

Micronutrient-rich dietary intake is associated with a reduction in the effects of particulate matter on blood pressure among electronic waste recyclers at Agbogbloshie, Ghana

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Abstract

Background: Informal recycling of electronic waste (e-waste) releases particulate matter (PM) into the ambient air. Human exposure to PM has been reported to induce adverse effects on cardiovascular health. However, the impact of PM on the cardiovascular health of e-waste recyclers in Ghana has not been studied. Although intake of micronutrient-rich diet is known to modify these PM-induced adverse health effects, no data are available on the relationship between micronutrient status of e-waste recyclers and the reported high-level exposure to PM.

Objectives: We investigated whether intake of micronutrient-rich diets ameliorates the adverse effects of ambient exposure to PM_{2.5} on blood pressure (BP).

Methods: This study was conducted from March 2017 to October 2018; involving the measurement of breathing zone PM_{2.5} using real-time monitor. Dietary micronutrient (Fe, Ca, Mg, Se, Zn, and Cu) intake was assessed using a 2-day 24-hour recall, while cardiovascular indices such as systolic BP (SBP) and diastolic BP (DBP) and pulse pressure (PP) were measured using a sphygmomanometer. Ordinary least-squares regression models were used to estimate the joint effects of ambient exposure to PM_{2.5} and dietary micronutrient intake on cardiovascular health outcomes.

The results: Fe was consumed in adequate quantities. However, Ca, Se, Zn, Mg, and Cu were inadequately consumed among e-waste recyclers and controls. Dietary Ca and Fe intake were associated with reduced SBP and PP of e-waste recyclers. Although PM_{2.5} levels were higher in e-waste recyclers, the controls exceeded the WHO 24-hour guideline value (25µg/m³). Exposure to 1µg/m³ of PM_{2.5} was associated with increased HR of e-waste recyclers by 0.06 bpm; implying informal recycling of e-waste may be a risk factor for tachycardia. Also, dietary Fe intake was associated with a reduction in systolic blood pressure levels of e-waste recyclers.

Conclusions: Consistent adequate dietary Fe intake was associated with reduced effects of PM_{2.5} on SBP of e-waste recyclers overtime. However, as all other micronutrients are essential in ameliorating adverse effects of PM on cardiovascular health, nutrition-related policy dialogues are necessary to educate informal e-waste recyclers and the general population on specific nutrients of concern and their impact on the exposure to ambient air pollutants.

Introduction

Ambient air pollution remains an environmental health problem, especially in low- and middle-income countries (LMICs). In the year 2016, ambient air pollution was responsible for 4.2 million deaths, and caused 17% of ischemic heart disease and stroke (WHO, 2019). Specifically, in Ghana, it is estimated that 17000 people die yearly from air pollution related causes (Chasant, 2019). Informal level recycling of electronic waste (e-waste); largely employing crude methods, is known to release pollutants; predominantly, particulate matter into the ambient air. Other components of the pollutants include nitrogen dioxide (NO₂), sulfur dioxide (SO₂), carbon monoxide (CO), heavy metals, rare earth metals and polychlorinated biphenyls (PCBs). Such environmental pollutants when inhaled overtime present serious pulmonary and cardiovascular health threats (Gangwar et al., 2019; Jin et al., 2015; McAllister, 2013). For example, PM when inhaled moves through the pulmonary endothelium and enters the bloodstream (!!! INVALID CITATION !!!) where it induces hypertension, airway irritation, coughs, difficulty in breathing, reduced lung function, non-fatal heart attacks, atherosclerosis, irregular heartbeat, anemia and in extreme cases indirectly causes early death due to lung cancer (Ghorani-Azam et al., 2016; WHO, 1986). Furthermore, exposure to PM also induces systemic inflammation and oxidative stress, which contribute to the pathophysiology of several neurological and cardiovascular diseases (Genc et al., 2012; Rao et al., 2018; Shukla et al., 2018; Wright & Ding, 2016). Particulate matter of diameter ≤ 2.5 µm (PM_{2.5}) in particular induces endothelial dysfunction characterized by impaired vasodilation, pro-inflammatory

and prothrombotic responses (Dai et al., 2016; Xia et al., 2019). This may augment systemic vascular resistance, leading to the development of hypertension.

Emerging evidence indicates that adequate nutrition may reduce the harmful effects of most air pollutants (Hennig et al., 2018; Petriello, Newsome, & Hennig, 2014; Petriello, Newsome, Dziubla, et al., 2014; Whyand et al., 2018). Micronutrients-rich diets, contain both antioxidant and anti-inflammatory properties which may reduce the risk of vulnerability to oxidative stresses associated with exposure to particulate matter (Hennig et al., 2012; Hennig et al., 2018; Hoffman & Hennig, 2017; Liu et al., 2018). Adequate intake of calcium (Ca), zinc (Zn) and magnesium (Mg) from the diet has been suggested to enhance endothelial function and further improves vascular and circulatory efficiency (Cormick et al., 2015; Cunha et al., 2012; DiNicolantonio et al., 2018; Entezari, 2015; Rosique-Esteban et al., 2018; Tang et al., 2016). In addition, micronutrients such as copper (Cu), selenium (Se), Zn, and vitamins (A, C and E) serve as antioxidants that influence the body's defenses against PM_{2.5} exposure. These antioxidants terminate the chain reactions of reactive oxygen species (ROS) by removing free radical intermediates and also inhibit other oxidation reactions in order to reduce blood pressure (BP) (Limón-Pacheco & Gonsebatt, 2009; Possamai et al., 2010). As micronutrients cannot be synthesized by the body and must therefore be consumed in adequate quantities to maintain normal physiological functions (Miller & Rayalam, 2017), their deficiency in human nutrition remains a critical global health issue (J. J. DiNicolantonio et al., 2018; Ekpenyong, 2017; McKeag et al., 2012).

Generally, studies investigating the potential modifying effect of micronutrient-rich diet intake on air pollutant-associated hypertension are limited (Balbus et al., 2013; Izumi et al., 2011; Lanphear, 2015; Miller & Rayalam, 2017; Porpora et al., 2019; Schulz et al., 2015). Also, available studies did not consider informal e-waste recyclers, who are particularly at-risk due to the nature of their work. Well-designed, robust studies are therefore needed to further understand the ways through which micronutrient-rich diet intake may counter the adverse effects of PM_{2.5} exposure on BP. Meanwhile, micronutrients-rich diets, contain both antioxidant and anti-inflammatory properties which may reduce the risk of vulnerability to ambient air pollutants (Hennig et al., 2012; Hennig et al., 2018; Hoffman & Hennig, 2017; Liu et al., 2018). Therefore, the paradigm of diet as a key modifier of the detrimental effects of environmental pollutant exposure is of significant interest, especially among individuals with repeated exposures to ambient pollutants.

In Ghana, air pollution due to informal e-waste recycling as well as from other sources, e.g., bio-mass burning and traffic-related emissions remain a public health concern. In the year 2016 for instance, the annual average PM_{2.5} concentration in the capital, Accra was 55 µg/m³. This is far above the WHO-recommended annual guideline of 10 µg/m³. Agbogbloshie, our study site is situated in Accra and provides a livelihood for many people. Prevailing work-related activities include informal e-waste recycling. Aside the toxic exposures informal e-waste recycling presents, the activity is physically demanding, thus may increase the requirement for nutrient intake from the diet. This longitudinal study addressed a critical knowledge gap regarding the population of e-waste recyclers by addressing the following questions: (1) Do e-waste recyclers consume micronutrients rich diets? (2) Is there a relationship between dietary micronutrient intake and BP? And (3) Can dietary micronutrient intake modify the effect of PM_{2.5} on BP among e-waste recyclers at Agbogbloshie and Madina-Zongo (MZ) controls? This study strategically included a comparison group residing in Madina Zongo (MZ) with similar characteristics to the e-waste workers; with respect to religion, internal migration from northern parts of Ghana. Madina Zongo (MZ) is located within 10 km from the Agbogbloshie e-waste site and is expected to be unexposed to e-waste recovery.

Methods

Study Design

This study data was drawn from the Geo-Health-II longitudinal cohort study. Three data collection waves among e-waste recyclers and non-e-waste recyclers; wave I [March-April 2017] (dry season), wave II [July-August, 2017] (rainy season), and Wave III [March-April 2018] (dry season) were done to achieve seasonal variation in work patterns and personal exposure. As detailed in studies at Agbogbloshie (Asampong et al., 2015; Feldt et al., 2014; Srigboh et al., 2016; Wittsiepe et al., 2017), a community Durbar was organized to familiarize participants with the study's objectives and procedures. After recruitment participating e-waste recyclers in one or more waves were 142 at Agbogbloshie and non-e-waste recyclers were 65 at Madina Zongo. For subsequent waves (II and III), mobile calls were used to recall participants. Community representatives also aided in recalling previously recruited participants. These helped reduce participant loss to follow up.

The inclusion criteria for participants of Agbogbloshie included adult males aged 18 years and above and have worked at the e-waste site for at least 6 months. Similarly, non-e-waste recyclers were supposed to be in the same age category with similar characteristics as e-waste recyclers with respect to culture, food consumed etc. and have never worked at the e-waste site. In addition, participants of Madina must have lived at the Madina-Zongo for at least 6 months. Study participants were compensated with 50 Ghana cedis (approximately US\$10, roughly an average day's wage), lunch and a T-shirt at each wave. The University of Ghana and the University of Michigan Institutional Review Boards (IRB) approved the study protocols. The local chief of Agbogbloshie and Madina-Zongo permitted and allowed our research team to enter the community to conduct this study.

Study Site

Agbogbloshie, a famously known for informal e-waste recycling and is located in central Accra. Particularly, this e-waste site is situated on the banks of the Odaw river and the Korle-Lagoon, approximately covering an area of 1.46 km² and has an estimated population of 80,000 people (Amoyaw-Osei et al., 2011; Simon, 2018; United Nations Population Fund, 2018). To the southwest of the recycling area lies an informal community popularly known as "Old Fadama" which houses the majority of the recyclers and other informal operators such as traders and street hawkers. The vast majority of people working in the scrap metal yard are young men and boys, culturally Dagombas or Konkombas who migrated from the northern part of Ghana in search of greener pastures. Graphically, the recycling area is flat with closely mounted small open sheds from which recyclers operates. This site receives and informally recycles a collection of obsolete electronic items such as fridges, television, mobile phones, computers, cars etc. The informal recycling methods employed consist of open air burning of wires to recover copper, as well as manual off-loading and dismantling of equipments/ devices.

Aside informal e-waste recycling, prevailing activities and business consist of buying and selling food stuff such as yams and onions. Further to this, Agbogbloshie is characterized by an extensive overlap of industrial, commercial, and residential zones. Generally, the Agbogbloshie scrap yard is noted for heavy clouds of smoke from typical daily burning of e-waste materials such as copper. The geographical location of Agbogbloshie is located is shown in the map below (Fig. 1).

Figure 1a. Map of Agbogbloshie electronic-waste recycling site. This site is located in Accra, Ghana. The large area marked grey is the e-waste processing zone where tasks such as dismantling, sorting, weighing, and burning and trading are carried out. To the south of the e-waste site is the Korle-Lagoon and the informal community called old Fadama. The map was drawn using Google Earth Pro V 7.3.2.5776. (10 July 2015). © Google 2019.

Figure 1b. Map of Madina Zongo located in Accra, Ghana. The area highlighted is the actual site where data were collected. The map was drawn using Google Earth Pro V 7.3.2.5776. (10 July 2015). © Google 2019.

Field Data Collection Procedures

Anthropometric and Blood Pressure Measurements

Height was measured and corrected to the nearest 0.1 cm using a Seca Stadiometer (Seca; Germany), with participant standing upright on a flat surface without shoes, and the back of the heels and the occiput against the stadiometer (Alkhajah et al., 2012; Boateng, 2014; Zeba et al., 2014). Weight was also measured and recorded to the nearest 0.1 kg using a portable Seca Scale (Seca770; Hamburg, Germany). The same model standard calibrated balance was used at both study sites. Body mass index (BMI) of each participant was calculated by dividing the weight in kilograms (kg) by height in meters squared (m^2). The body weight was also measured at each time point of data collection to assess whether or not there was a measurable change in body stores.

A trained nurse measured BP by using a sphygmomanometer with a portable cuff device (Omron model HEM 711AC, Omron Healthcare Inc, Lake Forest, IL). The BP measurement was according to the National Health and Nutritional Examination Survey method (Schulz et al., 2015). Participant's BP readings were taken on the right arm after a minimum of 10 minutes rest whilst comfortably seated with back supported, and the arm resting on a table at heart level (Padwal et al., 2017). The BP was measured 3 times on the right arm supported at heart level, afterwards the participants were made to sit at rest for 5 minutes, with 30 seconds between each measurement (Cao et al., 2015). The mean of the three readings was used in the analyses. Also, the pulse pressure (PP), an indicator of arterial stiffness, was calculated as the difference between the systolic BP (SBP) and the diastolic BP (DBP). The mean arterial pressure was computed as $(SBP + 2*DBP) / 3$.

Nutrient Intake Assessment

Data collection during each time point took place over a period of one to two weeks. Daily nutritional intake of participants was collected using a semi-structured 2-day 24-hour recall guide. We conducted the 24-hour recall twice to estimate the day-to-day variability per individual due to the variety of foods consumed on different days. Trained dieticians were employed to collect nutrition data in order to maximize consistency of the interview format across study sites and further minimize between site methodological biases. Interviewers obtained informed consent from participants before undertaking this nutrition survey. The interview was conducted in participants' native language or preferred language: Dagbani, Hausa, Twi, or English, to help ensure that participants fully understood the questions asked in accordance with the 2-day 24-hour recall guide. Our interview consisted of foods and beverages (e.g. the amount, time and types of meals/foods consumed) consumed on one weekday and one day of a just past weekend (Saturday or Sunday). In all cases, information was solicited within less than 24 hours of when that day ended. This was done either face to face or through phone calls. We also used graduated food models to quantify foods and beverages consumed by each participant.

Measures of Real-time Personal PM_{2.5} levels

For each wave optical and gravimetric breathing zone PM levels were measured for both the exposed group in Agboglobshie and the control group at Madina Zongo. Near continuous minute by minute real time PM₁, PM_{2.5}, PM₄, PM₁₀, and TSP were measured with an optical counter (Aerocet 831, Met One Instruments, Inc, OR, USA) that sampled at 2.83L/m. For quality control PM_{2.5} concentrations were considered invalid when TSP exceeded 2000 $\mu g/m^3$. Gravimetric measurements were done for only PM_{2.5} using a size selective impact sampler with a pre-weighed 47 mm Teflon filter (2 μm spore size, SKC PA, USA) and a flow rate of 10L/min. All the equipments were contained in a customized backpack with inlets in the breathing zone of the participants. A four-hour work-shift breathing zone

sample was taken from each participant and sampling was done during peak working periods (8:00am to 2:00 pm). In wave III, the sampling duration was reduced to approximately 2 hours due to the high levels of PM from Harmattan winds. Further description of the sampling process is described in Laskaris et al. (2019).

Data Analysis

Nutrient Analysis

The nutrient intake data collected was converted into grams using Ghanaian Food composition tables. Further to this, nutrient analysis was conducted using the ESHA F Pro software® to estimate individual micronutrient intake. After the nutrient analysis, data obtained from the ESHA F Pro comprised of amounts of calcium (Ca), magnesium (Mg), iron (Fe), zinc (Zn), copper (Cu) and selenium (Se) consumed. In addition, the mean probability of micronutrient adequacy was computed to estimate the percentage of participants who met the Recommended Daily Allowance (RDA) for adult males (Mahan & Raymond, 2016) overtime.

Statistical Analysis

The t-test statistics was used to compare the mean distribution of systolic, diastolic, pulse, arterial pressure and heart rate, PM and BMI measures between e-waste and non-e-waste recyclers.

Micronutrient intake by e-waste and non-e-waste recyclers

The study compared the differences in proportion of e-waste and non-e-waste recyclers who met the RDA of micronutrients using the z-test. This was done by dichotomizing each of the outcome measures based on the United States Department of Agriculture (USDA) guidelines (For & Children, 2011; Textor et al., 2011) for adults. This USDA definition outlines the threshold for micronutrient adequacy using data obtained from the micronutrient intake levels. In addition, a sensitivity analysis was conducted by comparing the actual mean distribution of the micronutrient intake between e-waste and non-e-waste recyclers using the Welch t-test. The ordinary least squares regression model with random effects was used to assess the impacts of daily income accrued and physical demands on dietary micronutrient intake in e-waste recyclers and non-e-waste recyclers.

Relationship between micronutrient intake and blood pressure levels

The study also assessed the relationship between BP and micro-nutrient intake using a multiple linear regression model with robust standard error that controls for confounders.

Micronutrient intake and its association with PM_{2.5} and blood pressure levels

The study assessed normality of all continuous outcome measures using the Shapiro Francia test. Non-normal outcome measures were log transformed before conducting further statistical analyses.

Random effect models were used to assess the effect of micronutrient intake on BP controlling for PM. P-values less than 0.05 were considered statistically significant. All statistical tests were conducted using Stata® version 15 (StataCorp, College Station, Texas, USA).

Results

Participants' mean age was 27.6±0.4 years. The overall mean SBP of e-waste recyclers was 120 millimeters of mercury (standard error of the mean: SE = 1.1 mm/Hg), mean DBP was 72.2 millimeters of mercury (SE = 0.9 mm/Hg), mean PP was 48.7 millimeters of mercury (SE = 1.1 mm/Hg) and mean HR was 73.7 millimeters of mercury (SE = 1.0

mm/Hg) for the three waves. Our study overtime found that mean arterial pressure (AP), systolic BP (SBP) and diastolic BP (DBP) were consistently higher in non-e-waste recyclers than e-waste recyclers. The PM_{2.5} levels were significantly higher in e-waste recyclers especially at waves I and II. However, the mean PM_{2.5} level of non-e-waste recyclers at wave III was 80.4 micrograms per cubic meter (SE = 5.6µg/m³), which is about four times the world health organization (WHO) 24-hour guideline value of 25µg/m³. Just like the e-waste recyclers, the non-e-waste recyclers also exceeded this guideline at all time points. A comparison was then made between the health characteristics over time (Supplementary Table 1). When BP outcomes were compared over time, the study found a significant decline in SBP and AP of e-waste recyclers (Table 1). Although the BMI of e-waste recyclers significantly increased overtime, non-e-waste recyclers were found to have a higher BMI reading especially at waves I and II.

Table 1—Health Characteristics of e-waste recyclers and non-e-waste recyclers in Accra-Ghana

Comparison of reported dietary intake of micronutrients between e-waste recyclers and non-e-waste recyclers are shown in table 2. Mean micronutrient intake of Fe, Mg and Zn from the diet were significantly different between e-waste and non-e-waste recyclers at wave me; dietary Fe (t (1) =2.70, *p*=0.004) and Zn intake (t (1) =2.81, *p*=0.01) were significantly higher in e-waste than non-e-waste recyclers whereas Mg intake was significantly higher in non-se-waste recyclers (*P*<0.05). In addition, nearly all e-waste and non-e-waste recyclers consumed adequate amounts of Fe from diet per the RDA at all waves analyzed. Figure 2 in the appendix also clearly compared dietary micronutrients of e-waste and non-e-waste recyclers overtime. To a large extent, micronutrients such as Ca, Cu, Se and Mg were inadequately consumed in both study groups per the RDA guidelines (Table 2). We further assessed the effects of e-waste exposure, job task and daily income earned on dietary micronutrient intake (Supplementary Table 2). Dietary Ca and Fe intake were positively related to daily earning of more than GH¢200 (~36 USD). Compared to participants who earned a daily earning of GH¢20, Zn intake was significantly related to all higher levels of daily income earned. Between recycler types, collectors significantly consumed higher amounts of Se than burners, dismantlers and sorters.

Table 2: Dietary Micronutrient intake and adequacy of e-waste and non-e-waste recyclers at different time points

The adjusted models, as compared to the unadjusted models, showed only occasional and relatively small changes in associations between dietary micronutrient intake and measures of BP. In our adjusted model, a significant inverse relationship was observed between Zn and SBP ($\beta = -0.03$; 95% CI = -0.05, 0.01, *p* = 0.02; Table 3) but not DBP ($\beta = -0.02$; 95%CI: -0.05, 0.01, *p*=0.24), PP ($\beta = 0.046$, 95%CI: -0.094, 0.002, *p*=0.05) and HR ($\beta = 0.009$; 95%CI: -0.030, 0.048, *p*=0.66). In addition, a unit increase in dietary Ca intake reduced SBP by 0.03mmHg (95% CI: -0.044, 0.003, *p*=0.022) and further decreased PP by 0.05mmHg (95% CI: -0.09, 0.01, *p*=0.021). Iron (Fe) intake from diet also significantly reduced SBP levels by 0.03mmHg (95% CI: -0.05, -0.01; *P*=0.002). These reductions by Fe were also observed for PP and AP levels in the model. Even though no significant difference was found, micronutrients such as Ca, Zn, Se, Fe and Cu marginally reduced the DBP. However, when the model was adjusted for income, BMI, smoking status, marital status, total calories consumed and dietary diversity scores, Ca reduced SBP, PP and HR whereas Fe reduced the SBP, PP and AP levels (Table 3). Further analyses based on multivariable regression models were conducted to determine the effect of micronutrient-rich dietary intake on BP of e-waste recyclers. It was found that every 1mg intake of Fe rich diets significantly reduced SBP of e-waste recyclers by 0.03mmHg (95%CI: -0.063, 0.00004; *p*<0.05).

Table 3: Relationship between dietary micronutrient intake (mg) and BP (mmHg)

Generally, higher PM_{2.5} exposure was associated with a significant increase in HR (β : 0.061; 95%CI: 0.007, 0.116; *p*=0.03) of e-waste recyclers at Agbogbloshie after adjusting for age, BMI, smoking status, total calories consumed and dietary diversity scores (Supplementary Table 3). However, in our joint effect model, Fe reduced SBP by 0.04mmHg (95% CI: -0.074, -0.012; *p*<0.01) and AP by 0.04mmHg (95%CI: -0.068, -0.004; *p*<0.05) after PM_{2.5} exposure (Table 4).

Furthermore, Mg slightly increased DBP by 0.02mmHg (95%CI: 0.001, 0.032; $p < 0.05$) and HR by 0.02mmHg (95%CI: 0.002, 0.047; $p = 0.02$) among both e-waste and non-e-waste recyclers. Nonetheless, dietary Cu intake also increased PP by 0.04mmHg (95%CI: 0.006, 0.079; $P < 0.05$) when both e-waste recyclers and non-e-waste recyclers were included in the model. Particularly in e-waste recyclers, 1mg of Fe consumed was associated with a 0.04mmHg reduction of SBP levels (95%CI: -0.073, -0.004; $P = 0.02$; Supplementary Table 4). Further in the model, 1mg intake of Cu was associated with a 0.04mmHg increase in PP among e-waste recyclers (95%CI: 0.001, 0.088; $p = 0.04$).

Table 4a: **Effects of dietary micronutrient intake on the association between PM_{2.5} and BP in both e-waste and non-e-waste recyclers**

Discussion

Several studies have reported the adverse effects of PM_{2.5} on BP outcomes (Majkova et al., 2010; Nachvak et al., 2016; Schulz et al., 2015; Whyand et al., 2018), with few focusing on how intake of micronutrient-rich diets may ameliorate these effects. To the best of our knowledge, this study is the first-ever to examine the role of micronutrient-rich dietary intake in reducing the harmful effects of PM among e-waste recyclers. The study found that consumption of micronutrients including Ca, Se, Zn, Cu and Mg were below the recommended intakes. In addition, PM_{2.5} exposures were higher in e-waste recyclers compared to non-recyclers at the control site. However, the control site was equally highly polluted as concentrations measured exceeded the WHO 24-hour air quality guideline value of 25µg/m³. These high PM_{2.5} levels recorded in the control site may perhaps be due to emissions from car exhaust (owing to high vehicular traffic in that area), dust from untarred roads, smoke from open burning of rubbish and biomass and other sources. Furthermore, we found as expected, that PM_{2.5} levels increased in the Harmattan season. Higher PM_{2.5} levels were found to be associated with increases in HR levels in e-waste recyclers. This is similar to findings by Breitner et al. (2019) and Xie et al. (2018). In contrast to our study, Cole-Hunter et al. (2018) and Dong et al. (2018) found a decrease in HR when PM_{2.5} levels increased. Possible reasons why our results may differ from Cole-Hunter et al. (2018) and Dong et al. (2018) may include; geographic and temporal variability of PM_{2.5} sources and constituents between the different study sites as well as existing differences in sociodemographic characteristics such as age. Generally, BP in non-e-waste recyclers was significantly higher than in e-waste recyclers over time ($p < 0.05$). This is surprising because it was expected that e-waste recyclers (they are exposed to higher PM_{2.5} levels) would have higher BPs than the non-e-waste recyclers. Therefore the observed higher BP among the control group compared to e-waste recyclers is probably due to a more sedentary lifestyle (Twinamasiko et al., 2018; UNDP, 2018) of members of the controls as compared to the e-waste recyclers.

Estimates of dietary micronutrient intake adequacy among e-waste and non-e-waste recyclers

Dietary Fe intake was adequately consumed among e-waste recyclers and non-e-waste recyclers, perhaps most likely owing to their frequent intake of traditional green leafy soups. However, the consumption of Ca, Mg, Se and Cu in both e-waste and non-e-waste recyclers were lower than the RDA set by the WHO. Our findings are in line with similar studies in Malawi (Joy et al., 2015) and South Africa (Kolahdooz et al., 2013) where Ca and Se intake was lower among adult males. This suggests that micronutrient deficiency may be a common problem among males in sub-Saharan Africa. Between groups, the average Ca, Se and Mg intake from the diet were lower in e-waste recyclers than non-e-waste recyclers, while the average Zn intake was lower in non-e-waste recyclers. Reasons for this pattern are not clear, but perhaps may be attributed to poverty, job types, lack of access to variety of micronutrient-rich foods and perhaps lack of knowledge of optimal dietary practices. Studies have predicted that micronutrients (such as Ca, Cu, Mg and Se) deficiencies may be associated with increased toxic effects of exposures to both PM and heavy metals (Bharatraj & Yathapu, 2018; Miller & Rayalam, 2017; Schulz et al., 2015). This suggests that, in populations such as informal sector

e-waste recyclers, where exposures to PM and metals appear high, a public health strategy of increasing dietary consumption of micronutrients, including, if possible, taking supplements to help prevent detrimental effects due to pollutant exposure is necessary.

Relationship between dietary micronutrient intake and cardiovascular indices

This study found that the dietary Ca intake was associated with reduced SBP and PP. This is consistent with other studies that examined dietary antioxidant intake and its relationship with BP (Cormick & Belizán, 2019; Khanam et al., 2018; Kim et al., 2012; Silva & Araújo, 2017; Villa-Etchechegoyen et al., 2019). However, in a double-blinded, placebo-controlled clinical trials, adequate intake of Ca-rich diet intake reduced DBP but not SBP (Drouin-Chartier et al., 2014; Entezari, 2015). The reported differences in these studies may be due to variable physiologic-hormonal factors such as angiotensinogen and aldosterone that are known to regulate the BP (Vaidya et al., 2015). Thus, considering only environmental influences, in defining the role of Ca intake in regulating BP may be limiting. Furthermore, dietary Fe reduced SBP, PP and AP levels in e-waste recyclers and non-e-waste recyclers. These are consistent with Lindberg et al. (2017) who found that adequate Fe intake was associated with reduced SBP of adults. This reduction was also found specifically among e-waste recyclers indicating that intake of Fe-rich diet may probably modify SBP levels. To the best of our knowledge, no previous data exist on dietary Fe intake and blood pressure of e-waste recyclers; therefore, inferences about causality may be premature.

Consistent with findings in other studies (Kim, 2013; Wang et al., 2018), the unadjusted model revealed that Zn intake was associated with reduced SBP, indicating its deficiency as a risk factor of high BP. However, in contrast, other studies have reported that dietary intake of Zn does not influence BP in either animals or humans. For example, in Taittonen et al. (1997) study, dietary Zn was not linked with BP of healthy children in a 6-year prospective study. Similar findings were noted in animal studies where for 4 weeks, a Zn deficient diet did not affect both SBP and DBP in normotensive rats (Sato et al., 2003). These inconsistent findings may be attributable to the degree of deficiency or adequacy of Zn intake, hypertensive status as well as the level of exposure to toxicants such as PM and heavy metal exposures. Meanwhile, the exposure to high levels of PM_{2.5} coupled with Zn deficiency may perhaps impair the vascular nitric oxide (NO) system. This may result in endothelial dysfunction and further reductions in endothelial-mediated vasoconstriction leading to increased BP levels (Dai et al., 2016; Daiber et al., 2019; Xia et al., 2019). Consequently, adequate intake of Zn-rich diets may be critical in preserving endothelial cell integrity and normal blood pressure, as Zn contains antioxidant and membrane-stabilizing properties (Daiber et al., 2017; Rainsford et al., 1998; Skene et al., 2019). More than half of both e-waste and non-e-waste recyclers were found to be deficient in Zn. Although their staple food, usually consumed are Zn-rich e.g., groundnuts, millets, soya beans and green leafy vegetables, the adoption of western food and cultures as well as urbanization may have led to poor intake of these traditional micronutrient-rich foods (de Jager et al., 2018).

Effects of dietary micronutrient intake on the association between PM_{2.5} exposure and BP outcomes

Results obtained in the current study generally provide evidence in support of the hypothesis that intake of micronutrients-rich diets may modify the adverse effects of PM_{2.5} on BP as reported by Schulz et al. (2015). For instance, in the joint effect model (Supplementary Table 4), adequate Fe intake dampened the effects of exposure to higher levels of PM_{2.5} on SBP after controlling for covariates in e-waste recyclers. These possible modifying effects of Fe intake may be attributed to the adequate consumption of Fe-rich diets assessed in e-waste as well as non-e-waste recyclers. To confirm the effect of Fe intake on BP after exposure, further studies such as experimental studies and clinical trials need to be carried out. Our findings, are consistent with Schulz et al. (2015) and offer support for the

assertion that adverse effects of PM_{2.5} on BP may be reduced in participants who consumed adequate amounts of micronutrient-rich diets.

We also noted that dietary Cu intake was associated with increased PP of e-waste recyclers at higher PM_{2.5} exposure levels. Similar effects were observed when both groups were included in the regression model. Few studies have focused on the relationships between dietary Cu intake and BP levels. Results from an experimental study showed increases in BP in Cu deficient rats (Klevay & Halas, 1991). In contrast, Lee et al. (2015) found that dietary Cu intake significantly increased BP. These differences in findings suggest the need for further studies to better understand mechanisms of action in respect of Cu deficiency on BP indices especially among toxicant exposed groups. Copper (Cu) is a major component of anti-oxidant enzymes essential for the normal functions of the cardiovascular system (Kurutas, 2015). Therefore, there is a possibility that deficiency of Cu coupled with high exposures to PM_{2.5} may lead to elevated BP and increased risks of cardiovascular events such as stroke. Furthermore, less than 20% of e-waste recyclers consumed adequate amounts of Cu though highly exposed to PM_{2.5}; suggestive of the significantly high PP levels after PM_{2.5} exposure.

Antioxidants such as Mg, Se, Zn, Cu and Zn inhibit oxidation reactions, by reducing the number of free radicals produced as well as the level of harm they may cause (Lee, 2018; Mehta & Gowder, 2015). The intake of diets rich in such antioxidants may reduce the effects of reactive oxygen species (ROS) by removing their intermediates and terminating their chain reactions (Tan et al., 2018). Yet, e-waste recyclers who are highly exposed to PM_{2.5} did not adequately consume these antioxidant-rich minerals. Although no significant relationships were observed, dietary micronutrients such as Mg, Se, Cu and Zn intake similarly reduced adverse effects of PM_{2.5} on some aspect BP. This suggests that adequate dietary intake of antioxidant-rich foods may subtly reduce the adverse effects of PM_{2.5} on BP.

Increasing evidence from experimental studies indicates that poor nutrition and pollutant exposure may interact and synergistically intensify the risk of cardiovascular diseases (Lorzadeh & Salehi-Abargouei, 2017; Péter et al., 2015). Our results suggest that individuals who consumed adequate micronutrient-rich diets may have reduced adverse effects owing to the association between PM_{2.5} and BP. Several other studies have outlined the effects of adequate dietary micronutrient intake on cardiovascular health. As suggested in the findings by Schulz et al. (2015) as well as the current study, adequate dietary micronutrient intake alone may not be sufficient to protect individuals against adverse effects of PM_{2.5} on BP. Steps which might reduce levels of PM_{2.5} exposure might include well distributed PM monitoring networks in informal recycling e-waste sites. The establishment of health-based National Ambient Air Quality standards of PM_{2.5} and PM₁₀ will greatly help control cardiovascular health effects in particularly exposed populations such as e-waste recyclers.

Limitations and Strengths

This study used self-reported 2-day 24-hour dietary recall in assessing micronutrient intake of participants from meals consumed and therefore liable for errors associated with the subjective measures. The memory-based dietary assessment method is largely pseudo-scientific, subject to recall bias, such as the underreporting of meal portions consumed. Given financial and logistical restraints, attempts were not made to evaluate biological indicators of oxidative stress, gene-environment interactions as well as participant's sensitivity to oxidative stress that may probably influence micronutrient levels in the body (González et al., 2014; Minelli et al., 2011; Narasimha Rai et al., 2013). Despite these limitations, the study had several unique strengths and contributions; including that the impact of the limitations mentioned above was probably offset by the more reliable and objective method used for PM_{2.5} measurement. Secondly, we believe that our study had value as the first to investigate the joint effects of PM_{2.5} and individual dietary micronutrient intake among e-waste recyclers in a natural setting. We measured BP and ambient

measures of real-time personal air quality over a 2-year period. In addition, computations of daily dietary micronutrient intake from whole foods rather than supplements were made.

Conclusions

Globally, air pollution is a growing public health issue associated with increasing rates of cardiovascular morbidity and mortality. This study assessed the effects of dietary micronutrient intake on blood pressure after PM_{2.5} exposure. Overall, personal monitoring of PM_{2.5} in breathing zone of study participants (e-waste and non-e-waste recyclers) indicated levels that exceeded the WHO 24-hour air quality guideline value of 25 µg/m³, although significantly higher levels of PM_{2.5} were measured at Agbogbloshie. Of importance, Fe-rich dietary intake was significantly higher among e-waste recyclers than controls. We found that the consumption of Fe-rich diet was associated with a reduction in systolic BP, even at high PM exposure levels among e-waste recyclers. Results from this study and others highlight the critical role that micronutrient-rich diet plays in ameliorating the negative effects of PM exposure on cardiovascular health. Given that increasing exposure to PM_{2.5} is a known risk factor for development of hypertension and perturbations in blood pressure levels, protracted monitoring of air pollution levels in the environment are necessary. It is therefore recommended that adequate intake of Fe-rich foods, such as green leafy vegetables as well as Fe supplements are implemented in order to augment the adverse health effects associated with air pollution. The fact that PM exposure was also high among non-e-waste recyclers means consumption of Fe-rich diets, or iron supplementation among the general population in Accra will not an understatement.

List Of Abbreviations

E-waste: Electronic waste

PM: Particulate matter

Ca: Calcium

Fe: Iron

Se: Selenium

Mg: Magnesium

Zn: Zinc

Cu: Copper

BP: Blood Pressure

SBP: Systolic Blood Pressure

DBP: Diastolic Blood Pressure

HR: Heart rate

PP: Pulse Pressure

ROS: Reactive Oxygen Species

BMI: Body Mass Index

MZ: Madina-Zongo

RDA: Recommended Daily Allowance

WHO: World Health Organization

USDA: United States Department of Agriculture

UNFPA: United Nations Population Fund

Declarations

Availability of Data and Materials

The datasets generated and/or analyzed during the current study are not publicly available due to privacy reasons, but are available from the corresponding author on reasonable request.

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Authors' contributions

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Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Tables

Due to technical limitations, Tables 1 - 4 are only available for download from the Supplementary Files section.

Figures



Figure 1

1a. Map of Agbogbloshie electronic-waste recycling site. This site is located in Accra, Ghana. The large area marked grey is the e-waste processing zone where tasks such as dismantling, sorting, weighing, and burning and trading are carried out. To the south of the e-waste site is the Korle-Lagoon and the informal community called old Fadama. The map was drawn using Google Earth Pro V 7.3.2.5776. (10 July 2015). © Google 2019. 1b. Map of Madina Zongo located in Accra, Ghana. The area highlighted is the actual site where data were collected. The map was drawn using Google Earth Pro V 7.3.2.5776. (10 July 2015). © Google 2019

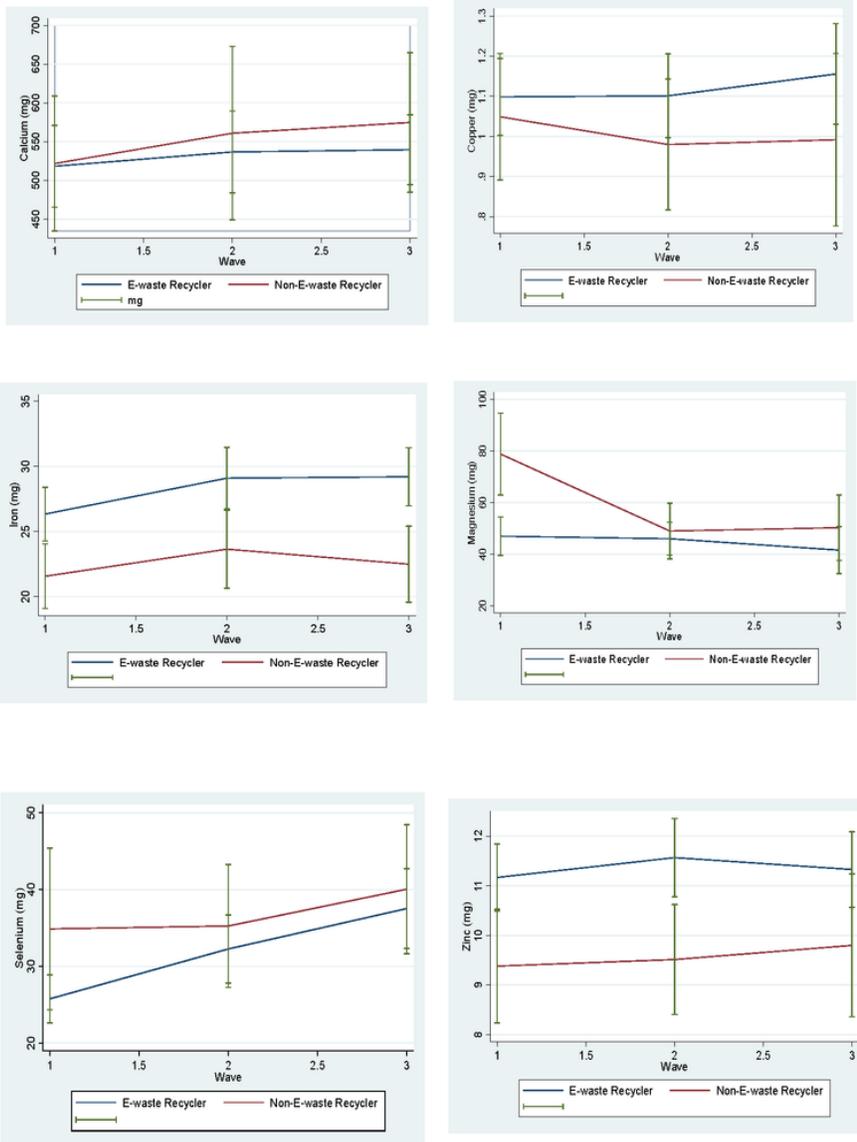


Figure 2: Dietary micronutrient intake of e-waste and non-e-waste recyclers overtime

Figure 2

Dietary micronutrient intake of e-waste and non-e-waste recyclers overtime

Supplementary Files

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