This operation is conducted in a building without proper ventilation or emission controls, such as a retort or other mercury fume condenser. The gold alloy is reduced to granules with a diameter of 2–3 mm to facilitate re-melting. The granulated gold is re-melted, and then casted into molds of the desired shape for the jewelry. After that, followed by forming processes, such as cutting, filling, hammering, turning, spinning, bending, and polishing, to achieve the precise shape and dimensions of the jewelry. Finally, the jewelry is cleaned with a degreasing solvent or by ultrasonic washing.

As well as producing gold jewelry, goldsmith activities generate solid and liquid wastes, including used clay bowls, used gypsum moldings, wastewater, and degreasing solvents. The wastes are collected in separate tanks and then are sent to gold smelters. These are the primary gold resources for urban gold smelters.

3.2. Gold Smelters' Activities

The gold smelter collected the wastes, then further processed the waste to separate the incorporated fine gold particles. The recovery technique is similar to that used in artisanal gold mining, which includes panning, amalgamation, and smelting. Used clay bowls and gypsum moldings are ground, and cleaning towels and papers are burned, which are then mixed with the wastewater and the soil to form a slurry in a flooded pond. The pond occupies an area of about 1–2 m^2 and is 30–40 cm deep. These processes are mostly done in the yard of the urban miner's house.

Some gold smelters use shallow dishes to pan the slurry, while others use a carpeted sluice box in which the gold particles settle because of the density of the gold. In this panning stage, the miners add liquid mercury to extract and separate the gold from other waste. Few urban miners use low-capacity rotating trommels, even though they are more efficient for obtaining amalgam gold than are the dishes or the carpeted sluice boxes. The weight ratio of mercury to gold in the produced amalgam is estimated as 50:1. The excess mercury is squeezed through a fabric and may be re-used 2–3 times before finally being discharged. The amalgam is burned in an open clay bowl. The mercury evaporates, leaving gold granules in the clay bowl. Finally, the gold is sold to gold traders.

3.3. Population Description

The population description of the UAGM workers is summarized in Table 1. Males and females were engaged in this work. The mean productive age was 35 years old and they have actively worked in the urban area with population densities reaching 20,000 per km^2 [12]. The UAGM workers consist of 48 goldsmiths and 57 gold smelters. Among them, two goldsmiths and seven gold smelters were excluded due to using dental amalgam fillings and cosmetics containing mercury and one gold smelter also is excluded due to impaired speech. There were 52 and 43 gold workers identified as being directly and indirectly exposed, respectively.

Table 1. Demographic characteristics of urban artisanal gold mining (UAGM).

Demographic Characteristics	Control Groups (n = 80)	UAGM (n = 95)
Goldsmith	0	46
UAGM	0	49
Direct exposed	0	52
Indirect exposed	0	43
Sex:		
Male	40	53
Female	40	42
Age:		
Mean	31	35
Median	28	33
Minimum	18	18
Maximum	64	64
Latest education level (%):		
No education	5	7.4
Elementary school	6.2	35.8
Junior high school	7.5	31.6
Senior high school	35	25.3
University	46.2	0
Income US$:		
Mean	240	265
Median	263	226
Minimum	55	80
Maximum	530	600
Working Year (year):		
Mean	8	16
Median	5	14
Minimum	0	2
Maximum	45	46
Working hours in a day:		
Mean	6	7
Median	7	5
Minimum	0	2
Maximum	13	14

The control group was selected comprised of urban people who have the same frequency of fish consumption, but have no direct exposure to inorganic mercury, including cosmetics containing mercury. Participants from the control group consist of six housewives, 20 students, seven taxi drivers, 14 retailers, seven civil servants, 18 fishermen, and eight were lecturers.

The UAGM workers have average incomes of US$265/month (US$9/day). Their income was slightly higher than the income of ASGM workers in Kalimantan, who earn about US$74–223/month [25]. Most of the gold workers had low education levels, having only attended elementary, junior, and senior high school, and none were university graduates. This might be a contributing factor in that they did not have good knowledge of mercury risk. None of them has a license for mercury handling or to conduct small scale-gold mining.

3.4. Mercury Exposure to Urban Gold Workers

The average total mercury concentration in the hair of gold workers was 8.9 μg/g ranged from 2.5 to 43.0 μg/g. However, the difference between the mercury concentrations in the hair of the indirectly- and directly-exposed were statistically significant (t-test 2.7, p-value = 0.000). The average total mercury concentration in the hair of the control group was 2.8 μg/g, which is considerably lower and significantly different (t-test 6.8, p-value < 0.000) from that of directly- and indirectly-exposed (Table 2). Comparison with the threshold limits for mercury of the Human Biomonitoring Commission of the German Federal Environmental Agency shows that the mercury level in the hair of both exposed

groups fell within the alert to high level, while participants from other sub-districts in the control group have a mercury level within the normal to alert level.

Table 2. Total mercury concentration in the hair of the control group and exposed group.

Statistical Test	Total Mercury Concentration in Hair (μg/g)		
	Control Group	Indirect Exposed	Direct Exposed
Mean (SD)	2.8 (1.9)	6.5 (3.5)	10.8 (9.5)
Median	2.5	5.0	6.6
Min–max	0–12	2.5–15	2.7–43.0
Independent *t*-test (each exposed group vs. control group)		7.7, $p < 0.000$	7.2, $p < 0.000$
Independent *t*-test (directly exposed vs. indirectly exposed)		2.7, $p < 0.000$	

3.5. Relationships between Working Years and Mercury Exposure

The directly- and indirectly-exposed groups have persistently worked in smelting areas as indicated by the working years. The working years also reflects the duration of mercury exposure. Figure 3 shows a significant and positive correlation between working years of either directly-exposed (Spearman, r = 0.54; $p < 0.000$) or indirectly-exposed (Spearman, r = 0.57; $p < 0.000$) and the total mercury concentration. This result reveals that the exposed group who works longer had an increasing tendency in the mercury level.

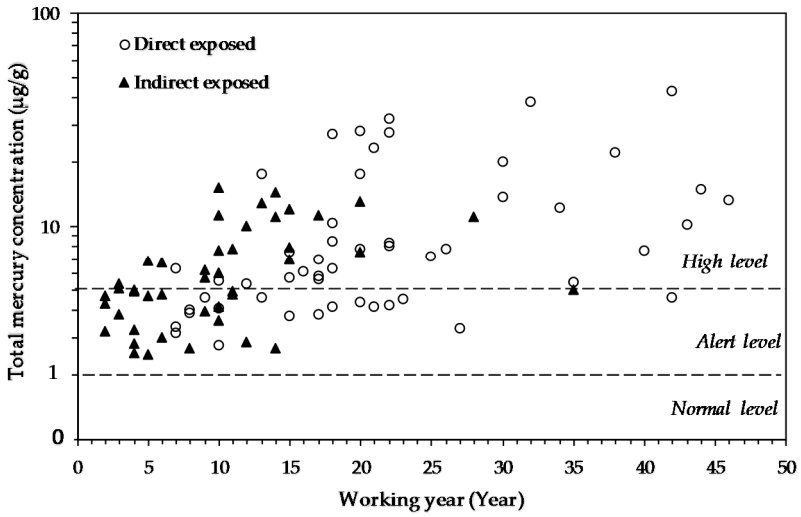

Figure 3. Relationships of working year and mercury concentration in the hair of directly- and indirectly-exposed groups.

3.6. Neurological Assessment

The neurological examination results of 34 gold workers and 17 control group subject showed various neurological disturbances, as shown in Figure 4. The most prevalent symptoms among the gold workers were tremors in the tongue, eyelid, finger, nose, pouring, posture holding, and Romberg test, reaching 85% occurrences, whereas 44%–56% had positive findings for unbalanced rigidity and ataxia, pathology reflex, sensory disturbance, constricted field of vision, and slow knee jerk and bicep reflexes. The prevalent symptoms of the control group were tremors in the tongue, eyelid, finger nose, pouring, posture holding, and Romberg test reaching 62% occurrences, while tests of irregular eye

movement, field of vision, knee jerk reflex and biceps reflex were the second dominant symptoms with 31%–44% occurrences.

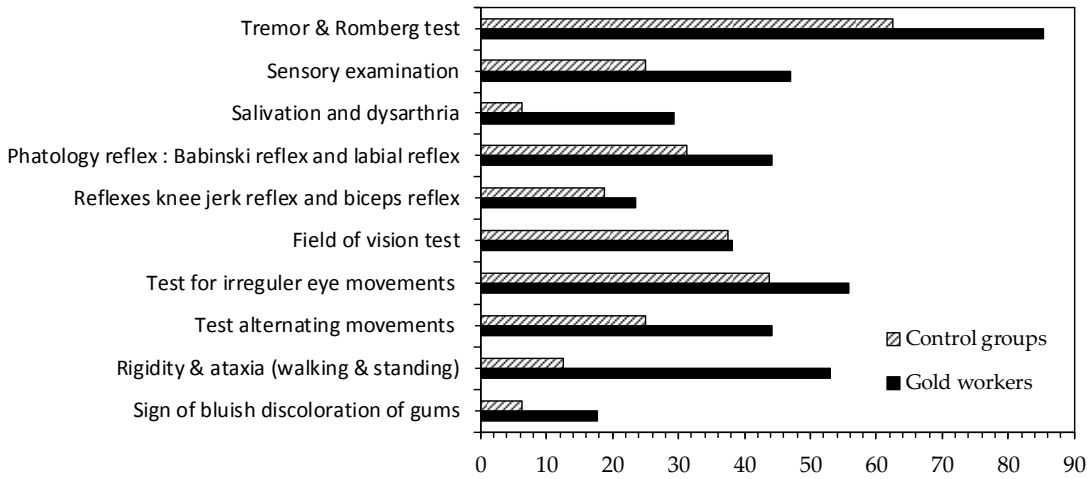

Figure 4. Occurrences of the 10 neurological symptoms in the control group and gold workers.

4. Discussion

Mercury vapor from gold refining and amalgam burning exposed to gold workers through inhalation. However, a large portion of mercury vapor emitted to the atmosphere may be precipitated in the environment [26]. Metallic mercury released to tailings and rivers can concentrate in the soil and sediment [24], eventually become bio accumulators. Since other people live around the urban mining, gold workers and people outsite urban mining have a high risk of being exposed to not only inorganic mercury, but also organic mercury through occupational and environmental routes. The total mercury in the hair of gold smelters reflects the exposure of inorganic and organic mercury.

Hair is generally associated with methylmercury exposure from fish; urine/blood are better indicators to organic and inorganic mercury exposure. However human scalp hair has been used as an alternative biological material for blood and urine in biomonitoring. The evaluation of mercury exposure using hair specimens is a well-established method in group studies [27]. Mercury has a longer half-life in hair and it remains stable for a long period in hair, making it useful to evaluate exposure for a few months, and it is easy to transport. Hair adjacent to the scalp is indicative for exposure that occurred 1–3 week earlier [27]. The US Environmental Protection Agency (EPA) assigned 0–1 ppm of hair mercury concentration a normal, 1–5 ppm as an alarm level, and >5 as a high level for human biomonitoring.

Mercury affects the human body through various mechanism. Clinical presentation of individual exposure depends on dose, duration of exposure, and form of exposure [28]. In chronic exposure, early presentation may appear as fine tremors in the extremities that will progress to the entire limb [28]. The classic triad of chronic toxicity are tremors, gingivitis, and erythrism (constellation of neuropsychiatric findings that includes insomnia, shyness, memory loss, emotional instability, depression, anorexia, vasomotor disturbance, uncontrolled perspiration, and blushing) [28].

4.1. Urban Artisanal Gold Mining (UAGM) Activity

Very small-scale gold mining was conducted traditionally in highly-populated areas. A similar process to the ASGM in mining sites drove us to name it “urban artisanal gold mining”. There are about 400 urban gold workers working in the urban mining site with six to eight workers in every site. Due to the small scope, some gold workers are able to handle three to four stages in gold work. Therefore, classifying the gold workers based on every task on the gold work was rather difficult.

Working without mercury emission control, the gold smelters came into contact with mercury in large quantities during amalgamation and burning the amalgam, while the goldsmiths were exposed to mercury vapor through refining the gold doré. The gold smelters might use 30–300 kg of liquid mercury per year. It is important to note that the gold smelters work in an open area, whereas the goldsmith works in an indoor area. In Rondônia, Brazil [29], a measurement of air contamination during reburning of gold doré in the dealer's shop revealed that mercury concentration inside the shop was high compared to either nearby the shop or the open area where amalgam was burned. In Paramaribo, Suriname [30], a higher mercury concentration range was also found inside the gold buy-up shop resulting from burning gold doré with improper retort function.

Mercury exposure during the gold work was probable. The processes in which a large fraction of mercury was released to the environment were in refining gold doré, amalgamation, and smelting the gold amalgam. Gold amalgam contains 40%–50% mercury [31] and gold doré 2%–5% [6]. The environment, as well as the gold workers, may be exposed. The amalgam or gold doré, when it was burned, the excess mercury was driven off into the ambient air of the work site because the work did not use mercury emission controls, such as retorts. Moreover, the work sites did not have proper ventilation. The goldsmiths performing refining-alloying of the gold doré may be directly exposed to mercury vapor. Likewise, the gold smelters conducting amalgamation and smelting the gold amalgam are potentially directly exposed to mercury vapor, while other workers handling other jobs such as hammering, bending, cleaning, polishing, collecting the waste, and crushing may be indirectly exposed.

4.2. Mercury Exposure

The average total mercury concentration in the hair of gold worker in Makassar was somewhat similar to the miners who worked in the excavation and smelting of gold ore. It was reported that the average total mercury concentrations in hair of smelting workers in Talawaan and Galangan were 13.14 and 17.09 μg/g, respectively [3].

The mercury level of the exposed group is beyond the normal level of the HBM threshold limit (Figure 3). There were 17 (or 33%) directly exposed workers and 19 (or 44%) indirectly exposed workers who had mercury levels that were within the alert level, whereas 33 (or 63%) and 24 (or 55%) of the directly- and indirectly-exposed workers, respectively, reached the high-level. Some of the gold workers have lower total mercury values because they did not work intensively in smelting, such as amalgamation and gold doré refining processes, thereby coming into infrequent contact with mercury. Mercury exposure to the directly- and indirectly-exposed who have worked for many years tends to increase (Figure 3). The total mercury in the hair of 19 (or 28%) of the exposed group who have worked more than 10 years have exceeded the alert level (1–5 μg/g). This indicates that both groups of exposed workers are effected by the exposure duration. Similar results of mercury exposure to goldsmiths in Pakistan showed that the workers with more years of experience had elevated mercury concentrations in their hair biological samples [14,32]. Participants from other sub-districts in the control group have a mercury level within the normal to alert level. There are 46 (or 55%) participants in the control group that have total mercury values in the alert level. This is probably because of dietary differences.

4.3. Neurological Asessment

Mercury exposure to the gold workers has reached alert to high levels where the adverse health effects are probable [3]. The results of the health assessment showed the occurrences of neurological symptoms among the gold workers (Table 3). Then, the results were separated into two groups based on the mercury level: alert level (1–5 μg/g) and high-level (>5 μg/g). This reveals the occurrences of neurological symptoms in the high level are more prevalent among the gold workers than in the alert level. In the control group, neurological symptoms were distributed similarly in the alert level and the high level. We assumed that intoxication was caused by various forms of mercury (elemental,

inorganic, and organic mercury). Exposure to the various forms of mercury may result in some similar and some different symptoms.

Table 3. Occurrences of the 10 neurological symptoms and mercury level in the gold workers and the control group.

Neurological Symptoms	Gold Workers		Control Group	
	1–5 μg/g	>5 μg/g	1–5 μg/g	>5 μg/g
Sign of bluish discoloration of gums	1	5	0	1
Rigidity and ataxia (walking & standing)	5	12	1	1
Test alternating movements	3	12	2	2
Test for irregular eye movements	7	12	3	3
Field of vision test	3	10	3	3
Reflexes knee jerk reflex and biceps reflex	3	8	1	2
Pathology reflex: Babinski reflex and labial reflex	7	7	3	1
Salivation and dysarthria	2	7	1	0
Sensory examination	6	8	2	2
Tremor and Romberg test	12	17	4	4

Based on the threshold limit of the Human Bio Monitoring (HBM) Commission of the German Federal Environment Agency.

The various neurological disturbances are shown in Figure 4. The result of the health assessment also recorded that every gold worker was diagnosed experiencing a different number of symptoms. We found that there were two gold workers experiencing nine neurological symptoms, whereas two gold workers showed negative findings for all 10 neurological symptoms, as shown in Figure 4. In comparison with health assessment of ASGM workers in Sulawesi and Kalimantan, it was reported that ataxia and tremors were the most prevalent symptoms [3].

On average, the UAGM workers suffered four out of 10 symptoms. It is found that a gold worker who had been working for many years experienced many more symptoms than those who had worked for only a few years. A clear indication of this reasonable correlation (Pearson, r = 0.59; p = 0.000) was found by plotting the working years and the sum of positive findings for neurological symptoms in the 34 gold smelters (Figure 5). Several studies reported a significant correlation between mercury-intoxicated symptoms and exposure duration [33,34]. This might suggest the effect of exposure duration on the health-related mercury intoxication.

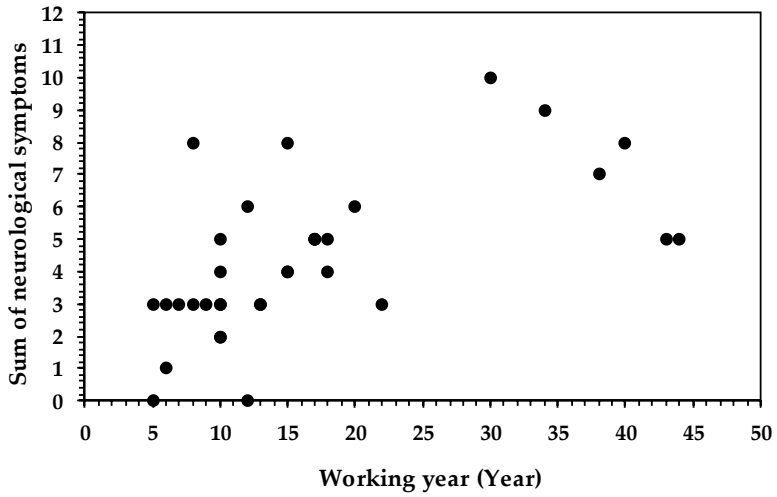

Figure 5. Relationships between working year and the sum of neurological symptoms.

In general, symptoms occur and progress more rapidly the higher the concentration of mercury encountered. Figure 6 demonstrates the relationship between the sum of neurological symptoms and the increase of total mercury concentration. There was significant correlation between the sum of neurological symptoms and the increase of total mercury concentration (Pearson, r = −0.49; $p = 0.004$). Several studies reported significant correlation between mercury intoxicated symptoms and hair mercury concentration [3,22,35–37]. Other studies showed a lack of correlation between the symptoms and mercury level in the hair [8,38]. Of the possible reasons for this is that the body retention of mercury in an individual depends on dietary and physiological factors that can modulate the metabolism of nutritive or toxic metals [39].

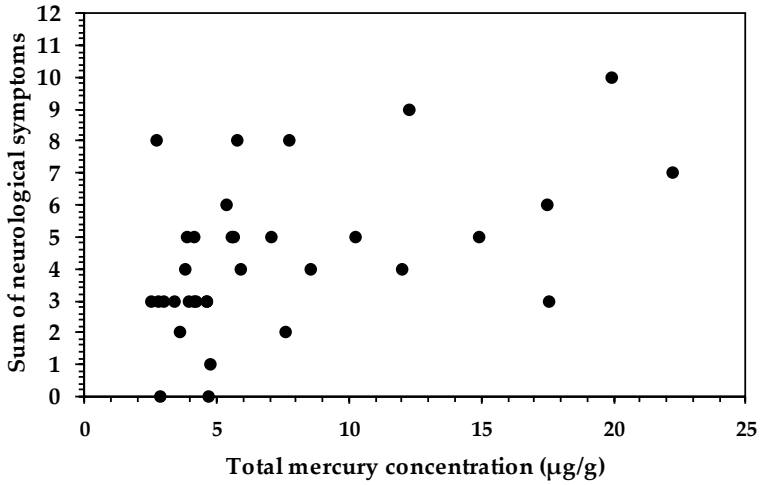

Figure 6. Relationships between total mercury concentration and the sum of neurological symptoms.

The findings in this study indicate mercury exposure to gold workers has reached alert to high levels. Urban artisanal gold mining, in fact, is a unique, informal work and the gold jewelry they produced represents an original product of Makassar. Government interventions are essential to move forward following international guidelines, such as introducing retorts to capture mercury fumes, implement better waste management, and apply recovery processes without amalgamation or centralized amalgamation sites [40]. On the other hand, strong stakeholder commitment is needed for long-term sustainability of this work, such as providing workers with higher education and financial loans to support application of cleaner technology in their gold work [41].

Furthermore, health assessments should also be performed to susceptible subpopulations, such as children and pregnant women. Studies have shown that the developing nervous system of children is very sensitive to mercury, while pregnant women can suffer persistent adverse effects on their children's development [35]. To prevent mercury exposure, problem-solving should be constructed which involves a network collaboration of all of the elements in the community; national and local government, industries, stakeholders, researchers, educational institutions, NGOs, civil society and gold workers. So far, local government, in colloboration with universities, has been conducting waste management training, medical check-ups, and consultations for the urban gold workers. In addition, universities, through community service and development programs, are managing to implement applied green methods for small-scale gold recovery towards green and healthy communities.

5. Conclusions

This study examined how urban gold workers in Makassar were exposed to mercury. Based on the HBM threshold limit, total mercury concentration in head hair of the gold workers fell within the alert to high-level. The total mercury concentration tends to increase with the increase of working years. This suggests the effect of mercury exposure duration. Several neurological symptoms were noted in

the majority of the gold workers. The gold workers who have a high-level of mercury were diagnosed were subject to a number of neurological symptoms. The health assessment also revealed a reasonable correlation between working years and the sum of positive findings for neurological symptoms. The awareness of gold worker about adverse health effects of mercury exposure should be raised. In addition to routine medical check-ups, it is important for the local government to extend interventions by introducing retorts to capture mercury fumes, implementing better waste management, applying recovery processes without amalgamation and centralized amalgamation sites.

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