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Metal Levels, Genetic Instability, and Renal Markers in Electronic Waste Workers in Thailand

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Abstract

Background: Informal electronic waste (e-waste) recycling is an increasingly important industry worldwide. However, few studies have studied the health risks in this group of workers.

Objective: To assess the associations between occupational exposures to metals and genetic instability and renal markers among e-waste recycling workers.

Methods: We recruited informal e-waste recycling workers from a community in northeastern Thailand. Participants completed a questionnaire, several health measurements, and provided urine and blood samples, which we then analyzed for a number of metals including lead (Pb), cadmium (Cd), and manganese (Mn). Samples were analyzed for a marker of RNA and DNA damage (*ie*, oxidative stress), 8-hydroxy-2'-deoxyguanosine (8-OHdG). Glomerular filtration rate (GFR) and fractional excretion of calcium (FECa%) were measured as markers of renal function. Correlations and regression models were used to assess associations between these various factors.

Results: We found significantly higher levels of Cd and Pb in blood of men compared with those in women. Men who worked >48 hours/week had significantly higher levels of 8-OHdG compared with men who worked ≤48 hours/week. Smoking was significantly associated with higher blood Pb and Cd concentrations among men.

Conclusion: Our results suggest gender differences in both blood concentrations of metals associated with e-waste recycling and smoking and highlight potentially elevated oxidative stress associated with longer work hours. Health promotion efforts are needed among informal e-waste recyclers to reduce possible risks of renal damage and cancer.

Keywords: Electronic waste; Oxidative stress; Thailand; Renal insufficiency; Heavy metal poisoning

Introduction

Electronic waste (e-waste, discarded electronic and electric equipment including mobile phones, televisions, refrigerators, computers, *etc*) has emerged in recent years as a major and

increasing public health problem. Globally, an estimated 41.8 million tonnes of e-waste were generated in 2014.¹ e-waste recycling is an important source of income in some low- and middle-income countries,¹ where recycling is often done in informal settings by self-employed work-

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ers using basic equipment and simple methods. These informal recycling activities recover valuable materials such as copper, iron, gold, silver, aluminum, and plastic.² Recycling of these materials provides substantial environmental and energy- and environmental-related benefits.^{3,4}

In Thailand, *e*-waste recycling has been occurring in areas of Kalasin, a northeastern region, since approximately 2005. Informal recycling in this region is often done inside workers' homes, and in or near kitchens, living areas, and food storage areas. Residents of this area have traditionally worked as farmers, but low rice prices and the destruction of rice crops from natural events has created economic instability; *e*-waste recycling (and, to a lesser extent, repair of electronics) represents an economic opportunity that can offset this instability among these workers. Adoption of this informal work has grown quickly; in our study area, the number of households participating in *e*-waste recycling grew from 100 in 2007 to more than 450 in 2016, with households often sharing information and knowledge about *e*-waste recycling practices. The informal nature of the work permits it to be done in conjunction with farming, and allows for the involvement of family members where necessary or possible.

The Labor Act of the Thai government does not address informal work, and the potential health hazards of this work have not been adequately assessed or managed by any government efforts.⁵ As a result, informal *e*-waste recycling workers in this region may be exposed to a number of various occupational hazards, including persistent organic pollutants, dioxins, polycyclic aromatic hydrocarbons, and toxic metals.⁶

The toxicants found in *e*-waste materials can be harmful to health individually. The settings and activities involved in informal *e*-waste recycling likely result

in exposures to mixtures of toxicants that may have additive or synergistic effects, or that may potentiate the toxicity of each toxicant.⁷ For example, the metals cadmium (Cd) and lead (Pb) are metals commonly found in *e*-waste materials;⁸ both of them are toxic to the renal system. These toxic metals increase oxidative stress in renal cell causing lipid peroxidation, glutathione depletion, and cell signaling and calcium metabolism disturbances.⁹ Increased calcium wasting and renal function insufficiency was reported in Cd- and Pb-exposed population.^{10,11} However, combined exposures to these and other metals can substantially increase or change their impact.¹²⁻¹⁴

To holistically assess the potential effects of mixed exposures to metals, individual toxicants and pathologies must be simultaneously evaluated. In addition, whole-body systemic impacts can be assessed using biomarkers such as 8-hydroxy-2'-deoxyguanosine (8-OHdG), which provides a measure of DNA and RNA damage by oxidative stress in the human body that can result from mixed exposures to metals.¹⁵ The objective of the current study was to measure urinary and blood biomarker levels among informal Thai *e*-waste recycling workers for a range of metals, and to assess renal impacts associated with these metals, as well as genetic instability potentially resulting from metal exposures, using urinary 8-OHdG.

Material and Methods

Site Selection

Our study took place in a community in the northeastern region of Thailand, approximately 500 km from Bangkok. Data were collected in July 2016. In recent years, several research teams had unsuccessfully tried to gain access to *e*-waste recycling workers in the northeastern region of

Thailand. To address and reduce community resistance to research efforts, we initiated a multilevel, long-term relationship with the community. This involved a series of research meetings and discussions with a range of individuals and government organizations, including staff at the local public health provincial office, staff at the Subdistrict Administrative Organization (SAO), the village leader, and the community health volunteer team leader. After a number of meetings with these individual community members, we arranged a combined meeting, at which all parties agreed that our research could proceed.

Recruitment

After community support was confirmed, we designed a recruitment strategy in partnership with the local public health staff. This strategy involved the use of community health volunteers to help identify known *e*-waste recycling workers in the community who could then be approached to participate in our study. Through this strategy, we identified *e*-waste recycling workers from four villages within a single sub-district to participate. Our target population was adult informal *e*-waste recycling workers age 18 years or older. After initial contact, all individuals were provided with an overview of the study. Interested individuals then signed an informed consent document and were recruited into the study.

Questionnaire and Health Measurements

All participants were interviewed in their native language and dialect (Thai, Isan Region) in their homes or at the local public health hospital by research staff from local universities using a 92-item questionnaire designed for the study. The questionnaire included items that addressed participant demographics, occupational history (with a special focus on informal *e*-waste recycling work), smoking status,

and self-reported health status. After completing the questionnaire, several health and anthropometric measurements were made on each participant. These measurements included height and weight, which were used to compute individual body mass index (BMI).

Urine and Blood Sample Collection

After participants completed the questionnaire and health measurements, they were asked to provide urine samples in polyethylene bottles. At the end of every sampling day, each participant's sample was separated into three aliquots: one for 8-OHdG, one for metal, and one for calcium and creatinine measurements. Five-to-ten milliliters of venous blood was then drawn by a trained public health nurse and collected in two separated tubes, with and without heparin (BD Vacutainer®). Serum and plasma were separated within two hours of collection. All samples were frozen and stored at -20 °C for further analysis.

8-OHdG Measurement

8-OHdG is a genetic instability biomarker. It was quantified using the Cayman® DNA/RNA oxidative damage (high sensitivity) competitive ELISA kit. Each urine sample was diluted 400 times with ultrapure water. Fifty microliters of each sample was added to goat anti-mouse IgG wells with 50 µL of an 8-OHdG-acetylcholinesterase conjugate tracer and a specific antibody to oxidatively damaged guanine, and allowed to interact at room temperature for one minute. Each plate was then emptied and rinsed five times with wash buffer. Ellman's Reagent (200 µL) was added to each well, and the samples were then incubated for 120 minutes at room temperature with orbital shaking. Finally, 8-OHdG concentration was quantified in each sample at the wavelength of 405 nm using a Spectra-Max M5 Multi-Mode microplate reader.

Metal Measurement

The Reference Laboratory and Toxicology Center, Bureau of Occupational and Environmental Disease, Ministry of Public Health in Bangkok measured metals in all urine and blood samples. Urine samples were stored at 4 °C prior to analysis. An Agilent 7500 ce inductively coupled plasma (ICP) mass spectrometer was used to measure concentrations of Pb, and manganese (Mn) in urine samples using previously described methods.¹⁶ Urinary Cd concentration was determined through graphite furnace atomic absorption spectrometry (GF-AAS) using a Agilent 280Z atomic absorption spectrometer using methods detailed previously.¹⁷ Urine samples were diluted by a factor of 10 using a solution of 0.1% Triton X-100, 0.2% (NH₄)₂HPO₄. All urinary metal levels were creatinine (Cr)-adjusted to account for differences in urinary generation rates. The urinary creatinine concentration was measured using a Thermo Scientific Konelab™ 30 automated analyzer, a method based on Jaffe reaction, according to the manufacturer's instructions (Thermo Electron Corporation, Vantaa, Finland).

Blood samples for heavy metal analysis were stored at -20 °C prior to analysis. An Agilent 7500 ce ICP mass spectrometer was used to measure concentrations of Mn in whole blood. Concentrations of Pb and Cd were each measured in whole blood samples with GF-AAS using an Agilent 280Z AA spectrometer and a SpectrAA 880 Varian spectrometer, respectively. Both elements were analyzed using previously described methods.¹⁷

Quality assurance was confirmed by simultaneous analysis of reference urine ClinChek® (RECIPE, Munich, Germany). Non-detectable whole blood and urine concentrations were replaced with the limit of quantitation value divided by the square root of two.¹⁸

Fractional Excretion of Calcium

Serum calcium and urinary Ca were quantified by colorimetric assay using an automated analyzer (Coulter HmX, Konelab 30 and Bechman Synchron CX3). Fractional excretion of calcium (FECa%) is the percentage of calcium clearance as a fraction of creatinine clearance, which we calculated as follows:¹⁰

$$FECa\% = \frac{Ca_U / Ca_S}{Cr_U / Cr_S} \times 100$$

where *Cr* represents creatinine. The subscripts indicate source of the sample—'U' for urine and 'S' for serum, all in mg/dL.

Glomerular Filtration Rate

Glomerular filtration rate (GFR) was estimated from serum creatinine using the modification of diet in renal disease (MDRD) equation:¹⁹

$$GFR = 175 Cr_S^{-1.154} Age^{-0.203} (\times 0.742 \text{ for women})$$

where *Cr_s* is measured in mg/dL and *Age* in years.

Ethics

All study methods and procedures were reviewed and approved by the University of Michigan (HUM00114562) and Mae Fah Luang University (REH-59104) institutional review boards.

Statistical Analysis

Thailand Labour Protection Act B.E.2541 sets the legal limit for a work week at 48 working hours.²⁰ We used this limit to categorize participants into two groups: those working ≤48 hours/week, and those working >48 hours/week. Smoking is an additional potential source of metal exposure, so we compared metals concentrations between smokers and non-smokers. Mean differences in age and biomarkers between sex, smokers vs non-smokers, and work-

Table 1: Comparison of mean (SD) age, working hours, urinary and blood metals levels, 8-OHdG, and renal markers between men and women informal e-waste recycling workers

Variable	Men		Women		p value
	n	Mean (SD)	n	Mean (SD)	
Age (yrs)	61	47.1 (11.4)	58	45 (13.5)	0.359
Work Hours per Week	57	41.1 (16.2)	57	39.6 (15.7)	0.611
Cd _U (µg/g Cr)	53	0.65 (0.44)	53	0.7 (0.42)	0.511
Pb _U (µg/g Cr)	53	6.58 (5.84)	52	8.41 (8.1)	0.185
Mn _U (µg/g Cr)	53	7.07 (28.86)	52	23.24 (98.41)	0.254
Cd _B (µg/L)	48	0.99 (0.74)	48	0.68 (0.42)	0.013
Pb _B (µg/dL)	48	4.02 (2.18)	48	2.79 (1.99)	0.005
Mn _B (µg/L)	48	15.38 (11.21)	48	16.29 (6.59)	0.628
8-OHdG (mg/g Cr)	53	121.8 (68.93)	52	143.02 (82.33)	0.155
FECa%	44	0.99 (0.61)	47	0.84 (0.64)	0.250
GFR (mL/min/1.73 m ²)	46	93.45 (18.2)	48	99.67 (26.96)	0.194

The subscripts 'U' and 'B,' respectively, represent the urinary and blood concentrations of the metals measured. 8-OHdG: Urinary 8-hydroxy-2'-deoxyguanosine, FECa%: Fractional excretion of Ca, GFR: Glomerular filtration rate

ers grouped by working hours/week were analyzed using *Student's t* test for independent samples. Bivariate relationships were assessed using Spearman's correlation coefficient and Mann-Whitney U test. Generalized linear models were used to assess the relationships between blood Cd and Pb with age, sex, working hour classification, and smoking status. Generalized linear models were also used to evaluate the relationship between 8-OHdG, GFR, FECa%, and age, sex, working hour group, smoking status, and metal level. All analyses were done with SPSS® for Windows® ver 21 (SPSS, Inc IBM SPSS, Armonk, NY, USA). A p value <0.05 was considered statistically significant.

Results

A total of 120 informal e-waste recycling workers participated in our study. The

mean age of the participating e-waste worker was 46.0 (SD 1.1) years; they worked an average of 40.4 (SD 1.5) hours/week. There were 62 (51.7%) men; 27 (22.5%) of the participants were current smoker (all male) and 30 (25.0%) reported that e-waste recycling was their primary job.

Blood Pb measurements exceeded the recommended community exposure limit of 5 µg/dL²¹ in 16.7% of the participants; no measurements exceeded the Thai occupational exposure limit of 60 µg/dL²². Levels of blood Cd and Pb were significantly higher in men than women (Table 1). Women showed higher levels of 8-OHdG and GFR than did men, but these differences were not statistically significant.

No studied women were self-reported smokers. Smokers had significantly higher levels of blood Cd and Pb than non-smokers (Fig 1A). Levels of 8-OHdG, GFR, and

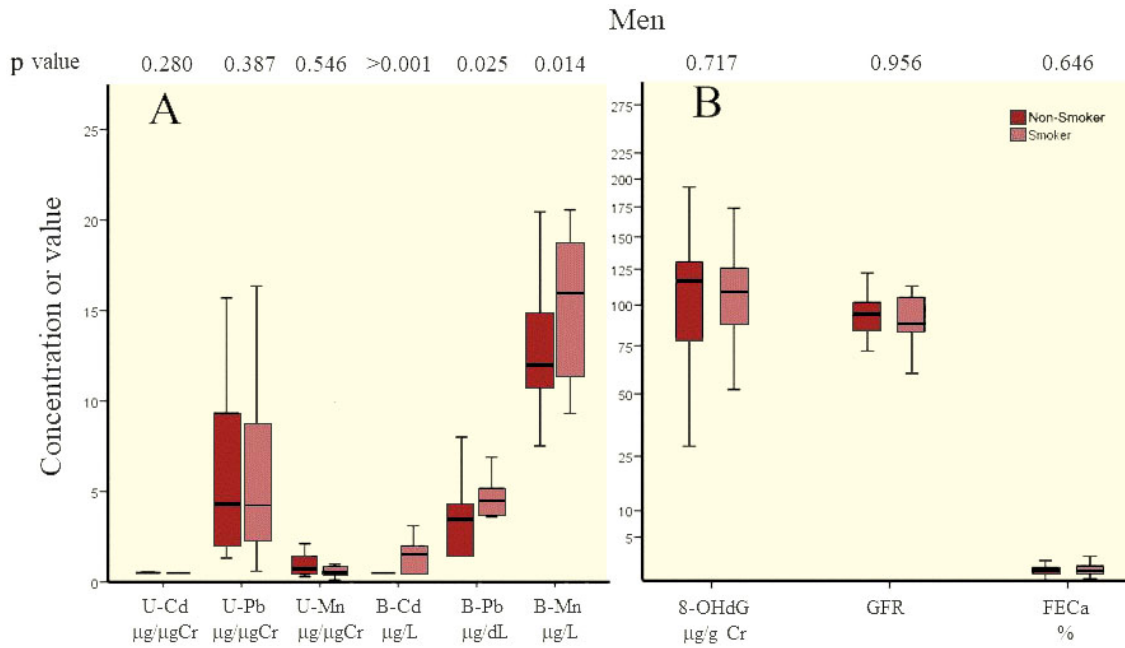


Figure 1: Box and whisker plot of (A) urinary and blood metals concentrations and (B) 8-OHdG, GFR, and FECa% between non-smoker and smoker men. The two groups were compared with Mann-Whitney U test. 'U' and 'B' designate urinary and blood concentrations, respectively.

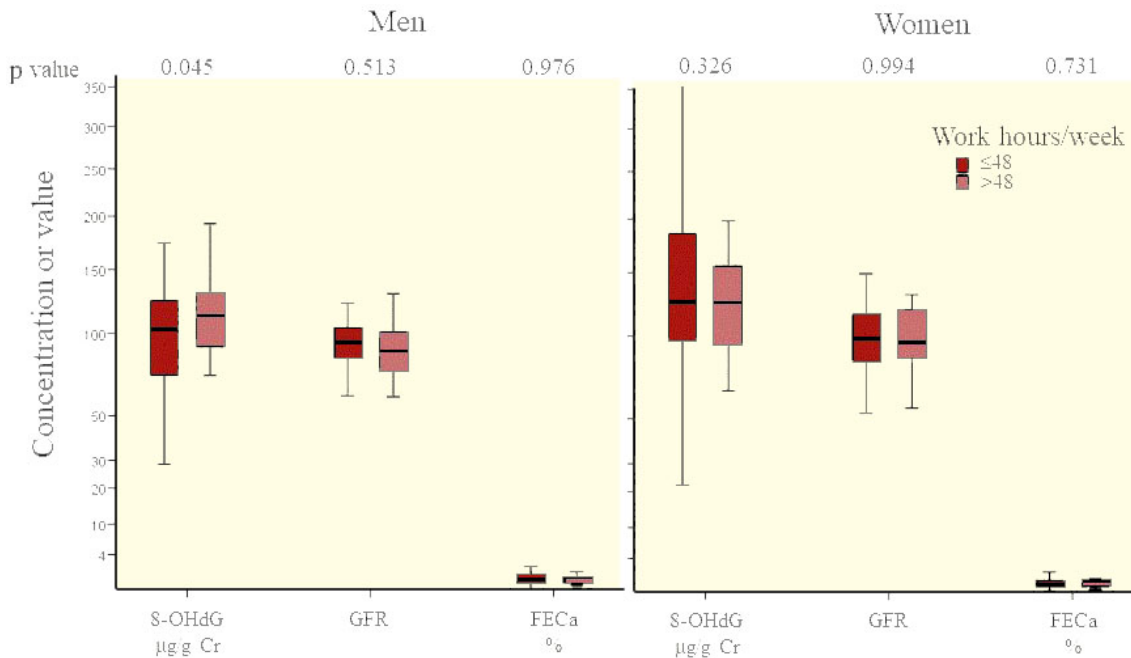


Figure 2: Box and whisker plot of 8-OH-DG, GFR, and FECa% between e-waste workers working ≤ 48 and those working > 48 hours/week. The two groups were compared with Mann-Whitney U test.

Table 2: Spearman's correlations between age, working hours, urinary metals, and blood metals and 8-OHdG, FECa and GFR

Variable	8-OHdG (µg/g Cr)		FECa%		GFR (mL/min/1.73 m ²)	
	n	ρ	n	ρ	n	ρ
Men						
Age (yrs)	52	0.14	43	0.21	46	-0.35*
Work Hours/Week	49	0.21	42	0.06	44	-0.20
Cd _U (µg/g Cr)	53	-0.19	44	0.13	45	0.11
Pb _U (µg/g Cr)	53	0.24	44	-0.06	45	-0.05
Mn _U (µg/g Cr)	53	0.27*	44	-0.08	45	-0.15
Cd _B (µg/L)	47	0.16	44	-0.13	46	0.09
Pb _B (µg/dL)	47	-0.006	44	0.23	46	-0.16
Mn _B (µg/L)	47	0.20	44	0.40**	46	0.09
Women						
Age (yrs)	52	0.06	47	0.12	48	-0.38**
Work Hours/Week	51	-0.09	46	-0.10	47	0.30*
Cd _U (µg/g Cr)	52	-0.18	47	-0.07	48	-0.08
Pb _U (µg/g Cr)	52	0.18	47	-0.12	47	0.42**
Mn _U (µg/g Cr)	52	0.24	47	0.29	47	0.08
Cd _B (µg/L)	47	0.08	47	0.33*	48	-0.21
Pb _B (µg/dL)	47	0.03	47	-0.07	48	0.27
Mn _B (µg/L)	47	-0.08	47	-0.29	48	-0.06

*p<0.05, **p<0.01; The subscripts 'U' and 'B,' respectively, represent the urinary and blood concentrations of the metals measured.

FECa% were not significantly different between smokers and non-smokers (Fig 1B). Studied men who reported working >48 hours/week had significantly (p=0.045) higher levels of 8-OHdG compared to men working ≤48 hours/week (Fig 2).

Correlations between 8-OHdG, FECa%, and GFR stratified by sex are shown in Table 2. In men, significant correlations were found between 8-OHdG and uri-

nary Mn level, FECa%, and blood Mn concentration; and between GFR and age. In women, significant correlations were found between FECa% and blood Cd, and between GFR and age and urinary Pb level.

The generalized linear model regression results for blood Cd, Pb, Mn are shown in Table 3. Smoking status was the only significant predictor of blood Cd and Pb concentrations.

After controlling for potential confounding factors (age, sex, working hours/week, and smoking status), urinary Pb concentration was found to be a significant predictor of GFR (Table 4). However, 8-OHdG and FECa% showed no significant association with concentrations of the studied metals in models that controlled for potential confounders.

Discussion

Our findings suggested sex differences in blood concentrations of metals associated with e-waste and smoking, and highlights potentially elevated oxidative stress levels associated with longer work weeks. Our study is one of the first to evaluate the impacts of metals exposures on renal damage and genetic instability markers among informal e-waste recycling workers, and one of the first to evaluate body burden of metals among e-waste recycling workers in Thailand. With a mean age of 46 years, our sample of e-waste recycling workers was older than those of many other studies;²³⁻²⁵ with the sample roughly split between men and women, it was also more sex-balanced than many studies. While both men and women in this study appeared to do similar e-waste recycling work, we found significantly higher levels of blood Cd and Pb in men than women (Table 1). Male participants who worked >48 hours/week had significantly higher levels of 8-OHdG, which represents whole body oxidative damage²⁶ from systemic oxidative stress

Table 3: Linear regression analysis of blood Cd and Pb as a function of age, sex, working hours, and smoking status among e-waste recycling workers (n=92)

Variable	Blood Cd			Blood Pb			Blood Mn		
	B	SE	p	B	SE	p	B	SE	p
Age	0.00	0.01	0.93	-0.001	0.02	0.96	-0.12	0.08	0.13
Male sex	-0.05	0.13	0.69	0.57	0.46	0.22	-3.47	2.21	0.12
Work hours/week	0.003	0.004	0.35	0.02	0.01	0.20	1.52	2.00	0.45
Current smoker	0.91	0.16	<0.001	1.07	0.57	0.06	6.94	2.76	0.01
Intercept	0.56	0.26	0.04	2.16	0.94	0.02	21.28	3.84	<0.001

caused by toxicant exposure, compared with men who worked ≤ 48 hours/week (Fig 2). Smoking was significantly associated with higher blood Pb and Cd concentrations among male smokers (Fig 1); our study included no female smoker, and so this association could not be assessed for females.

The significant positive correlation between urinary Pb concentration and GFR was unexpected (Table 4). This differed from our *a priori* assumption that Pb is a renal toxicant that should be associated with reduced GFR (*ie*, we expected a negative correlation between GFR and urinary Pb concentration). Lead disturbs tubular transport mechanisms, and a typical characteristic of lead exposure is Fanconi syndrome, *ie*, increased excretion of essential nutrients such as Ca into urine.²⁷ We used FECa% as an index to identify insufficient tubular transport function, but failed to identify a significant correlation between FECa% and blood or urinary Pb concentration. Renal dysfunction characterized by reduced GFR among Pb-exposed individuals is not well understood.²⁸ Blood Pb levels related to renal impairment may be above 10–15 $\mu\text{g}/\text{dL}$;²⁹ in our study, no participant had blood Pb level >10 $\mu\text{g}/\text{dL}$ (Table 1). The relationship between renal function impairment and Pb exposure in this population need to be further clarified.

Toxic metals have a long biological half-

life in the human body and can result in systemic toxicity following high levels of exposure, or following chronic exposure in older and elderly populations. Pb and Cd, both renal toxicants, are commonly found in *e-waste*.^{8,30,31} Our results showed higher levels of blood Pb and Cd levels in men than women, and among smoker men (Table 1, Fig 1). Smoking is an additional source of Pb and Cd;³² smokers take deep breaths to inhale cigarette smoke,³³ which can increase exposures to other toxicants in the work place. Our results suggested the possibility of sex-based differences in occupational exposure to Pb and Cd among *e-waste* recycling workers. However, after controlling for age, sex, and smoking sta-

TAKE-HOME MESSAGE

- Electronic waste recycling is an important source of income in some low- and middle-income countries
- Observed blood cadmium, lead and manganese levels were higher among electronic waste who smoked compared to those who did not.
- Oxidative stress, an early signal of cancer risk, was associated with the number of hours spent recycling electronic waste per week.
- Indicators of renal impairment (*ie*, impaired glomerular filtration rates) associated with higher metals exposures.

Table 4: Regression analysis of 8-OHdG, GFR and FECa as a function of age, gender, working hours, smoking status, and metal body burden among informal e-waste recycling workers

Variable	8-OHdG			GFR			FECa%			FECa%		
	B	SE	p	B	SE	p	B	SE	p	B	SE	p
n	99			89			87			87		
Age	0.16	0.63	0.80	-0.78	0.18	<0.001	0.01	0.01	0.14	0.01	0.010	0.10
Male sex	14.39	18.58	0.44	5.58	5.12	0.28	-0.14	0.16	0.38	-0.16	0.16	0.30
Work hours/ week	0.25	0.50	0.62	0.10	0.14	0.49	0.001	0.004	0.90	0.001	0.004	0.89
Current smoker	7.41	22.27	0.74	-5.09	6.20	0.41	-0.010	0.23	0.97	0.01	0.20	1.00
Mn _U (µg/g Cr)	0.01	0.11	0.93									
Pb _U (µg/g Cr)				1.01	0.30	0.001						
Cd _B (µg/L)							0.05	0.13	0.71			
Mn _B (µg/L)										0.01	0.01	0.20
Intercept	102.76	40.84	0.011	121.91	11.90	<0.001	0.55	0.42	0.19	0.39	0.41	0.34

The subscripts 'U' and 'B,' respectively, represent the urinary and blood concentrations of the metals measured.

tus, only smoking status remained a significant predictor of blood Pb and Cd (Table 3), suggesting that this modifiable factor may represent a potential occupational intervention point to reduce metals exposures among e-waste recycling workers. Our results matched those of several other studies. For example, in China, blood Cd, Mn, Pb, and creatinine levels in e-waste community population were significantly higher than non-e-waste communities.³⁴ Similarly, higher blood Cd and Pb levels were also observed among e-waste workers from Ghana compared with non-e-waste worker.²⁵

While smoking was associated with higher blood levels of Pb and Cd (Fig 1A), it was not associated with 8-OHdG levels (Fig 1B), which suggested that factors other than smoking would increase 8-OHdG. Smoking involves exposures to a wide variety of toxicants known to increase cancer risk,³⁵ and 8-OHdG levels are elevated in cancer patients¹⁵ and workers exposed to carcinogens in the workplace²⁶. We found

that 8-OHdG in men working >48 hours/week, a Thai labor standard, was significantly higher than men working ≤48 hours/week (Fig 2), suggesting that longer working hours, which reduce recovery time from occupational exposures, may increase oxidative stress. Men working >48 hours/week also had higher (though not significantly so) levels of blood Pb, Cd, Mn, and urinary Mn compared with men with working hour ≤48 hours/week (Fig 3), further highlighting the increased exposures associated with longer working hours.

e-waste recycling consists of a variety of activities, and the pattern and types of toxicants vary depending on the equipment being recycled.^{1,24} Use of a holistic marker of DNA and RNA damage, such as 8-OHdG, allows for assessment of oxidative stress resulting from a variety of exposures, and as such, 8-OHdG represents a useful tool for health monitoring among e-waste recyclers to assess genetic instability (and, therefore, cancer risk) associated

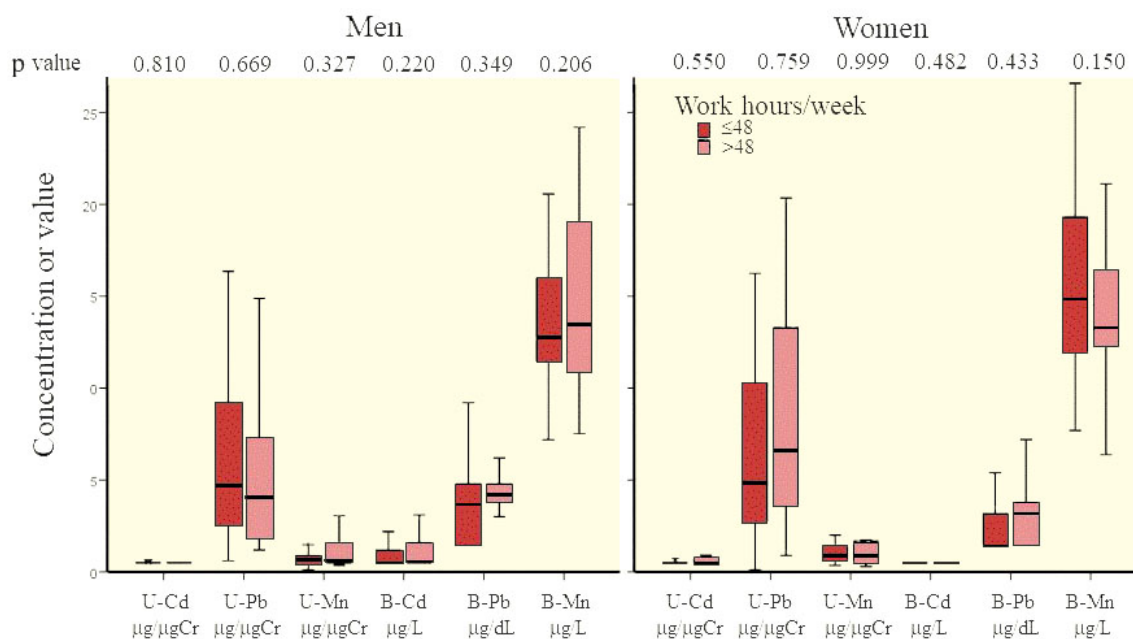


Figure 3: Box and whisker plot of urinary and blood metals between e-waste workers working ≤ 48 and those working >48 hours/week. The two groups were compared with Mann-Whitney U test. ‘U’ and ‘B’ designate urinary and blood concentrations, respectively.

with their varied tasks and exposures.

We observed an association between 8-OHdG and working hours in men (Fig 2); we did not observe a similar correlation in women, suggesting that there may be sex-based differences in work-related oxidative stress. In addition, we observed significant correlations between FECA% and blood Cd levels among participating women (Table 3), but not in men, further highlighting potential sex-based differences. Women have been shown to be more sensitive to metal toxicity than men because of difference in Ca metabolism, kidney sensitivity, difference in P450 phenotype, pregnancy, and iron store status.³⁶ In addition, a previous study on Cd-exposed women shows that FECA% is a sensitive marker for the diagnosis of early stage of kidney abnormality in Cd-exposed people.¹⁰ The significant correlation we observed between blood Cd level and FECA% in women suggested that renal dysfunction in women may be related to

Cd exposure, and highlighted a potentially preventable mechanism of renal toxicity.

In addition to renal toxicity, Cd has a long biological half-life (10–30 years) and Cd-exposed populations show peak Cd body burden at age 40–60 years, which is the same period of life when bone metabolism becomes weak.³⁷ This situation could lead to Cd-related bone pathology. Exposures to Pb and other osteotoxicant from e-waste recycling activities could therefore possibly increase bone metabolism abnormality among women. The FECA% estimates we computed offer an inexpensive and simple technique for assessing early changes in bone.

Our study had several limitations. The small sample size limits the generalizability of the results, although the relative homogeneity among e-waste recycling workers in North-East Thailand likely means that our results are generalizable to workers throughout the region. Second, the cross-sectional nature of our study prevents us

from assessing causality. Third, due to logistical challenges in the rural community we assessed, our blood and urine measures were not collected at standardized times, which introduced additional temporal variability into our data. Nevertheless, despite these limitations we believe that our study provides useful information concerning exposures and health impacts among this vulnerable and marginalized community of informal *e*-waste recycling workers. Our study also represents an important expansion in *e*-waste research beyond the countries where most similar research has been done (*eg*, China, India, and Ghana).^{6,38,39}

In conclusion, our study showed that longer working hours and smoking contribute to increased exposures to a number of metals among informal male *e*-waste recycling workers in Thailand, and an association between metal exposures and increased oxidative stress and renal markers among female *e*-waste recyclers. Given these results, health promotion efforts—including smoking cessation—should be directed to these workers to improve their health and prevent disease. The informal nature of *e*-waste recycling work in Thailand results in additional challenges that must be addressed. Informal work is not recognized by the country's Labor Act, making it difficult to apply labor standards or develop occupational health and safety management systems, but the health and safety needs of workers in this important and growing industrial sector must be addressed.

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Conflicts of Interest

This research project was supported by Rackham International Research Institute and University of Michigan Graham Sustainability Institute. Our research team does not have any conflicts of interest to declare.

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