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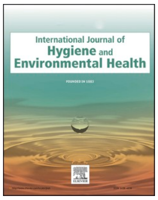

Lead exposure by E-waste disposal and recycling in Agbogbloshie, Ghana

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ABSTRACT

Background: Agbogbloshie in Ghana is the world's biggest dumpsite for the informal recycling of electronic waste (e-waste). E-waste is dismantled by rudimentary methods without personal or environmental protection. Workers and occupants are exposed to lead. There are no data so far about the extent and the consequences. We therefore analyzed blood lead levels (BLL) and creatinine levels (CL).

Methods: Full blood samples and basic data (i.e. age, job, length of stay) were collected from dumpsite volunteers. BLL were measured by atomic absorption spectrometry; CL were assessed using the standard clinical laboratory procedures of Aachen Technical University. European BLL reference values were used as Ghana lacks its own. Statistical analysis was by non-parametric tests (Mann-Whitney *U* test), with $p < 0.05$.

Results: Participants of both sexes ($n = 327$; 12–68 years; median age 23 years) were assessed. Most workers were aged <30 years. The collective's BLL was in pathological range for 77.7%; 14% had a BLL >10.0 μg/dl with symptoms consistent with high lead exposure including severe (6.5%) and intermediate (39%) renal disorder. BLL above 15.0 μg/dl were found in 5.9% of all workers which is the German threshold for those working with lead. Elevated CL in a pathological range were found in 254 participants. This is problematic as 75% of the lead entering the body is excreted via urine.

Conclusion: Most of our volunteers had pathological BLL and CL. Preventive strategies are necessary to reduce health risks, particularly for vulnerable populations (i.e. children, pregnant women).

1. Introduction

The informal processing of electronic waste (e-waste) is a growing global problem causing adverse health and environmental consequences (WHO, 2021; Asante et al., 2012). In 2019, 53.6 million tons (Mt) of e-waste was produced worldwide. About 50–80% of it will end up in Ghana, China, inda, and Nigeria (Puckett and Smith, 2002; Orisakwe and Frazzoli, 2010; Lundstedt, 2011) and the main center in Ghana is Agbogbloshie Scrap Market in Greater Accra (Brigden et al., 2008). However, the true chemical contamination of the place is largely unknown (Caravanos et al., 2011) although it is considered to be a major risk for the workers and the general population living near-by (Issah et al., 2022). The bulk (82.6%) of this e-waste was recycled informally using primitive methods that lacked personal or environmental protection, thus releasing hazardous mixtures of multiple toxicants into the air, earth, food and water sources (WHO, 2021; Asante et al., 2012; Huang et al., 2014; Bocca et al., 2013). The informal processing and recycling of electric and electronic waste is a significant source of lead exposure. For example, open cable burning, acid leaching into water (using nitric acid or mercury, cyanide salt) and cooking circuit boards to extract precious metals exposes workers directly and by inhalation to many hazardous compounds, including lead and cadmium (WHO, 2021; Asante et al., 2012). The World Health Organization (WHO) identified ten chemicals that are most closely linked to adverse health impacts from informal e-waste recycling include lead, other heavy metals, dioxins and more (WHO, 2021; Asante et al., 2012; Huang et al., 2014; Bocca et al., 2013). The toxicokinetics of the these chemicals varies, but they can enter the body by ingestion (food, water, breastmilk, dust contamination of objects put in mouth), inhalation (especially aerosol gases and particles from open burning), transplacental exposure, or by dermal exposure (Forti et al., 2020; Adanu et al., 2020; Adusei et al., 2020; Akormedi et al., 2013; Baldé et al., 2017; Caravanos et al., 2011; Daso et al., 2016;

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Feldt et al., 2014; Kaifie et al., 2020).

The health risk to e-waste workers from lead exposure is the focus of this paper. Lead is a non-degradable hazardous element with cumulative toxicity. There is no safe exposure level to lead, even at low levels (WHO, 2021; Asante et al., 2012). It is a known neurotoxin, nephrotoxin, and genotoxin. It also impairs blood glucose levels, respiratory, cardiovascular and immune systems (Grant et al., 2013), (Zeng et al., 2019; Lu et al., 2018; Dawud et al., 2022). Lead affects pregnancy by increasing stillbirths, spontaneous abortions, and premature births. Lead also reduces birthweights and birth lengths, results in adverse neonatal outcomes with psychological and neurological effects, and reduces postnatal growth and development (WHO, 2021), (Asante et al., 2012), (Grant et al., 2013), (Zeng et al., 2019; Lu et al., 2018; Dawud et al., 2022).

Children and fetuses are especially vulnerable to the neurotoxic effects of lead. BLLs as low as 3.5 μg/dl may be associated with decreased intelligence in children, behavioral difficulties and learning problems (Mishra et al., 2022; Jeong et al., 2015; Lanphear et al., 2016). It is predominantly male children and adolescents who are involved in e-waste work in Agbogbloshie (WHO, 2021; Asante et al., 2012). Even if they are not at the waste site, children can live in home-based family workshops where informal recycling takes place. Young children absorb 4–5 times more lead than adults (except pregnant women) (Mishra et al., 2022). The lead in the bones of pregnant women is released into the blood and becomes a source of exposure to the developing fetus (Mishra et al., 2022). Other additional lead exposure routes for children include breastfeeding and their changing and developing physiology (e.g. breathe more rapidly and ingest more food and air relative to their size with lower rates of toxin elimination compared to adults). In early years there is more hand-to-mouth activities and time spent crawling and playing in dust or dirt, while adolescents have more high risk behavior compared to adults (WHO, 2021; Asante et al., 2012; Kaifie et al., 2020; Zeng et al., 2019; Mishra et al., 2022; Zhang et al., 2022; WHO, 2022). The dust puts crawlers to specific ang high risk since its lead content is several times higher than nearby reference areas (Lu et al., 2018).

Lead as a substance has a high affinity for various chemical subgroups of amino acids. In addition, mitochondria are highly sensitive to lead (Thomas, 2020). However, its high binding power to δ-ALAD is essential for its distribution in the body. This is why lead binds to erythrocytes and can be transported to all organs where it accumulates in practically all organ systems. However 90% of lead (in adults) and 60% (in children) is deposited in the bones and teeth, where it can remain for decades (WHO, 2021; Asante et al., 2012; Mishra et al., 2022; Aalami et al., 2022), and the rest accumulates in other organs, where it has acute and chronic toxic effects (Bolt et al., 2019). The triad of lead intoxication is intestinal colic, anemia and paralysis of the radial nerve (Zhanga et al., 2020). Lead can inactivate enzymes and is toxic to many cells - e.g. bone marrow, cells of central and peripheral neural system, lung cells and the gastrointestinal system (Mishra et al., 2022; Zhang et al., 2022; WHO, 2022). Some of these effects may be caused by a dysregulation of microRNA (Aalami et al., 2022).

Absorbed lead will initially enter the bloodstream quickly and easily via fine particles, aerosols and their vapors. It is most commonly absorbed through the gastrointestinal system, followed by inhalation of lead contaminated fume (e.g. burning processes), and skin absorption (Zeng et al., 2019). All exposures occur in e-waste recycling. Hence an acute load or even intoxication can be measured in full blood samples. The excretion of lead occurs mainly through urine (75–80%). Lead's impact on health is dependent on the concentration of BLL which is normally reported in [µg/l] (Table 1) ((anonymous), 1996). High BLL can result in diseased states already mentioned, including renal dysfunction, learning disability, reduction of the intelligence quotient (IQ) and more critically fatal outcomes (Tutdibi et al., 2008; Meiβner et al., 2011; Mittag et al., 2015). This is one reason why biomonitoring of acute and long-term exposure to lead are recommended for informal e-waste processing.

Table 1

Blood lead levels and their toxic effects ((anonymous), 1996).

Effects	Blood lead levels [µg/dl]	
	Children	Adults
Nervous system disorder		
Increase of hearing threshold	5.0–47.0	
Decrease of IQ	10.0–15.0[a]	
Impairment of visumotor test performance	<10.0	50.0
Peripheral neuropathy		30.0–70.0
Hematopoietic dysfunction		
Elevated EP	>15.0	50.0
Hematocrit (HKT)/hemoglobin (Hb) decreased		27.0
Anemia (HKT <35%)	>20.0	80.0–100.0
Others		
Renal dysfunction	10.0	
Increased blood pressure		5.0–35.0
Smaller malformations (hem-/lymphangioma, cryptorchidism)	6.7[b,c]	
Decrease of birth weight		12.0–13.0
Premature birth (<37th week)		>14.0
Disorder of vitamin D metabolism	15.0–20.0	

[a] Sporadic <10.0 µg/dl.

[b] Only with summation of single anomalies.

[c] Umbilical cord blood.

However, at Agbogbloshie and probably at other places with informal recycling there is a social factor which must be taken into account for any risk management: Although the health risks from lead are well known also by most of the scrub workers, many e-waste workers do not want any changes in rules or regulations in dealing with e-waste because they are afraid of earning less money than before (Akormedi et al., 2013; Amoyaw-Osei et al., 2011). Our participants when interviewed stated that they earned two to four times more money recycling e-waste compared to an activity in the region of their origin. Hence many workers take the risk of encountering lead to support their families. However, children must also work at the landfill to support their families (WHO, 2021), (Asante et al., 2012; Schluep et al., 2012), and it is predominantly male children and adolescents who are involved in e-waste work in Agbogbloshie (WHO, 2021), (Asante et al., 2012). This is alarming because of the deleterious effect of lead on the nervous system of children as already stated. Nevertheless, it is not always possible to get another job that pays a better wage for this population other than working in more dangerous occupation like e-waste burning (Acquah et al., 2019).

The aim of this study was to analyze the BLL of the people living and working at and around the dumpsite to get an idea of their lead exposure, and to enable health and safety personnel to perform health risk estimations. Furthermore, the collective should cover all activities done at the dump site to differentiate which jobs carry the highest risk of lead exposure.

2. Methods

2.1. Study site

Agbogbloshie is one of the districts of Accra in Ghana. It is the world's biggest dumpsite for the informal recycling of e-waste, and one of the top ten most toxic places worldwide (Bernhardt and Gysi, 2013). It's located in the south industrial area, just north of the Korle Lagoon and in-between two creeks. All steps for informal e-waste processing take place here including the purchasing, sorting, dismantling, and burning of e-waste, each person with their own working space onsite. Health and safety procedures for these workers are absent. There is no political will to follow through legislation for environmental protection or e-waste management in Ghana (e.g. "Basel Convention" or "Nairobi Declaration" on e-waste) (Amoyaw-Osei et al., 2011; Lundgren, 2012; Schluep et al., 2012; Nartey, 2016). It is hardly affordable to separate the e-waste from its toxic materials professionally with adequate procedures concerning occupational health and safety (Amoyaw-Osei et al., 2011).

Lead is found in lead-acid batteries, printed circuit boards, large domestic appliances, isolation sheaths of cables and wires, and others (Amoyaw-Osei et al., 2011; Manhart, 2015). A detailed overview about the material and its toxic ingredients is given in (Huang et al., 2014). Health risks and soil contamination are mainly caused by heavy metals, especially lead (Caravanos et al., 2011; Nartey, 2016).

All steps of informal e-waste recycling at Agbogbloshie are very rudimentary, non-electronic and under poor working conditions. Bare hand sorting, dismantling with just simple tools like hammers, screw drivers and stones, and open burning are used to access the valuable metals are standard procedures (Adanu et al., 2020; Schluep et al., 2012; Acquah et al., 2019). Lead fumes are also released again when lead is melted down to create new lead-bars for selling (Amoyaw-Osei et al., 2011).

Dismantlers and burners have the greatest exposure to lead (WHO, 2021; Asante et al., 2012). Exposure is enhanced by working 10–12 h per day without protective equipment like gloves or masks, and in low hygienic conditions preventing handwashing before eating (Akormedi et al., 2013; Amoyaw-Osei et al., 2011; Nartey, 2016; Acquah et al., 2019). E-waste workshop workers are exposed to lead dust from dismantling and desoldering activities (582 and 486 μg/100 m^2 on work surfaces respectively; 3610 and 19,172 mg/kg on floor respectively) (Nartey, 2016). Suspended air particulates of lead are inhaled and ingested by the workers, but can also be blown by the wind to contaminate water sources and soil, thus entering the food chain (Caravanos et al., 2011; Amoyaw-Osei et al., 2011; Fosu-Mensah et al., 2017; Obiri et al., 2016; Kyere et al., 2017). Fine particles in fumes may penetrate deep into the lungs and will be absorbed there, while larger particles are absorbed orally by dust and contaminated hands (Geibel, 2003; Wittsiepe et al., 2016). This seems to be a common problem not only for scrap workers, but also for the population living around the dumpsite. Especially during the dry season there is additional exposure by the air (dust) from the trade winds, even into their private living spaces (Lau et al., 2014), and food or water (Aftab et al., 2023; Caicedo-Rivas et al., 2022; Steinhausen et al., 2022).

The dumpsite is surrounded by residential and commercial areas like Accra food market on the other side of the creek, the slum “Old Fadama” where about 100,000 people are living now (Opponga et al., 2020), but also by schools, and therefore the winds can possibly blow lead dust particles and lead contaminated fumes to these areas (Kyere et al., 2015, 2017). A specific problem caused by Agbogbloshie’s geographical location in that during the dry season strong trade winds regularly blow from northeast to southwest. Since the market and five large schools with about 1000 pupils in each are located downwind of the dumpsite, it must be assumed that during the dry season lead contaminated dust contaminates this downwind region and thereby exposes this population. Children are especially vulnerable to any lead exposure.

2.2. *Study design, collective, data acquisition and analysis*

The design was a cross-sectional study. Volunteers of both sexes were recruited by the investigators directly from the dumpsite ($n = 327$; age range 12–68 y; median age 23 y). Inclusion criteria were: living and working in or close to the e-waste dumpsite at Agbogbloshie, and a willingness to join (for minors the consent of a parent or legal guardian was necessary). The participants reflected the full range of activities at and around the dumpsite: e-waste collecting and sorting, dismantling, burning, “woman sellers”, market traders, factory workers and school pupils.

The volunteers were informed in detail about the study. Several interpreters were involved since up to 40 different languages are spoken on the site, and there is no lingua franca. After a detailed standardized interview by the authors of the study (work, social background, eating, smoking behavior, etc.; local translators were recruited before), full blood samples were obtained. The study was consulted by the ethical commission at RWTH Aachen Technical University/Germany (Ek 093/15) and at Legon University/Accra (MNIMR-IRB CPM 058/14–15).

The 327 blood samples were analyzed for CL and BLL, from which 323 CL datasets (98,8%) and 322 BLL datasets (98.5%) were evaluated. Creatinine was analyzed using the standard clinical laboratory procedures of Aachen Technical University, while BLL was measured by atomic absorption spectrometry (AAS) as described in detail by Consoir (2021), Consoir et al. (submitted). Differences between subgroups according to their work and assumed exposure were analyzed with non-parametric tests (Mann-Whitney *U* test or X^2-Test where appropriate) since data did not follow normal distribution. $P < 0.05$ was defined as significant.

2.3. *Interpretation of results*

Ghana does not yet have its own population-specific blood reference values (see also Consoir (2021), Consoir et al. (submitted) and relies so far on other countries. For normal creatinine blood reference levels, the standard clinical laboratory handbook of Thomas [16] was used: for women >18 years it was 0.46–1.00 mg/dl and for men >18 years it was 0.57–1.18 mg/dl. For children aged 11–13 years it was 0.42–0.71 mg/dl, and for ages 13–15 years it was 0.46–0.81 mg/dl. As there was no reference level for children aged 15–17 years, they were included in the 13–15 year old group in this study.

3. Results

In categorizing the types of work undertaken by our 327 volunteers we found: 24 (7.3%) were burners, 23 (7.0%) were e-waste collectors, 23 (7.0%) dismantlers, 18 (5.6%) were sorters, and 21 (6.4%) were women/market sellers. A total of 137 (41.9%) worked in the market, 24 (7.3%) worked in the factory nearby which is located downwind from the dump site, and 57 (17.5%) were school children from the neighboring school (Fig. 1). The creatinine levels of the collective are shown in Fig. 2. Most concentrations were between 0.2 and 3.6 mg/dl. On average, the workers had creatinine levels of 1.76 mg/dl. Some outliers showed concentrations of up to 4.8 mg/dl which indicates a renal insufficiency grade 2. The creatinine levels sorted by age are demonstrated in Fig. 3. One out of two children aged 12 had a pathological CL result (0.3%), and 51/68 children aged 13–17 years had pathological results (15.6%) (Fig. 3). All women older than 18 years had creatinine levels above 1.00 mg/dl (4.9%), and 187/240 men older than 18 years showed pathological results (57.2%). In total 254 participants (77.7%) showed pathological results of elevated creatinine levels (Fig. 3).

Renal function can be calculated using the formula for chronic kidney disease epidemiology collaboration (CKD-EPI-Formula), see Formula 1 [46]. This formula calculates the glomerular filtration rate (GFR) which shows the amount of primary urine produced in a given time by a healthy kidney. When the creatinine level is above the reference value, the GFR will decrease and substances like lead may eventually accumulate (Levey et al., 2009). With CKD-EPI the renal disorder is classified in stadium I to V. Stadium I: GFR >90 ml/min, stadium II: 60–89 ml/min, stadium III: 30–59 ml/min, stadium IV: 15–29 ml/min and stadium V: <15 ml/min. While stadium I is normal renal function, stadium II is mild-, stadium III is intermediate-, stadium IV is severe renal disorder, and stadium V is renal insufficiency. A quarter (27.9%) of workers from all working sectors had a normal renal function, 26.7% suffered mild renal disorder (stadium II), 38.9% suffering intermediate renal disorder (stadium III) and 6.5% suffering from severe renal disorder (stadium IV).

Subject BLL are given in Fig. 4 while Fig. 5 illustrates the BLLs according to the respective activity. The mean BLL value was 6.44 μg/dl. Most BLLs were between 2.6 and 7.7 μg/dl, but the range was from 0.8 to 15.1 μg/dl and included high rogue results (one dismantler had 25.4 μg/dl, one market worker had 31.4 μg/dl, and one pupil reached 34.5 μg/dl (0.31% each)). Rogue results in this case are all values above the upper

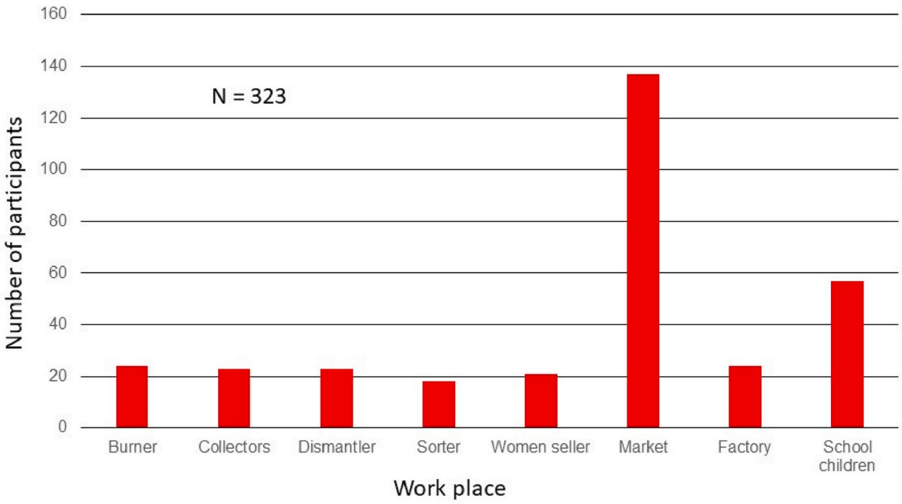

Fig. 1. Number of participants, differentiated by their respective work activity.

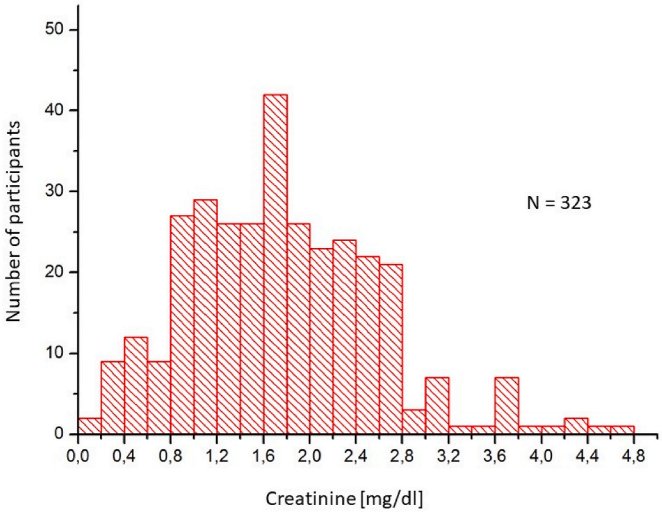

Fig. 2. Creatinine levels of the collective.

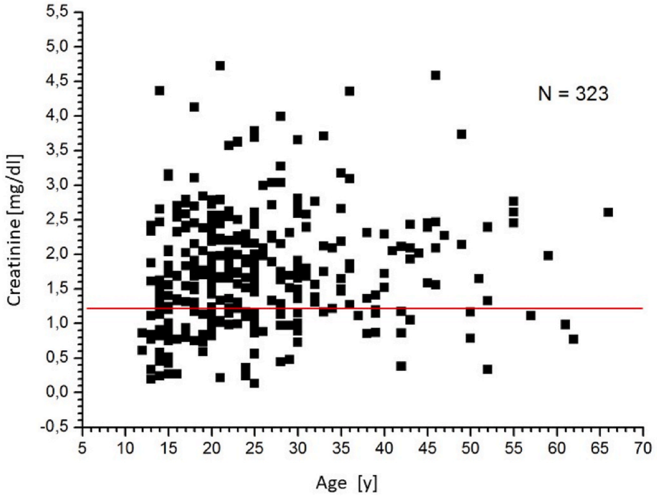

Fig. 3. Creatinine by age.

Formula 1

Formula to calculate the glomerular filtration rate [46].

Sex	Serum creatinine [mg/dl]	eGFR-formula (multiplicate with 1.159 for people with black skin color) [ml/min/1.73m^3]
Female	**≤ 0.7**	$\boldsymbol{GFR = 144\,x\,(\frac{serumcreatine}{0.7})^{-0.329}\ \mathrm{x}\ (0.993)^{\mathrm{age}}}$
Female	**> 0.7**	$\boldsymbol{GFR = 144\,x\,(\frac{serumcreatine}{0.7})^{-1.209}\ \mathrm{x}\ (0.993)^{\mathrm{age}}}$
Male	**≤ 0.9**	$\boldsymbol{GFR = 141\,x\,(\frac{serumcreatine}{0.9})^{-0.411}\ \mathrm{x}\ (0.993)^{\mathrm{age}}}$
Male	**> 0.9**	$\boldsymbol{GFR = 141\,x\,(\frac{serumcreatine}{0.9})^{-1.209}\ \mathrm{x}\ (0.993)^{\mathrm{age}}}$

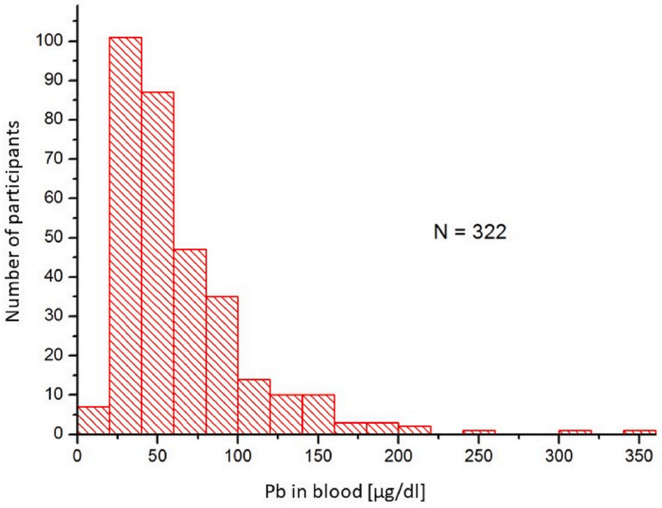

Fig. 4. Lead concentrations in the blood of the participants.

whisker shown in Fig. 6. BLL above 15.0 µg/dl is the tolerable threshold in Germany for men aged 18–65 years who are occupationally exposed to lead as given in TRGS 903 ((anonymous), 2013), ((anonymous), 2017), and this threshold was reached or exceeded by 18 men (5.59%) and in 1 child (0.31%). The jobs held by these latter 19 participants were: 8 burners, 4 dismantlers, 3 collectors, 2 workers from the market, and 1 each from school and sorting. There is so far no equivalent threshold established for a Ghanian population.

BLL above 3.0 µg/dl for women (German reference value, no

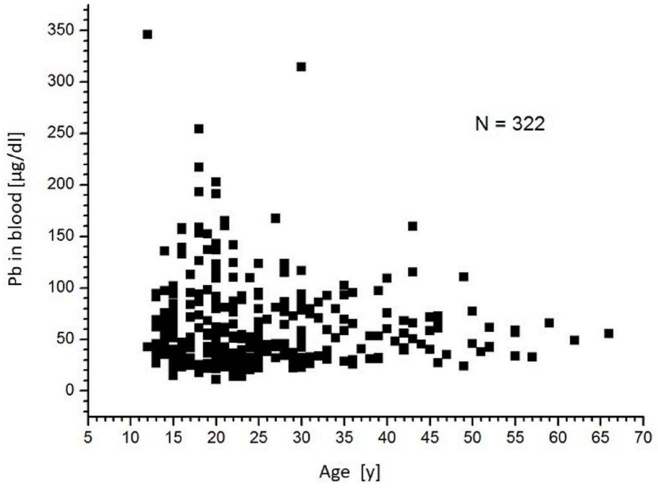

Fig. 5. Blood lead concentration dependent on age.

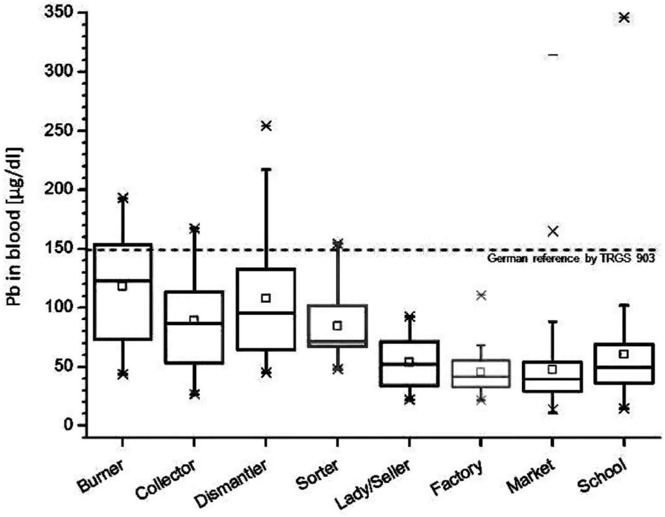

Fig. 6. BLL differentiated according to the activity of the participants.

reference for Ghana available, see above) were measured by 17 women sellers (5.28% of all participants or 81% of all 21 women in collective, respectively). BLL above 4.0 μg/dl for men (again German reference value) were measured in 144 male workers (44.72% of all participants or 60% of all males older than 18 years). BLL above 1.5 μg/dl for girls of the age of three to 17 and for boys aged 11–17 years, or above 2.0 μg/dl of lead on whole blood for boys in the age of three to 10 (again German reference values) were measured by 45 children (13.7% of all participants or 66% of all 68 children under the age of 18).

The BLL were sorted by the participant's age in Fig. 5. All outliers were found in persons aged 12–30 years. Most of the workers were younger than 30 years. Here two different tendencies were observed, the young group with several individuals with several high BLL, and a slight although significant increase of the BLL with age. The BLL differentiated according to the respective professions of the workers are shown in Fig. 6. Persons working directly with the e-waste material on the dump site had the highest BLL, led by the burners with the highest values (all data given with quartile 3 and 1) (11.83 μg/l (+3.96(Q3); −4.13(Q1)), followed by dismantlers (9.5 μg/dl (+3.77; −2.67)), collectors (8.66 μg/l (+2.64; −3.1)), and sorters (7.79 μg/l (+2.41; −11)). Women sellers (5.2 μg/l (+2.08; −1.79)), factory workers (4.17 μg/l (+1.53; −0.91)), market business people (3.95 μg/l (+1.49; −1.01)), and pupils (4.99 μg/l (+1.97; −1.35)) were not in direct contact with the metal at the site, however via environmental exposure they also had significantly increased BLL compared to a non-exposed collective (Fig. 5). Fourteen percent of all participants had BLL>10.0 μg/dl, but without showing clear symptoms chronic lead poisoning (Table 1).

4. Discussion

We investigated the lead exposure of the people working or living at or near-by the e-waste dump site Agbogbloshie in Accra, Ghana. Compared to a non-exposed collective the study group and all sub-collectives show increased BLL. Those persons who worked directly with e-waste had the highest BLL values in the collective. However, the BLL of bystanders (women sellers) on the site, as well as people living near-by (factory workers, market business people, school pupils) were also increased. As mentioned in the introduction, the informal recycling of e-waste at the dumpsite is generally accepted as the source of the lead exposure, with dismantling and burning identified as the riskiest activities, especially if performed by children (Lundgren, 2012).

There are two pathways that non-dissolved lead can enter the human body - fine dust can be absorbed through the lungs, and particles of different sizes can be absorbed by the gastrointestinal tract through diet, contaminated touching hands to mouth, and dermal routes (e.g. cuts in hand) (Thomas, 2020). Dust seems to be a specific risk at dumpsites since it may content up to 4.1-fold the lead than reference areas near-by (Yekeen et al., 2016). Depending on the size of the inhaled particles, the lungs can absorb between 70 and 100% of the lead, while only 5–20% is absorbed via the gastrointestinal tract. Nevertheless, larger particles make up the bulk of potentially ingested lead. Lead is mostly eliminated via urine, and to a lesser degree by feces (Thomas, 2020), ((anonymous), 2017).

Food may also cause a relevant exposure. Eating fish or lots of vegetables may have an influence on the BLL. Although the population eats fish regularly, this seems not to be the trigger (Abboah-Offei, 2016; Boateng, 2015). However food still seems to play a role in uptake of lead beside working at the dumpsite because of the high concentrations of lead found in cooked food and in vegetables, lettuce and Fufu (Ankar-Brewoo et al., 2020). Cooked food like fried rice, soup and chicken have 10 to 30 times higher lead concentrations than the maximum of acceptable daily intake of 0,3 mg/kg body weight. One reason may be the cookware contains lead content. Leafy vegetables, onions, tomatoes, lettuce and spinach, which probably grow at farms nearby Agbogbloshie or which are sold locally at the market, may cause a health risk and increase BLL by having high amounts of lead in it or as dust at the surfaces (Amoyaw-Osei et al., 2011; Boateng, 2015; Marfo, 2014). The reason for the high amount of lead in leafy vegetables and fruits is that plants absorb the lead from the contaminated soil through their roots and store it in their leaves. Soil samples, particularly those from the burning grounds, do have high levels of lead (Marfo, 2014; Itai et al., 2014). Dust, fume, or food from this place, or places in the intermediate vicinity, may increase BLL. But even if the food has been produced in a lead-free environment it will be contaminated when sold at the local market due to the winds, especially the strong trade winds from north-east, that blow the lead containing dust from the dump site over the market. This is a major problem during dry season, but also a problem year-round because of the long biological half life time of lead. In regions contaminated with heavy metals this burden is ubiquitous which includes inside homes, transport into homes by shoes and clothes, especially when one or more members of the household are working with such metals ((anonymous), 1996). This causes a constant exposure of the population at and around Agbogbloshie.

Considering this background, the results of the blood samples should be compared to reference values and limit values for occupational health and safety as well as the background exposure of the non-exposed population in other regions of Ghana. Unfortunately such values are not yet established for Ghana but the scientific background is in preparation (Consoir, 2021). For other countries there are different reference values for men, women and children. These background values show some exposure to lead, but the majority do not have any health issue. In Germany, the reference value is 3.0 μg/dl for women and 4.0 μg/dl for men. It is 1.5 μg/dl for girls aged 3 to 17 and for boys aged 11–17 years. It is 2.0 μg/dl of lead in whole blood for boys aged 3 to 10 ((anonymous), 2009), ((anonymous), 2019). These values apply to all who do not get in contact with lead at their workplace (e.g. "non-exposed population").

Hence working with toxic substances like lead requires a special threshold. At the workplace, a distinction can then be made between the so-called "Biological Tolerance Value" (Biologischer Arbeitsstoff Toleranzwert, BAT)) and the "Biological Reference Value" (Biologischer Arbeitsstoff Referenzwert, BAR). When BAT is exceeded, symptoms will occur. However, BAR is defined by the 95th percentile of the background exposure and is not correlated to symptoms or disease. Many different cut-off values make an accurate and unified assessment difficult. Previously the BAT for women above 45 years and men of any age was 40.0 μg/dl, and for women under 45 years (who may become pregnant) it is 30.0 μg/dl (Bolt et al., 2019). German authorities have decided to set the cut-off (BAT) of lead in blood for occupationally exposed men at 15.0 μg/dl, because of a lack of correlation between lead in the air and BLL ((anonymous), 2017), ((anonymous), 2021). This change was combined with some other updates based on scientific data. Previously lead was categorised as a class 2 carcinogen (carcinogenic in animal testing, no threshold available), but now it was reclassified as class 4 (carcinogenic, mechanism known, threshold evaluated) with 15.0 μg/dl BLL as the threshold which protects against the carcinogenic effect as well as against the most critical toxic effect (neurological symptoms) ((anonymous), 2021). It is impossible to convert this by a simple equation into a threshold in the air at the workplace but by complex mathematic models a maximal tolerable concentration ("MAK Wert") of 0.004 mg/m3 could be established ((anonymous), 2021). However, because of the growth retarding effect of lead, neither the compliance with the BAT nor with the MAK threshold guarantees that there is no risk for foetuses ((anonymous), 2021). This is of special importance for all families living at and around Agbogbloshie.

Biomonitoring therefore becomes the most important control instrument for exposure to toxic substances like lead. In ((anonymous), 2017) it has been reviewed that the World Health Organization (WHO) requires BLL to be set at 10.0 μg/dl as a critical limit, especially for children. Another organization (National Toxicology Program (NTP)) states that an even lower BLL threshold (higher than 50 μg/l) may cause negative effects on health. WHO also recommends a "Provisional Tolerable Weekly Intake" (PTWI) of 25 μg/kg body weight. This corresponds to roughly 3.6 μg/kg or about 200 μg per day for adults weighing 60 kg.

However, the background lead exposure in Germany and its effect on BLL should be used with care when compared to the BLL of workers in Agbogbloshie Accra. For example, many factors of daily life in Agbogbloshie like the choice of food eaten (e.g. salt vs. fresh water fish), or local geology (e.g. water, soil), have a significant influence on lead exposure and so specific reference values for the non-exposed population in Ghana should be established. The first of such results published in 2021 show a mean BLL of 8.0 μg/dl for men and 7.6 μg/dl for women, both when older than 25 years) (Consoir, 2021), Consoir et al. (submitted). It should be noted that these values are nearly twice as high as those for the German population. Possible reasons are discussed in detail in (Consoir, 2021), Consoir et al. (submitted). However, the BLL found at the dump site were significantly increased even when compared to the preliminary values of a non-exposed Ghanaian population (Adusei et al., 2020).

Biomonitoring of BLL plays an important role in occupational health management in the formal industrial sector (Viegas et al., 2020). Lead can be measured in almost any biological material, but analysis of blood samples is the standard procedure in the European Union to early detect acute or chronic health hazards. This is the only way to determine if someone has had exposure to lead and if has been ingested via inhalation or the gastrointestinal pathway (Marfo, 2014). However, there is a complete absence of any biomonitoring or alternative measures to assess the lead exposure of the informal e-waste workers in Ghana (Tuakuila et al., 2015). Unfortunately in the e-waste dismantling and burning processes, where the exposure and uptake of lead seems to be the highest, child labor is routinely used. It was found, that the hazardousness of lead is particularly evident here (Nartey, 2016) and it has been well described that lead exposure is more deleterious on the not fully developed nervous system of children. Here neurophysiological symptoms were observed at BLL of 10.0–30.0 μg/dl ((anonymous), 1996). Leading symptoms were persistent, and likely irreversible deficiencies of intelligence and psychomotoric skills. To date, a threshold concentration of BLL on the central nervous functions of children could not be established.

All data available, including the findings of this study, consistently show that there is a significant and chronic exposure to lead by the Agbogbloshie workers. The German reference values are exceeded in most cases, the biological limits such as BAT and BAR are often reached, or the BLL collected exceed them. If the reference limits suggested by Consoir (2021), Consoir et al. (submitted) are applied to the workers at the dumpsite in Agbogbloshie the BLL show a significant exposure. Independent from Germany's or Consoir's data it must be concluded that there is a significant health risk for the people working at Agbogbloshie.

Creatinine may be an indicator for health damage by lead because the kidneys are one of the target organs of this heavy metal ((anonymous), 1996), (Restek-Samarzija and Momcilovic, 1993). With a cut-off for creatinine set at 1 mg/dl for women older than 18 years old, 1.17 mg/dl for men older than 18 years old, 0.71 mg/dl for children younger than 13 years, and 0.81 mg/dl for children younger than 15 years old (including the children between 15 and 17 as shown above), we found 77.7% of all measured blood levels were within a pathological range (thresholds given by (Thomas, 2020)). Compared to other studies the values measured at Agbogbloshie were significantly elevated (Feldt et al., 2014; Feldt, 2017). This shows that significant damage has already occurred. The results of this study are also evident in other large e-waste dumpsites, such as in China (Wang et al., 2012; Zhang et al., 2020). Lead exposure could be presumed to be the reason, although without clear evidence. Since lead damages the kidney at a low toxic dose, this would be a matter for further discussion. However, it is impossible to postulate an exclusively relation between lead as damaging agent and the kidneys since there are several confounders which may cause renal insufficiency. Several studies report kidney dysfunction in sugar cane workers who were not exposed to lead (Wesseling et al., 2015, 2016, 2020; Roncal-Jimenez et al., 2016; Glaser et al., 2016; Dharma-Wardana, 2018; Sorensen and Garcia-Trabanino, 2019; Nerbass et al., 2019; Hansson et al., 2021; Al-Bouwarthan et al., 2022; Geladari et al., 2023). Another confounder which may interfere with lead is smoke: like lead it may also induce anemia (Appiah-Dwomoh et al. (in press)), (Honda et al., 2017).

5. Limitations

This study suffers from some limitations. The main one is the multilingualism of Ghana. There are about 40 different languages spoken at Agbogbloshie and there is no lingua franca for all of them as it exists in other parts of Africa (e.g. Swahili in East Africa). Therefore, sometimes a chain of translators was necessary to get information about the respective kind of work, the duration of the stay at the dumpsite etc. Another problem was the significant difference in culture and education. For some of the participants it obviously doesn't matter when they were born and their age had to be estimated for the study. Consequently, we did not focus on a direct correlation between age and BLL. But it was possible to differentiate between adults with their different types of exposure and children. By this we were able to prove that children were also at risk and any preventive strategy must include them. Unfortunately it was impossible to perform a multivariance analysis. Because of the multitude of confounders, overlapping activities the multiple sub-collectives would have too small sample size to achieve sufficient power of the analysis. However, since it was the goal of the study to check whether there is a relevant exposure or not and many people show different and overlapping activities it is acceptable to focus on descriptive statistics which shows the significance of the topic.

6. Conclusions

Both the workers at Agbogbloshie dumpsite and those in the surrounding population were exposed to lead to an extent that a health risk was evident. Taking poverty and the social situation into account it is difficult to suggest immediate recommendations to improve the situation. First steps might include a ban on recycling lead batteries onsite, to change clothing before entering the place of residence, and to wash hands before eating. Children under the age of at least 14 and women of a childbearing age should not work on the site. Provision of better equipment would help – e.g. wire stripping pliers to avoid cooking the sheaths off the wiring. A minimum level of biomonitoring should be provided although it may be rejected by those with dangerously increased BLL who would rather accept the health consequence when they earn more than twice the salary than elsewhere, and they don't wish to leave. Any strategy to increase knowledge about health and heavy metals will help (Kawakami, 2019). Secondary sources of lead should also be eliminated, e.g. replace lead contaminated cooking utensils with stainless steel ones (Ankar-Brewoo et al., 2020). At the farms nearby it would be possible to plant trees at the edge of the fields to help filter the polluted soil (Marfo, 2014; Fosu-Mensah et al., 2017). However, these interventions can only reduce some of the exposure.

In future it will be necessary to perform a complete restoration by removing significantly contaminated soil by at least several meters deep among other actions. Another way to reduce the burden could be to expand "Extended Producer Responsibility" (Organization for Economic Co-operation and Development), thus reducing the total amount of informally recycled e-waste (Lundgren, 2012). Ultimately although such regulations already exist, countries like Germany need to realize this and to stop the export of e-waste from industrialized countries to Africa or Asia.

CRediT authorship contribution statement

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