# Health consequences of exposure to e-waste: a systematic review

*Kristen Grant, Fiona C Goldizen, Peter D Sly, Marie-Noel Brune, Maria Neira, Martin van den Berg, Rosana E Norman*


## Summary

**Background** The population exposed to potentially hazardous substances through inappropriate and unsafe management practices related to disposal and recycling of end-of-life electrical and electronic equipment, collectively known as e-waste, is increasing. We aimed to summarise the evidence for the association between such exposures and adverse health outcomes.

**Methods** We systematically searched five electronic databases (PubMed, Embase, Web of Science, PsycNET, and CINAHL) for studies assessing the association between exposure to e-waste and outcomes related to mental health and neurodevelopment, physical health, education, and violence and criminal behaviour, from Jan 1, 1965, to Dec 17, 2012, and yielded 2274 records. Of the 165 full-text articles assessed for eligibility, we excluded a further 142, resulting in the inclusion of 23 published epidemiological studies that met the predetermined criteria. All studies were from southeast China. We assessed evidence of a causal association between exposure to e-waste and health outcomes within the Bradford Hill framework.

**Findings** We recorded plausible outcomes associated with exposure to e-waste including change in thyroid function, changes in cellular expression and function, adverse neonatal outcomes, changes in temperament and behaviour, and decreased lung function. Boys aged 8–9 years living in an e-waste recycling town had a lower forced vital capacity than did those living in a control town. Significant negative correlations between blood chromium concentrations and forced vital capacity in children aged 11 and 13 years were also reported. Findings from most studies showed increases in spontaneous abortions, stillbirths, and premature births, and reduced birthweights and birth lengths associated with exposure to e-waste. People living in e-waste recycling towns or working in e-waste recycling had evidence of greater DNA damage than did those living in control towns. Studies of the effects of exposure to e-waste on thyroid function were not consistent. One study related exposure to e-waste and waste electrical and electronic equipment to educational outcomes.

**Interpretation** Although data suggest that exposure to e-waste is harmful to health, more well designed epidemiological investigations in vulnerable populations, especially pregnant women and children, are needed to confirm these associations.


**Funding** Children's Health and Environment Program, Queensland Children's Medical Research Institute, The University of Queensland, Australia.

*Lancet Glob Health* 2013; 1: e350–61

Published Online October 30, 2013 http://dx.doi.org/10.1016/S2214-109X(13)70101-3

See Comment page e313



**Children's Health and Environment Program, Queensland Children's Medical Research Institute** (K Grant MIPH, F C Goldizen BA, Prof P D Sly MD, R E Norman PhD), **School of Population Health** (R E Norman), **The University of Queensland, Herston, QLD, Australia; Department of Public Health and Environment, World Health Organization, Geneva, Switzerland** (M-N Brune MSc, M Neira MD); **and Institute for Risk Assessment Sciences, Utrecht University, Utrecht, Netherlands** (Prof M van den Berg PhD)

Correspondence to: Prof Peter D Sly, Queensland Children's Medical Research Institute, Royal Children's Hospital, Herston, QLD 4029, Australia **p.sly@uq.edu.au**

## Introduction

Electronic and electrical waste (e-waste), also referred to as waste electrical and electronic equipment, is defined as any end-of-life "equipment which is dependent on electrical currents or electromagnetic fields in order to work properly".[1] Included in this definition are small and large household appliances; information technology and telecommunications equipment; lighting equipment; electrical and electronic tools, toys, and leisure and sports equipment; medical devices; monitoring and control instruments; and automatic dispensers.[2] Components of electrical and electronic equipment such as batteries, circuit boards, plastic casings, cathode-ray tubes, activated glass, and lead capacitors are also classified as e-waste.[3] Although e-waste is informally processed in many regions, high-volume informal recycling has been reported in China, Ghana, Nigeria, India, Thailand, the Philippines, and Vietnam.

Pollutants are released as a mixture, and the effects of exposure to a specific compound or element cannot be considered in isolation. However, a more complex understanding of the interactions between the chemical components of e-waste is needed. Exposure to e-waste is a complex process in which many routes and sources of exposure, different lengths of exposure time, and possible inhibitory, synergistic, or additive effects of many chemical exposures are all important variables. Exposure to e-waste is a unique variable in itself and the exposures implicated should be considered as a whole. Sources of exposure to e-waste can be classified into three sectors: informal recycling, formal recycling, and exposure to hazardous e-waste compounds remaining in the environment (ie, environmental exposure). Informal electronic waste recycling includes the dismantling of end-of-life electronics to retrieve valuable elements with primitive techniques, without or with very little technology to minimise exposure or protective

equipment, allowing the emission of dangerous chemicals.[4,5] Formal electronic waste recycling facilities use specifically designed equipment to safely remove salvageable materials from obsolete electronics while protecting workers from adverse health effects. However, these centres are very expensive to build and run and are rare in less developed countries. Varying national safety standards can mean that workers at formal or semiformal recycling centres still risk exposure at low doses.[6] Because of the high levels of environmental, food, and water contamination, residents living within a specific distance of e-waste recycling areas are also at risk of environmental exposure, although at lower levels than through occupational exposure.[5,7,8]

Exposure routes can vary dependent on the substance and recycling process (table 1). Generally, exposure to the hazardous components of e-waste is most likely to arise through inhalation, ingestion, and dermal contact. In addition to direct occupational (formal or informal) exposure, people can come into contact with e-waste materials, and associated pollutants, through contact with contaminated soil, dust, air, water, and through food sources, including meat.[9–21] Children, fetuses, pregnant women, elderly people, people with disabilities, workers in the informal e-waste recycling sector, and other vulnerable populations face additional exposure risks. Children are a particularly sensitive group because of additional routes of exposure (eg, breastfeeding and placental exposures), high-risk behaviours (eg, hand-to-mouth activities in early years and high risk-taking behaviours in adolescence), and their changing physiology (eg, high intakes of air, water, and food, and low rates of toxin elimination).[22] The children of e-waste recycling workers also face take-home contamination from their parents' clothes and skin and direct high-level exposure if recycling is taking place in their homes.

See Online for appendix

Specific chemical elements and compounds are associated with e-waste, either as components of the equipment or released during the recycling process (table 1).[23] Persistent organic pollutants are a group of lipophilic, bioaccumulative substances that are very resistant to breakdown because of long half-lives. Common persistent organic pollutants found in electrical and electronic equipment components include: brominated flame retardants (polybrominated diphenyl ethers), polybrominated diphenyls, dibrominated diphenyl ethers, polychlorinated biphenyls, polychlorinated or polybrominated dioxins and dibenzofurans dioxins, hexabromocyclododecanes, and perfluroalkyls. Persistent organic pollutants released during dismantling, typically from incineration and smelting, include polychlorinated dibenzodioxins, polychlorinated dibenzofurans, and dioxin-like polychlorinated biphenyls. Polycyclic aromatic hydrocarbons are naturally occurring, hydrophobic substances that are formed during incomplete combustion of coal, gas, oil, meat, tobacco, incense, and wood.[10,24] These hydrocarbons are formed and released into the environment during the burning of e-waste materials.[25] Potentially hazardous chemical elements are also components of electrical and electronic equipment; the most common are lead, cadmium, chromium, mercury, copper, manganese, nickel, arsenic, zinc, iron, and aluminium.[26]

Regional intergovernmental organisations, international organisations, national governments, and non-governmental organisations have actively worked to address the practical application of e-waste regulations and initiatives to prevent negative effects on health from the informal recycling of e-waste. However, the focus of e-waste policies and initiatives is only now beginning to shift from a mainly environmental emphasis to one that includes health. New challenges are emerging, and international conventions such as those in Basel,[3] Rotterdam,[27] and Stockholm[28] will struggle to effectively address growing domestic e-waste streams in developing countries. Evidence of the human health effects of e-waste exposure will be key to the development of effective protective policies. We aimed to summarise the evidence relating to the possible association between exposure to e-waste and health, and outcomes related to education and violence.

## Methods

### Search strategy and selection criteria

We undertook a systematic review that followed the 2009 PRISMA guidelines.[29] We developed a review protocol with methods and inclusion criteria we specified in advance (appendix). We incorporated epidemiological studies meeting the following inclusion criteria: the aim of the study was to explore an association between exposure to e-waste and waste electrical and electronic equipment and outcomes related to mental health and neurodevelopment, physical health (including mechanistic events such as DNA damage and effects on gene expression), education, violence, and criminal behaviour; the study was published in a peer-reviewed journal, and reported original research; and the study examined outcomes in human beings. We excluded studies reporting results in plants, animals, and in-vivo or in-vitro populations; reviews, letters to the editor, and abstracts; and those that did not report an outcome related to exposure to e-waste.

We searched five electronic databases (PubMed, Embase, Web of Science, PsycNET, and CINAHL) from , Jan 1, 1965, to Dec 17, 2012, with the search terms: (e-waste OR electronic waste OR WEEE) AND (health OR development OR mental OR education OR behaviour OR learning OR psychological OR psychiatric* OR environment* OR exposure* OR food OR fish OR human breast milk; appendix). We used broad search terms to ensure that publications were not overlooked, and many were then excluded. Our search was not

restricted to the English language, nor by any other means. Relevant articles published in languages other than English were translated. We also assessed reference lists of included studies for other relevant studies.

### Data collection

After preliminary screening, studies deemed relevant were retrieved for assessment. Eligibility was assessed independently by two reviewers (KG and FCG), and disagreements were resolved by consensus for all included reports. A data extraction sheet was pilot tested and revised to include: publication details, study characteristics (period, design, location, and sample size), exposure and outcome measures, exposure variables (exposure sector, and chemicals included and analysed), and study outcome (appendix). All possible reported measures of effect size were included. We assessed risk of bias by focusing on a set of methodological issues including whether or not the sample was representative of the population; study design (prospective, retrospective, or ecological); ascertainment of exposure to e-waste (whether objective markers of exposure were used and individual biological samples were taken or whether samples were pooled or residence in an e-waste recycling area was used as a proxy for exposure); assessment of health outcome (clinical diagnosis or physical measurements and tests *vs* self-reported) and whether masking of outcome assessment was done; selection of the non-exposed controls and appropriate methods to control confounding that might affect the results of this systematic review.

| | Component of electrical and electronic equipment | Ecological source of exposure | Route of exposure |
|---|---|---|---|
| **Persistent organic pollutants** | | | |
| Brominated flame retardants<br>Polybrominated diphenyl ethers | Fire retardants for electronic equipment | Air, dust, food, water, and soil | Ingestion, inhalation, and transplacental |
| Polychlorinated biphenyls | Dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors | Air, dust, soil, and food (bio-accumulative in fish and seafood) | Ingestion, inhalation or dermal contact, and transplacental |
| **Dioxins** | | | |
| Polychlorinated dibenzodioxins and dibenzofurans | Released as combustion byproduct | Air, dust, soil, food, water, and vapour | Ingestion, inhalation, dermal contact, and transplacental |
| Dioxin-like polychlorinated biphenyls | Released as a combustion byproduct but also found in dielectric fluids, lubricants and coolants in generators, capacitors and transformers, fluorescent lighting, ceiling fans, dishwashers, and electric motors | Released as combustion byproduct, air, dust, soil, and food (bioaccumulative in fish and seafood) | Ingestion, inhalation, and dermal absorption |
| Perfluroalkyls | Fluoropolymers in electronics | Water, food, soil, dust, and air | Ingestion, dermal contact, inhalation, and transplacental |
| **Polyaromatic hydrocarbons** | | | |
| Acenaphthene, acenaphthylene, anthracene, benz[a] anthracene, benzo[a]pyrene, benzo[e]pyrene, benzo[b]fluoranthene, benzo[g,h,i]perylene, benzo[j] fluoranthene, benzo[k]fluoranthene, chrysene, dibenz[a,h]anthracene, fluoranthene, fluorene, indeno[1,2,3-c,d]pyrene, phenanthrene, and pyrene | Released as combustion byproduct | Released as combustion byproduct, air, dust, soil, and food | Ingestion, inhalation, and dermal contact |
| **Elements** | | | |
| Lead | Printed circuit boards, cathode ray tubes, light bulbs, televisions (1·5–2·0 kg per monitor), and batteries | Air, dust, water, and soil | Inhalation, ingestion, and dermal contact |
| Chromium or hexavalent chromium | Anticorrosion coatings, data tapes, and floppy disks | Air, dust, water, and soil | Inhalation and ingestion |
| Cadmium | Switches, springs, connectors, printed circuit boards, batteries, infrared detectors, semi-conductor chips, ink or toner photocopying machines, cathode ray tubes, and mobile phones | Air, dust, soil, water, and food (especially rice and vegetables) | Ingestion and inhalation |
| Mercury | Thermostats, sensors, monitors, cells, printed circuit boards, and cold cathode fluorescent lamps (1–2 g per device) | Air, vapour, water, soil, and food (bioaccumulative in fish) | Inhalation, ingestion, and dermal contact |
| Zinc | Cathode ray tubes, and metal coatings | Air, water, and soil | Ingestion and inhalation |
| Nickel | Batteries | Air, soil, water, and food (plants) | Inhalation, ingestion, dermal contact, and transplacental |
| Lithium | Batteries | Air, soil, water, and food (plants) | Inhalation, ingestion, and dermal contact |
| Barium | Cathode ray tubes, and fluorescent lamps | Air, water, soil, and food | Ingestion, inhalation and dermal contact |
| Beryllium | Power supply boxes, computers, x-ray machines, ceramic components of electronics | Air, food, and water | Inhalation, ingestion, and transplacental |

*Table 1:* **Chemical classification of e-waste components and sources and routes of exposure**

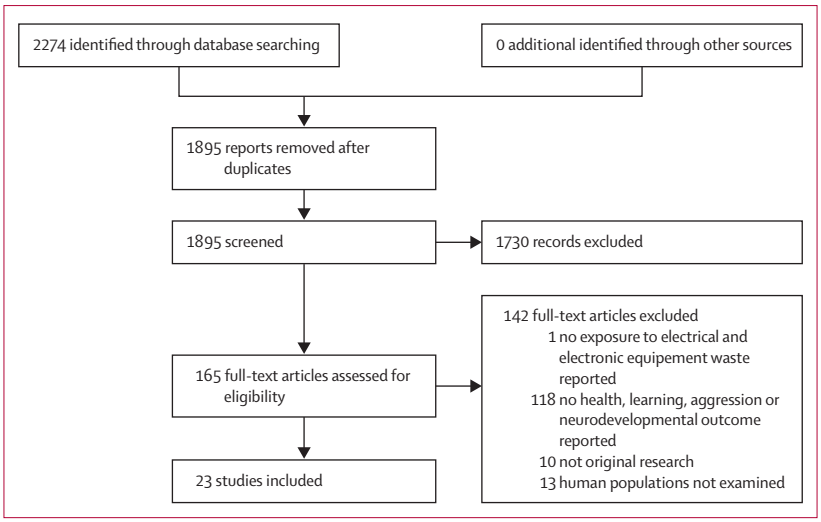


*Figure:* **Study selection for inclusion in systematic review**

## Results

Of the 165 studies that we screened and assessed for eligibility, 23[30–51] reported associations between exposure to e-waste or waste electrical and electronic equipment and physical health, mental health, neurodevelopment, and learning outcomes (figure). All included studies were from southeast China, and almost all included the major e-waste recycling towns of Guiyu (n=14), Taizhou (n=1), and Luqiao (n=1). We excluded most studies because they did not assess the health, educational, and behavioural consequences of exposure to e-waste (n=118; figure).

Findings of 16 of the 23 studies[30-45] showed associations between exposure to e-waste and physical health outcomes, including thyroid function, reproductive health, lung function, growth, and changes to cell functioning. Although all studies investigated the association between exposure to e-waste and outcomes, the chemical components of e-waste analysed differed between studies, and included polybrominated diphenyl ethers, polychlorinated dibenzodioxins and polychlorinated dibenzofurans, polycyclic aromatic hydrocarbons, polychlorinated biphenyls (including dioxin-like polychlorinated biphenyls), perfluroalkyls, and chemical elements (chromium, lead, manganese, and nickel). Outcomes were reported from Guiyu and Taizhou in southeast China, and included environmental, informal, and formal exposure routes.

Five studies[30–34] have examined the effects of exposure to e-waste on thyroid function (table 2). These studies included mainly ecological assessments that compared health outcomes of populations in towns involved in e-waste recycling with those in non-exposed (control) towns. The reported effects on thyroid-stimulating hormone (TSH) are not consistent, with two studies reporting increased TSH concentrations in the exposed populations[30,31] and three reporting decreased concentrations associated with e-waste exposure (table 2).[32–34] Similarly, concentrations of tetraiodothyronine (T4) in the exposed population have either been lower[30,32] or no different[33] from those in the control population. Although Yuan and colleagues[31] showed that working with e-waste was an independent predictor of serum TSH concentrations,[31] the investigators acknowledged limitations in the interpretation of results because of a failure to account for other effects on TSH concentrations, including T4 concentrations not measured.

Zheng and colleagues[35] investigated associations between exposure to metals (eg, chromium, manganese, and nickel) and lung function in 144 schoolchildren (aged 8–13 years) from Guiyu, an e-waste dismantling site, and from Liangying, a control town with no evidence of e-waste recycling.[35] Boys aged 8–9 years living in Guiyu had a lower forced vital capacity than those living in Liangying (1859 mL *vs* 2121 mL, p=0·03).[35] Findings from height-adjusted multivariate regression analysis showed significant negative correlations between blood chromium concentrations and forced vital capacity in children aged 11 and 13 years (β=–14·02, p=0·018, and β=–43·23, p=0·027, respectively), and serum nickel concentrations in children aged 10 years (β=–18·47, p=0·035).[35]

Pregnancy outcomes in populations exposed to e-waste have been investigated in seven studies (table 2).[41–47] Despite different exposure settings and toxicants assessed, there have been consistent effects of exposure with increases in spontaneous abortions,[40] stillbirths,[37,42] and premature births,[37,40,42] and reduced birthweights[37,40,42] and birth lengths[39,40] in most studies. Adverse birth outcomes have been associated with increased exposures to polycyclic aromatic hydrocarbons[37] and persistent organic pollutants, including polybrominated diphenyl ethers,[36] polychlorinated biphenyls,[37] and perfluroalkyls.[40] The main exception to these effects is the lack of association between exposures to metals and adverse birth outcomes.[36]

Findings from the two ecological studies[35,43] showed that physical growth indicators, such as weight, height, and body-mass index, were significantly lower in children living in the e-waste recycling town of Guiyu than in those living in the control area Liangying (table 2).[35] Height and weight were also negatively correlated with concentrations of blood manganese and serum nickel in one of these ecological studies. However, findings from the other did not show adverse effects of lead on growth in young children.[43]

In two studies,[44,45] lead was investigated as the main chemical agent associated with mental health outcomes related to e-waste exposure (table 2). In one study,[44] investigators assessed temperament in children, and measured neonatal behavioural neurological assessment scores in another.[45] Children in Guiyu had higher concentrations of lead in their blood than did those living in towns with no e-waste recycling, which was

| | Exposure setting | Exposed population | Primary toxicant | Health effect |
|---|---|---|---|---|
| **Thyroid function** | | | | |
| Ju et al[30] | Ecological: exposed town *vs* control town | Mothers and newborn babies (n=93) | Not assessed | Maternal: TSH higher (2·63 *vs* 2·10 mIU/L) and free T4 lower (16·47 *vs* 160·76 pmol/L) in exposed group. Cord blood: TSH (6·35 *vs* 5·47 mIU/L), free T4 (8·45 *vs* 9·52 pmol/L) |
| Yuan et al[31] | Formal recycling | Formal and informal workers *vs* not exposed (n=49) | PDBE | Serum PDBE: 382 *vs* 158 ng/g lipid weight, p=0·045. Serum TSH: $1·7 \times 10^{-6}$ *vs* $1·1 \times 10^{-6}$ mIU/L, p<0·01 |
| Zhang et al[32] | Ecological: exposed town *vs* control town | Pregnant women (n=50) | PCCDs and PCCFs, PCBs and PDBEs | Higher body burdens of PCCD and PCCFs, PCBs, and PDBEs. Serum TSH: 1·15 *vs* 2·65 nmol/L, p=0·015. Free T4: 112·5 *vs* 139·0 nmol/L, p=0·015 |
| Wang et al[33] | Ecological: workers in exposed town *vs* those in control town | Population (n=442) | PBDEs | Lower TSH (1·26 *vs* 1·57 μIU/mL), T3 (1632·4 *vs* 1817·2 pmol/L), and free T3 (4188·8 *vs* 4404·4 pmol/L), all p<0·001. No difference in T4. |
| Han et al[34] | Ecological: exposed town *vs* control town | Population (n=369) | Not assessed | Serum TSH: $1·8 \times 10^{-6}$ *vs* $3·3 \times 10^{-6}$ mIU/L. No p value reported |
| **Lung function** | | | | |
| Zheng et al[35] | Ecological: exposed town *vs* control town | School children (aged 8–13 years; n=144) | Chromium, manganese, and nickel | Blood manganese: 374·92 nmol/L *vs* 271·18 nmol/L, p<0·01. Nickel: 5·3 *vs* 3·0 mg/L, p<0·01. FVC in boys aged 8–9 years: 1859 *vs* 2121 mL, p=0·03. Decrease in FVC with increased chromium (11-year-old β =–14·02, p=0·018, 13-year-old β=–43·23, p=0·027), decreased FVC with increased nickel (10-year-olds β=–18·47, p=0·035) |
| **Reproductive health** | | | | |
| Guo et al[36] | Ecological: exposed town *vs* control town | Mother–infant pairs (n=220) | Lead, chromium, cadmium, and nickel | No differences in birthweight, birth length, or gestational age. Negative correlation between placental nickel and gestational age ($r_s$ =–0·16, p=0·017) |
| Guo et al[37] | Ecological: exposed town *vs* control town | Mother–infant pairs (n=183) | PAHs | Cord blood total PAH: 108·5 *vs* 79·63 ppb, p=0·003, chromium: 1·57 *vs* 1·05 ppb, p=0·049, BaP: 2·14 *vs* 1·64 ppb, p=0·001. DahA 12·26 *vs* 11·59 ppb, p=0·031. Increased BaA, chrysene, and BaP in neonates with adverse birth outcomes (prematurity, low birthweight, still birth, and malformations) (p<0·05). BaA negatively associated with neonatal height (r=–0·23, p=0·006); chrysene and BaP negatively associated with gestational age (*r*=–0·20, p=0·013; *r*=–0·17, p=0·042, respectively). |
| Wu et al[38] | Ecological: exposed town *vs* control town | Mother–infant pairs (n=153) | PBDEs | Higher total PBDEs in those with adverse birth outcomes (41·97 *vs* 9·88 ng/g, p=0·004). No effect on neonatal length, GA, or infant sex |
| Wu et al[39] | Informal recycling | Mother–infant pairs (n=167) | PCBs | Cord blood PCBs: 338·6 *vs* 140·2 ng/g, correlated with mothers' recycling activity. Higher total PCBs with adverse birth outcomes (*t*=–2·26, p=0·03). Negative associations between individual PCB congeners and neonatal height, neonatal weight, Apgar score, gestational age, and BMI (all p<0·05) |
| Wu et al[40] | Informal recycling | Pregnant women (n=167) | PFOA | Serum PFOA: 17·0 *vs* 8·7 ng/mL (p<0·001) correlated with recycling activity. Negative association between PFOA and spontaneous abortion (*t*=–3·035, p=0·003), preterm birth (*t*=–2·209, p=0·029), 1 log increase in PFOA associated with 15·99 (95% CI 2·72–4·25) reduction in GA, 267·3 g (37·2–573·3) reduction in birthweight, 1·91 cm (0·52–3·31) reduction in birth length and 1·37 (0·32–2·42) reduction in Apgar score |
| Li et al[41] | Ecological: exposed town *vs* control town | Newborn infants (302) | Chromium | Cord blood chromium, 2006: 306·2 *vs* 1·95 mg/L; 2007: 99·9 *vs* 32·48. No association with birthweight or birthlength |
| Xu et al[42] | Informal recycling | Newborn infants (n=531) | Lead | Cord blood lead: 10·87 *vs* 2·25 mg/dL (p<0·01), correlated with recycling activity. Higher rates of adverse birth outcomes: stillbirth (4·72% *vs* 1·03%, p<0·05), preterm birth (5·68% *vs* 5·24%, p<0·05), lower birthweight (3168 *vs* 3258 g, p<0·05), and lower Apgar scores (9·6 *vs* 9·9, p<0·05) |
| **Growth** | | | | |
| Zheng et al[35] | Ecological: exposed town *vs* control town | School children (aged 8–13 years; n=144) | Manganese and nickel | Height: 126·8 *vs* 135·0 cm, p<0·001. Weight: 24·7 *vs* 30·2 kg, p<0·01. BMI: 15·2 *vs* 16·5, p<0·01. Negative correlations between serum manganese and height ($r_s$=–0·303, p<0·001) and weight ($r_s$=–0·228, p=0·006) and serum nickel and height ($r_s$=–0·417, p<0·001), weight ($r_s$=–0·399, p<0·001), and BMI ($r_s$=–0·213, p=0·011) |
| Huo et al[43] | Ecological: exposed town *vs* control town | Children (younger than 6 years; n=226) | Lead | Blood lead: 15·3 *vs* 9·94 mg/dL (p<0·01). No differences in height, weight, chest circumference, or head circumference |
| **Mental health outcomes** | | | | |
| Liu et al[44] | Ecological: exposed town *vs* control town | Children (aged 3–7 years; n=303) | Lead | Blood lead: 0·64 *vs* 0·40 μmol/L (13·2 *vs* 8·3 mg/dL), p<0·01. Temperament scores: activity level (mean±SD 4·53±0·83 *vs* 4·18±0·81, *t*=3·377), adaptability (4·96±0·73 *vs* 4·67±0·83, *t*=2·96) and approach withdrawal (4·62±0·85 *vs* 4·3±0·89, *t*=2·877) |
| Li et al[45] | Ecological: exposed town *vs* control town | Newborn babies (n=152) | Lead | Cord blood lead: 11·3 *vs* 6·0 mg/dL, p<0·001; meconium lead: 2·5 *vs* 1·2 mg/g, p<0·001. NBNA scores: total (38·45 *vs* 38·92, *Z*=–2·023, p=0·043), behaviour cluster (10·91 *vs* 11·29, p=0·012). Negative associations between meconium lead and total NMNA (*r*=–0·903, p<0·01), activity tone (*r*=–0·637, p<0·01), and behavioural (*r*=–0·826, p<0·01) scores |

TSH=thyroid-stimulating hormone. T4=tetraiodothyronine. PDBE=polybrominated diphenyl ethers. PCCD=polychlorinated dibenzodioxins. PCCF= polychlorinated dibenzofurans. PCB=polychlorinated biphenyls. FVC= forced vital capacity. PAH= polycyclic aromatic hydrocarbons. BaP=benzo[a]pyrene. DahA=dibenz[a,h]anthracene. BaP=benzo[a]pyrene. BMI=body-mass index. ppb=parts per billion. NBNA=neonatal behavioural neurological assessment.

***Table 2:*** **Health effects of exposure to e-waste**

| | Exposure setting | Exposed population | Main toxicant | Effect |
|---|---|---|---|---|
| **DNA damage** | | | | |
| Chen et al[47] | Ecological: exposed town *vs* control town | Population (n=138) | Not assessed | Micronuclei in binucleated cells: median 4·0% (range 2·0–7·0) *vs* 1·0% (0·0–2·0), p<0·01 |
| Yuan et al[31] | Recycling activity | Recycle workers *vs* farmers (n=49) | Not assessed | Micronuclei in binucleated cells: median 5·0% (range 0·0–96·0) *vs* 0·0% (0·0–5·0), p<0·01 |
| Wang et al[48] | Recycling activity | Recycle workers *vs* not exposed (n=104) | Lead, copper, and cadmium | Micronuclei in binucleated cells: median 4·0% (range 2·0–7·0) *vs* 1·0% (0·0–2·0), p<0·01. Positive correlation between blood lead and micronuclei in binucleated cells ($r$=0·245, p<0·01). No associations with copper or chromium |
| Liu et al[46] | Recycling activity | Recycle workers *vs* not exposed (n=201) | Not assessed | Micronuclei in binucleated cells: median 16·92% *vs* 3·47%, p<0·01, chromosomal aberration (5·5% *vs* 1·7%), and DNA damage (comet assay). Women more affected than men (p<0·05) |
| Li et al[41] | Ecological: exposed town *vs* control town | Newborn infants (n=302) | Chromium | Comet assay: DNA damage (33·2% *vs* 10·7%, p<0·01), length of tail (4·49±1·92 μM *vs* 2·09±0·65, p<0·01). Blood chromium correlated with DNA damage ($r_s$=0·95, p<0·01) and tail length ($r_s$=0·95, p<0·01) |
| **Gene expression** | | | | |
| Li et al[49] | Ecological: exposed town *vs* control town | Men | Not assessed | miRNA expression profiles in spermatozoa: differential regulation (109 downregulated, 72 upregulated) |
| Li et al[50] | Ecological: exposed town *vs* control town | Newborn infants (n=423) | Cadmium | Metallothionein expression in placenta: 67·0% *vs* 3·7%, p<0·01; and correlated with cord blood ($r^2$=0·21, p=0·01) and placenta ($r^2$=0·76, p=0·01) cadmium concentrations |
| Zhang et al[51] | Ecological: exposed town *vs* control town | Pregnant women (n=105) | Not assessed | Placental S100P protein (0·026 *vs* 0·032, p=0·045) and mRNA (0·175 *vs* 1·462, p<0·001); metallothionein expression (0·051 *vs* 0·035, p=0·003) |

*Table 3*: **Changes at the cellular level resulting from exposure to e-waste**

correlated with location of residence in Guiyu (particularly having an e-waste workshop within 50 m), parents' involvement in e-waste recycling, (including time involvement), the use of the home as a recycling workshop, and the gnawing of toys by children.[42] Neonates had increased lead concentrations in cord blood and meconium, which were correlated with maternal involvement in e-waste recycling, time spent living in Guiyu before and during pregnancy, time spent in recycling facilities while pregnant, and the father's involvement in e-waste activities.[45] Neonatal behavioural neurological assessment scores differed significantly between the Guiyu group and the control group.[45] Increased concentrations of lead were associated with abnormalities in temperament scores[44] and low neonatal behavioural neurological assessment scores[45] (table 2).

We identified eight studies that included health outcomes at the cellular level caused by exposure to e-waste and waste electrical and electronic equipment.[31,41,46–51] All study populations were from southern China and studies were cross-sectional (table 3).

People living in e-waste recycling towns or working in e-waste recycling had evidence of greater DNA damage than did those living in the control down, with increased frequencies of micronucleated binucleated cells in peripheral blood.[31,46–48] Although exposure to e-waste is implicated in this DNA damage, the studies generally do not have the power to exclude other contributory factors. In one study,[31] no significant differences were recorded in other measures of oxidative DNA damage (ie, serum levels of superoxide dismutase, malondialdehyde, glutathione peroxidase, and 8-hydroxy-2′-deoxyguanosine) between the exposed and control groups. Additionally, the exposed group had higher chromosomal aberration rates than did the control group (5·5% *vs* 1·7%), and significant differences in DNA damage in the comet assay (one cell gel electrophoresis) between the two populations were recorded (significant increases in percentage of DNA in the tail, and differences in tail moments).[46] In this study, the potential confounding effect of cigarette smoking was excluded.[41] Higher rates of DNA damage were reported in women than in men, which the investigators attributed to greater exposure to pollutants because of time spent indoors.[46]

Significant differences were reported in lymphocytic DNA damage in neonates between the e-waste recycling town of Guiyu and the neighbouring fishing town Chaonan.[41] Neonates from Guiyu had greater DNA damage with significantly higher injury rates and lengths of tails in the comet assay than did neonates from Chaonan (table 3).[41] The investigators detected significant correlations between blood chromium concentrations and DNA damage in neonates.[41] A possible correlation was found between exposure to e-waste and changes in miRNA expression profiles in spermatozoa.[49] Li and colleagues[49] identified differential expression for 182 miRNAs by comparing the exposed and unexposed population, and noted a potential association between environmental exposure to e-waste and sperm quality and count.

Neonates from Guiyu had higher placental metallothionein expression (a biomarker of exposure to toxic metals) than did those from Chaonan.[50] Zhang and colleagues[51] noted significant downregulation of S100P proteins, higher expression of metallothionein, and higher placental cadmium concentrations in mothers exposed to e-waste from Guiyu than in non-exposed mothers from the control town Shantou (table 3). Mean relative mRNA and protein S110P concentrations were significantly lower in pregnant women from Guiyu than

in those from Shantou (table 3), and metallothionein expression was higher in Guiyu than in Shantou (table 3).[51] However, potential confounders were recorded that might account for these results: S100P concentrations were negatively correlated with gestational age; metallothionein expression was positively correlated with gestational age and Apgar score, but negatively correlated with maternal age.[51]

We identified one study[52] that related exposure to e-waste and waste electrical and electronic equipment to educational outcomes. Lead was analysed as the main chemical agent due to environmental exposure routes. Wang and colleagues[52] assessed the effects of blood lead concentrations on intelligence quotient (IQ) in children aged 11–12 years in the e-waste recycling town of Luqiao, the tinfoil manufacturing area Lanxi, and the control town Chun'an. Researchers identified no significant differences in IQ at the three sites. Because of small individual site sample sizes, the results were combined, and intellectual deficits were recorded in children with blood lead concentrations lower than 0·48 µmol/L every 0·04 µmol/L increase in blood lead level resulted in a 0·71 (95% CI –1·30 to –0·12) point decrease in IQ.[52] No studies investigated an association between e-waste exposure and aggression, violence, or criminal behaviour.

We assessed evidence for causality between exposure to e-waste and outcomes within the Bradford Hill framework.[53] We used the criteria for grading evidence developed by the World Cancer Research Fund (WCRF) as a guideline.[54]

## Discussion

To the best of our knowledge, this report is the first systematic review of published studies assessing the evidence of the effects of exposure to e-waste in children and adults. We identified 23 studies that examined associations between exposure to e-waste and health and learning outcomes, but no studies in which an association between exposure to e-waste and violence or criminal behaviour was investigated. We included violence and criminal behaviour as potential outcomes because of proposed associations between exposure to heavy metals, aggression, and violent crime.[55,56] We assessed evidence of causality between exposure to e-waste and many outcomes within the Bradford Hill framework, focusing on temporality, strength, and consistency of the associations, dose–response relation, plausibility, and the consideration of alternative explanations.

Our ability to assess temporality of associations was limited by the absence of prospective or longitudinal studies. Temporal associations, by definition, were not possible to establish in cross-sectional studies. We recorded weak associations between e-waste exposure and changes in thyroid function, adverse neonatal outcomes, changes in temperament and behaviour, decreases in lung function, and changes in cellular expression and function. Most associations remained significant when confounding variables were considered. However, the absence of prospective and longitudinal studies, and the small sample sizes (only one study had a sample size >450 people),[42] are concerns. Of note is the issue of the transport of environmental contamination. Substantial quantities of pollution are found not only very close to e-waste recycling locations, but, because of contamination of the surrounding environment (specifically soil and water) and the resulting food chain, high levels of pollution due to e-waste are also found throughout southern China, including control population locations.[4,7,57] Nonetheless, we still recorded differences between exposed and control populations in many studies, even without controlling for exposure in control groups.

Consistency of associations was hard to assess because of diverse outcomes and variation in chemical exposure variables. However, we noted consistent associations in studies assessing the effects of e-waste exposure on measures of DNA damage and cellular expression. In all studies, investigators reported higher frequencies of micronucleated binucleated cells in all e-waste-exposed populations than in unexposed controls. DNA damage (ie, DNA injury rates and tail length) was more prevalent in all e-waste-exposed populations than in controls—a finding consistent across studies. In the four studies assessing the effects of the components of e-waste on neonatal birth outcomes, the infants with adverse birth outcomes had increased concentrations of polybrominated diphenyl ethers,[38,39] polycyclic aromatic hydrocarbons,[37] and perfluroalkyls.[40] However, these conclusions need to be further substantiated because both cases (neonates with adverse birth outcomes) and controls (neonates with healthy birth outcomes) were taken from the study and not the general population.

We did not establish a dose–response relation for exposure to e-waste. Because the chemical elements and compounds to which people are exposed are released as a very complex mixture, the physiological response is to the mixture, instead of to individual chemicals. Dose–response relations of the chemical mixtures that arise in e-waste have not been extensively studied. Additionally, a typical linear dose–response pattern is not predicted for many of the chemicals involved in e-waste, especially compounds that have endocrine-disrupting effects.[58] Non-monotonic (ie, non-linear), or low-dose associations have typically been associated with some of these chemical compounds.[58] An association between exposure to e-waste and various outcomes in human beings is very likely. Mechanisms of action, from animal and in-vitro models, have been developed for individual and mixtures of chemical compounds implicated in e-waste. Additionally, important associations have been recorded between the chemical compounds found in e-waste and mental, physical, and learning outcomes due to non-e-waste sources of exposure (appendix). Many of the individual chemical pollutants found in e-waste have substantial effects on human health (appendix). The International Agency for Research on

Cancer has identified TCDD (2,3,7,8-tetrachlorodibenzo-p-dioxin), cadmium, hexavalent chromium, and beryllium as carcinogenic;[59–61] some polychlorinated biphenyls and some polycyclic aromatic hydrocarbons as probably carcinogenic;[62,63] and polybrominated diphenyl ethers, metallic nickel, and some polycyclic aromatic hydrocarbons as possibly carcinogenic.[60,62,64] Because of insufficient evidence, mercury, some dioxins, and some polycyclic aromatic hydrocarbons cannot be classified as carcinogenic.[59,61,62,65] Polybrominated diphenyl ethers, polycyclic aromatic hydrocarbons, chromium, nickel, and aluminium are confirmed genotoxins,[66–71] because these compounds have damaged DNA in vitro, and in tests on animals and human beings. Copper, iron, and aluminium are known cytotoxins.[69,71,72] Exposure to dioxins, dioxin-like polychlorinated biphenyls, perfluroalkyls, lead, and possibly cadmium has been associated with increased incidence of chronic diseases later in life, including obesity, type 2 diabetes, hypertension, and cardiovascular diseases.[73–79] Lung cancer, lung damage, and decreased lung function are also associated with compounds common in e-waste, including polycyclic aromatic hydrocarbons, hexavalent chromium, cadmium, nickel, arsenic, and lithium.[59,60,62,68,80–87]

We recorded adverse perinatal and neonatal outcomes, such as impaired fetal growth, low birthweight and birth length, low head circumference, stillbirth, preterm delivery, and below average childhood growth in mothers exposed to polybrominated diphenyl ethers, polychlorinated biphenyls, dioxins, perfluroalkyls, polycyclic aromatic hydrocarbons, and cadmium.[73,88–94] Exposure to hazardous e-waste compounds affected reproductive development and fertility. Lead has been linked to delayed puberty in girls;[95] polychlorinated biphenyls, TCDD, and perfluroalkyls decrease sperm quality;[96–98] and exposure to polybrominated diphenyl ethers seems to decrease female fertility.[99] Many persistent organic pollutants are also endocrine disruptors, with an especially strong effect from early life exposure.[100,101]

The hazardous compounds found in e-waste have strong neurodevelopmental and neurobehavioural effects, especially in children. Polybrominated diphenyl ethers, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, lead, cadmium, and mercury are associated with decreased intelligence (as measured by IQ) and impaired cognitive functioning,[49,102–113] whereas polybrominated diphenyl ethers, polychlorinated biphenyls, mercury, and cadmium have been linked to neurodevelopmental abnormalities. Changes in mental health, including behavioural disturbances, attention deficits, hyperactivity, and conduct issues have been reported after childhood exposures to polychlorinated biphenyls, lead, mercury, and aluminium.[114–118] Some investigators have proposed associations between lead and polychlorinated biphenyl exposure and an increased risk of aggression and international rates of violent crime.[55,56] Data also suggest that lead exposure, combined with genetic predisposition, can trigger schizophrenia.[119–121] Although debated, heavy metals might have a role in the development of the neurodegenerative diseases Alzheimer's disease (aluminium)[122] and Parkinson's disease (lead).[123]

The effects of simultaneous exposure to many chemicals—eg, involvement in e-waste recycling—are not well explored or understood. This knowledge gap becomes an even larger problem in areas where other hazardous wastes are present in the environment. Although e-waste contains a unique combination of persistent hazardous compounds, other sources of exposure are difficult to rule out, especially in China, where all included studies were undertaken. However, in studies that accounted for confounding variables, investigators still recorded significant associations between e-waste and adverse outcomes in exposed populations. Working with e-waste was an independent risk factor

***Panel:* Research gaps and recommendations for future study**

**Gaps in research**

- Retrospective studies are not effective measures of the long-term health effects of e-waste exposure
- Issues in study design, particularly the pooling of samples, restrict the analysis and comparison of results
- All the studies qualifying for inclusion in our report focus on study sites in China, despite evidence of dangerous informal e-waste processing in many countries; although research has been published from other regions, a direct association between e-waste exposure and health outcomes in human beings has not been assessed
- Large gaps exist in the physical health, mental health, educational, and behavioural outcomes of exposure to individual chemical compounds released during e-waste recycling
- More understanding of potential synergistic and inhibitor effects of exposure to chemical mixtures, the effects of long-term exposure, and the outcomes of low-dose exposure to e-waste is needed
- The unique risks to children and vulnerable populations have not been given enough consideration

**Recommendations**

- Prospective, long-term cohort studies are needed to study exposed children and adults from the time of exposure, measuring body burden and investigating health and educational, employment, and other outcomes of interest
- A standardised and validated questionnaire should be introduced to remove the issues of different definitions of electronic waste, confounding factors, and health effects, and to standardise exposure recall data collection
- Additional research into the potential combination and inhibitor effects of the unique chemical mixtures present in e-waste is needed
- Additional research should be done in the growing e-waste regions of Africa, India, and Brazil
- A collaborative research agenda should be determined by international experts
- Although additional evidence is needed, rapidly growing streams of e-waste, the involvement of vulnerable populations, direct evidence of health effects, and biological plausibility of additional health effects need timely investigation and implementation of exposure-minimising interventions
- Public health professionals are not sufficiently aware of the health consequences of e-waste exposure; increased awareness and capacity building is needed within the health sector

associated with genotoxic damage when other variables, such as smoking and age, were accounted for.[31,48] The mechanisms of action of the mixture of chemicals that make up e-waste are not completely known, nor are the full range of effects that arise from the combined exposure to many chemical elements and compounds. We used the grading system developed by the WCRF[54] as a guideline to assess the level of evidence. We concluded that the evidence is suggestive of an association between e-waste exposure and change in thyroid function, changes in cellular function and expression, adverse neonatal outcomes, changes in temperament and behaviour, and decreases in lung function.

Extensive use of an ecological study design in the included reports introduced a risk of ecological fallacy (in which associations at the individual level are deduced from those found at the population level) in the interpretation of results. Although populations exposed to e-waste generally had a higher frequency of adverse health effects—especially for thyroid functioning, adverse birth outcomes, and changes in cellular functioning—the use of ecological data limits conclusions made at the individual level. Some studies relied on pooling of serum samples from exposed and control populations to make associations between adverse effects and chemical exposure. Studies based on retrospective assessment can be prone to information bias[42] and possible overreporting of disease in exposed groups, especially when child outcomes were measured by parent reports.[44] Although the investigators who associated adverse birth outcomes in neonates with concentrations of serum and umbilical cord chemical compounds did find significant associations,[37–40,42] the cases and controls were chosen from the study and not the general population, creating a sample bias (in which non-random population selection arises) or diagnostic bias (in which the exposure is already known for the cases and controls). Widespread environmental pollution from e-waste recycling sites hinders the identification of specific sources and routes of exposure. Additionally, alternative sources of local pollution, remote industrial pollution, and the biomagnification of pollutants in the food chain create complexity in exposure and body burden measurements.

At the outcome level, several studies that used a retrospective case–control design did not adjust results for confounding variables. In some studies, investigators did not adjust for the effect of confounders, especially smoking and age, on neonatal outcomes.[37–40] Possible alternative sources of exposure including outdoor air pollution, pesticides, and industrial pollution, have not been accounted for in the interpretation of results, which has diminished the plausibility of certain health outcomes being due to e-waste exposure alone. Our report might also have been biased by the inclusion of only published scientific literature because studies with findings showing significant (*vs* null) associations are more likely to be published.

In conclusion, few epidemiological data, weak associations, inconsistent findings across studies, and poor understanding of biological mechanisms preclude the establishment of a causal relation between exposure to e-waste and adverse health outcomes in the assessment of evidence by conventional epidemiological approaches. However, the widespread production and use of electronic and electrical equipment, the increasing contamination of the environment, and the persistence and bioaccumulation of these chemical components warrant special consideration of e-waste as an emerging health risk for many populations. A precautionary approach towards exposure, especially in children, seems warranted. Additionally, we recorded extensive evidence of a causal link between exposure to individual chemical compounds common in e-waste and negative health outcomes (appendix). The strong biological plausibility of an association between e-waste exposure and health outcomes justifies investment in further research into the unique exposure scenarios and potential health consequences of e-waste exposure. Several research gaps have been identified by our report, and we provide recommendations to fill these gaps (panel).

The health effects of exposure to e-waste must become a priority of the international community. Informal e-waste recycling has long been accepted as a source of dangerous environmental pollution, but the health risks it poses to exposed populations are only beginning to be recognised. An international research agenda should be set by experts to increase the body of evidence of the health effects of e-waste exposure, especially in children and vulnerable populations. Simultaneously, the international health community, academia, policy experts, and non-governmental organisations, in conjunction with national governments, should create policy solutions, educational programmes, and interventions to reduce e-waste exposure and its health effects.

#### Contributors

PDS, M-NB, and MN initiated the report. KG, REN, and MvdB wrote the review protocol. KG did the initial search and collection of articles. KG and FG independently reviewed articles and determined included articles. KG, FCG, REN, PDS, and M-NB wrote the first and final versions. All authors independently reviewed and approved the final manuscript.

#### Conflicts of interest

We declare that we have no conflicts of interest.

#### Acknowledgments

M-NB and MN are staff members of the World Health Organization. The authors alone are responsible for the views expressed in this publication and they do not necessarily represent the decisions, policy, or views of the World Health Organization. Funding was provided by the Children's Health and Environment Program, Queensland Children's Medical Research Institute, The University of Queensland.

#### References

1 United Nations Environment Programme (UNEP). E-waste volume I: inventory assessment manual. Osaka, Japan: United Nations Environmental Programme, Division of Technology, Industry and Economics, International Environmental Technology Centre, 2007.

2 Council of the European Parliament. Directive 2002/96/EC of the European Parliament and of the Council of 27 January 2003 on waste electrical and electronic equipment (WEEE). March 13, 2003. *OJEU* 2003; **37:** 24–38.

3 United Nations Environment Programme (UNEP). Basel convention on the control of transboundary movements of hazardous waste and their disposal. 1989. http://www.basel.int/Portals/4/Basel%20Convention/docs/text/BaselConventionText-e.pdf (accessed Oct 17, 2013).

4 Wong CS, Wu SC, Duzgoren-Aydin NS, Aydin A, Wong MH. Trace metal contamination of sediments in an e-waste processing village in China. *Environ Pollut* 2007; **145:** 434–42.

5 Wong CS, Duzgoren-Aydin NS, Aydin A, Wong MH. Evidence of excessive releases of metals from primitive e-waste processing in Guiyu, China. *Environ Pollut* 2007; **148:** 62–72.

6 Schluep M, Hagelüken C, Meskers C, et al. Market potential of innovative e-waste recycling technologies in developing countries. R'09 World Congress; Davos, Switzerland; Sept 14–19, 2009. 1–8.

7 Yu XZ, Gao Y, Wu SC, Zhang HB, Cheung KC, Wong MH. Distribution of polycyclic aromatic hydrocarbons in soils at Guiyu area of China, affected by recycling of electronic waste using primitive technologies. *Chemosphere* 2006; **65:** 1500–09.

8 Fu J, Zhou Q, Liu J, et al. High levels of heavy metals in rice (*Oryza sativa* L.) from a typical E-waste recycling area in southeast China and its potential risk to human health. *Chemosphere* 2008; **71:** 1269–75.

9 Robinson BH. E-waste: an assessment of global production and environmental impacts. *Sci Total Environ* 2009; **408:** 183–91.

10 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for polycyclic aromatic hydrocarbons (PAHs). Atlanta, GA: US Department of Health and Human Services, Public Health Service, 1995.

11 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for chlorinated dibenzo-p-dioxins (CDDs). Atlanta, GA: US Department of Health and Human Services, Public Health Service, 1998.

12 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for mercury. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 1999.

13 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for polychlorinated biphenyls (PCBs). Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2000.

14 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for polybrominated biphenyls and polybrominated diphenyl ethers. Atlanta, GA: US Department of Health and Human Services, Public Health Service; 2004.

15 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for lead. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2007.

16 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for cadmium. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2012.

17 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for beryllium. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2002.

18 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for zinc. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2005.

19 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for nickel. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2005.

20 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicological profile for barium. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2007.

21 Agency for Toxic Substances and Disease Registry (ATSDR). Toxicoloigcal profile for chromium. Atlanta, GA: US Department of Health and Human Services, Public Health Service, 2012.

22 Pronczuk de Garbino J. Children's health and the environment: a global perspective. A resource manual for the health sector. In: Pronczuk de Garbino J, ed. New York: World Health Organization, 2004.

23 Frazzoli C, Orisakwe OE, Dragone R, Mantovani A. Diagnostic health risk assessment of electronic waste on the general population in developing countries' scenarios. *Environ Impact Assess Rev* 2010; **30:** 388–99.

24 Liu G, Niu Z, Van Niekerk D, Xue J, Zheng L. Polycyclic aromatic hydrocarbons (PAHs) from coal combustion: emissions, analysis, and toxicology. *Rev Environ Contam Toxicol* 2008; **192:** 1–28.

25 Wang Y, Tian Z, Zhu H, et al. Polycyclic aromatic hydrocarbons (PAHs) in soils and vegetation near an e-waste recycling site in South China: concentration, distribution, source, and risk assessment. *Sci Total Environ* 2012; **439:** 187–93.

26 Jinhui L, Huabo D, Pixing S. Heavy metal contamination of surface soil in electronic waste dismantling area: site investigation and source-apportionment analysis. *Waste Manag Res* 2011; **29:** 727–38.

27 United Nations Environment Programme (UNEP). Rotterdam convention on the prior informed consent procedure for certain hazardous chemicals and pesticides in international trade. 1998. http://www.unido.org/fileadmin/user_media/Services/Environmental_Management/GUDDIS/Legal_Frameworks/rotterdam_convention.pdf (accessed Oct 17, 2013).

28 United Nations Environment Programme (UNEP). Stockholm convention on persistent organic pollutants. 2001. http://www.pops.int/documents/convtext/convtext_en.pdf (accessed Oct 17, 2013).

29 Moher D, Liberati A, Tetzlaff J, Altman DG, The Prisma Group. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: the PRISMA Statement. *PLoS Med* 2009; **6:** e1000097.

30 Ju Y, Xu G, Chen L, Shi J. Effects of the electronic waste pollution on the levels of thyroid hormone and its receptor expression in the parturient woman and the newborn. *Wei Sheng Yan Jiu* 2008; **37:** 536–39 (in Chinese).

31 Yuan J, Chen L, Chen D, et al. Elevated serum polybrominated diphenyl ethers and thyroid-stimulating hormone associated with lymphocytic micronuclei in Chinese workers from an E-waste dismantling site. *Environ Sci Technol* 2008; **42:** 2195–200.

32 Zhang J, Jiang Y, Zhou J, et al. Elevated body burdens of PBDEs, dioxins, and PCBs on thyroid hormone homeostasis at an electronic waste recycling site in China. *Environ Sci Technol* 2010; **44:** 3956–62.

33 Wang H, Zhang Y, Liu Q, Wang F, Nie J, Qian Y. Examining the relationship between brominated flame retardants (BFR) exposure and changes of thyroid hormone levels around e-waste dismantling sites. *Int J Hyg Environ Health* 2010; **213:** 369–80.

34 Han G, Ding G, Lou X, et al. Correlations of PCBs, dioxin, and PBDE with TSH in children's blood in areas of computer e-waste recycling. *Biomed Environ Sci* 2011; **24:** 112–16.

35 Zheng G, Xu X, Li B, Wu K, Yekeen TA, Huo X. Association between lung function in school children and exposure to three transition metals from an e-waste recycling area. *J Expo Sci Environ Epidemiol* 2013; **23:** 67–72.

36 Guo Y, Huo X, Li Y, et al. Monitoring of lead, cadmium, chromium and nickel in placenta from an e-waste recycling town in China. *Sci Total Environ* 2010; **408:** 3113–17.

37 Guo Y, Huo X, Wu K, Liu J, Zhang Y, Xu X. Carcinogenic polycyclic aromatic hydrocarbons in umbilical cord blood of human neonates from Guiyu, China. *Sci Total Environ* 2012; **427:** 35–40.

38 Wu K, Xu X, Liu J, Guo Y, Li Y, Huo X. Polybrominated diphenyl ethers in umbilical cord blood and relevant factors in neonates from Guiyu, China. *Environ Sci Technol* 2010; **44:** 813–19.

39 Wu K, Xu X, Liu J, Guo Y, Huo X. In utero exposure to polychlorinated biphenyls and reduced neonatal physiological development from Guiyu, China. *Ecotoxicol Environ Saf* 2011; **74:** 2141–47.

40 Wu K, Xu X, Peng, Liua J, Guo Y, Huo X. Association between maternal exposure to perfluorooctanoic acid (PFOA) from electronic waste recycling and neonatal health outcomes. *Environ Int* 2012; **48:** 1–8.

41 Li Y, Xu X, Liu J, et al. The hazard of chromium exposure to neonates in Guiyu of China. *Sci Total Environ* 2008; **403:** 99–104.

42 Xu X, Yang H, Chen A, et al. Birth outcomes related to informal e-waste recycling in Guiyu, China. *Reprod Toxicol* 2012; **33:** 94–98.

43 Huo X, Peng L, Xu X, et al. Elevated blood lead levels of children in Guiyu, an electronic waste recycling town in China. *Environ Health Perspect* 2007; **115:** 1113–17.

44 Liu J, Xu X, Wu K, et al. Association between lead exposure from electronic waste recycling and child temperament alterations. *Neurotoxicology* 2011; **32:** 458–64.

45 Li Y, Xu X, Wu K, et al. Monitoring of lead load and its effect on neonatal behavioral neurological assessment scores in Guiyu, an electronic waste recycling town in China. *J Environ Monit* 2008; **10:** 1233–38.

46 Liu Q, Cao J, Li KQ, et al. Chromosomal aberrations and DNA damage in human populations exposed to the processing of electronics waste. *Environ Sci Pollut Res Int* 2009; **16:** 329–38.

47 Chen L, Guo H, Yuan J, et al. Polymorphisms of GSTT1 and GSTM1 and increased micronucleus frequencies in peripheral blood lymphocytes in residents at an e-waste dismantling site in China. *J Environ Sci Health A Tox Hazard Subst Environ Eng* 2010; **45:** 490–97.

48 Wang Q, He AM, Gao B, et al. Increased levels of lead in the blood and frequencies of lymphocytic micronucleated binucleated cells among workers from an electronic-waste recycling site. *J Environ Sci Health A Tox Hazard Subst Environ Eng* 2011; **46:** 669–76.

49 Li Y, Li M, Liu Y, Song G, Liu N. A microarray for microRNA profiling in spermatozoa from adult men living in an environmentally polluted site. *Bull Environ Contam Toxicol* 2012; **89:** 1111–14.

50 Li Y, Huo X, Liu J, Peng L, Li W, Xu X. Assessment of cadmium exposure for neonates in Guiyu, an electronic waste pollution site of China. *Environ Monit Assess* 2011; **177:** 343–51.

51 Zhang Q, Zhou T, Xu X, et al. Downregulation of placental S100P is associated with cadmium exposure in Guiyu, an e-waste recycling town in China. *Sci Total Environ* 2011; **410:** 53–58.

52 Wang X, Miller G, Ding G, et al. Health risk assessment of lead for children in tinfoil manufacturing and e-waste recycling areas of Zhejiang Province, China. *Sci Total Environ* 2012; **426:** 106–12.

53 Hill AB. The environment and disease: association or causation? *Proc R Soc Med* 1965; **58:** 295–300.

54 World Cancer Research Fund, American Institute for Cancer Research (AICR). Food, nutrition, physical activity, and the prevention of cancer: a global perspective. Washington DC: AICR, 2007.

55 Carpenter DO, Nevin R. Environmental causes of violence. *Physiol Behav* 2010; **99:** 260–68.

56 Needleman HL, McFarland C, Ness RB, Fienberg SE, Tobin MJ. Bone lead levels in adjudicated delinquents. A case control study. *Neurotoxicol Teratol* 2002; **24:** 711–17.

57 Bi X, Thomas GO, Jones KC, et al. Exposure of electronics dismantling workers to polybrominated diphenyl ethers, polychlorinated biphenyls, and organochlorine pesticides in South China. *Environ Sci Technol* 2007; **41:** 5647–53.

58 Vandenberg LN, Colborn T, Hayes TB, et al. Hormones and endocrine-disrupting chemicals: low-dose effects and nonmonotonic dose responses. *Endocr Rev* 2012.

59 World Health Organization International Agency for Research on Cancer (IARC). Beryllium, cadmium, mercury, and exposures in the glass manufacturing industry. *IARC Monogr Eval Carcinog Risks Hum* 1993: **58:** 1–21.

60 World Health Organization International Agency for Research on Cancer (IARC). Chromium, nickel and welding. *IARC Monogr Eval Carcinog Risks Hum* 1990: **49:** 527–28.

61 World Health Organization International Agency for Research on Cancer (IARC). Polychlorinated dibenzo-para-dioxins and polychlorinated dibenzofurans. *IARC Monogr Eval Carcinog Risks Hum* 1997: **69:** 1–15.

62 World Health Organization International Agency for Research on Cancer (IARC). Some non-heterocyclic polycyclic aromatic hydrocarbons and some related exposures. *IARC Monogr Eval Carcinog Risks Hum* 2010: **92:** 754–73.

63 World Health Organization International Agency for Research on Cancer (IARC). A review of human carcinogens: chemical agents and related occupations. *IARC Monogr Eval Carcinog Risks Hum* 2012: **100:** 249–378.

64 World Health Organization International Agency for Research on Cancer (IARC). Agents Classified by the IARC Monographs. *IARC Monogr Eval Carcinog Risks Hum* 2011; **1–106:** 1–17.

65 Straif K, Baan R, Grosse Y, Secretan B, El Ghissassi F, Cogliano V, for the WHO International Agency for Research on Cancer Monograph Working Group. Carcinogenicity of polycyclic aromatic hydrocarbons. *Lancet Oncol* 2005; **6:** 931–32.

66 Barber JL, Walsh MJ, Hewitt R, Jones KC, Martin FL. Low-dose treatment with polybrominated diphenyl ethers (PBDEs) induce altered characteristics in MCF-7 cells. *Mutagenesis* 2006; **21:** 351–60.

67 De Flora S, Bagnasco M, Serra D, Zanacchi P. Genotoxicity of chromium compounds. A review. *Mutat Res* 1990; **238:** 99–172.

68 Hirano M, Tanaka S, Asami O. Classification of polycyclic aromatic hydrocarbons based on mutagenicity in lung tissue through DNA microarray. *Environ Toxicol* 2011; published online Sept 2. DOI:10.1002/tox.20761.

69 Lankoff A, Banasik A, Duma A, et al. A comet assay study reveals that aluminium induces DNA damage and inhibits the repair of radiation-induced lesions in human peripheral blood lymphocytes. *Toxicol Lett* 2006; **161:** 27–36.

70 Danadevi K, Rozati R, Banu BS, Grover P. Genotoxic evaluation of welders occupationally exposed to chromium and nickel using the Comet and micronucleus assays. *Mutagenesis* 2004; **19:** 35–41.

71 Hartwig A, Kruger I, Beyersmann D. Mechanisms in nickel genotoxicity: the significance of interactions with DNA repair. *Toxicol Lett* 1994; **72:** 353–58.

72 Seth R, Yang S, Choi S, Sabean M, Roberts EA. In vitro assessment of copper-induced toxicity in the human hepatoma line, Hep G2. *Toxicol In Vitro* 2004; **18:** 501–09.

73 Everett CJ, Frithsen I, Player M. Relationship of polychlorinated biphenyls with type 2 diabetes and hypertension. *J Environ Monit* 2011; **13:** 241–51.

74 Everett CJ, Mainous AG, Frithsen IL, Player MS, Matheson EM. Association of polychlorinated biphenyls with hypertension in the 1999–2002 National Health and Nutrition Examination Survey. *Environ Res* 2008; **108:** 94–97.

75 Halldorsson TI, Rytter D, Haug LS, et al. Prenatal exposure to perfluorooctanoate and risk of overweight at 20 years of age: a prospective cohort study. *Environ Health Perspect* 2012; **120:** 668–73.

76 Korrick SA, Hunter DJ, Rotnitzky A, Hu H, Speizer FE. Lead and hypertension in a sample of middle-aged women. *Am J Public Health* 1999; **89:** 330–35.

77 Longnecker MP, Michalek JE. Serum dioxin level in relation to diabetes mellitus among Air Force veterans with background levels of exposure. *Epidemiology* 2000; **11:** 44–48.

78 Luoma PV, Nayha S, Pyy L, Hassi J. Association of blood cadmium to the area of residence and hypertensive disease in Arctic Finland. *Sci Total Environ* 1995; **160:** 571–75.

79 Zhang A, Hu H, Sanchez BN, et al. Association between prenatal lead exposure and blood pressure in children. *Environ Health Perspect* 2012; **120:** 445–50.

80 Abakay A, Gokalp O, Abakay O, et al. Relationships between respiratory function disorders and serum copper levels in copper mineworkers. *Biol Trace Elem Res* 2012; **145:** 151–57.

81 Guha Mazumder DN. Chronic arsenic toxicity: clinical features, epidemiology, and treatment: experience in West Bengal. *J Environ Sci Health A Tox Hazard Subst Environ Eng* 2003; **38:** 141–63.

82 Martin AK, Mack DG, Falta MT, et al. Beryllium-specific CD4+ T cells in blood as a biomarker of disease progression. *J Allergy Clin Immunol* 2011; **128:** 1100–06.

83 Pearson P, Britton J, McKeever T, et al. Lung function and blood levels of copper, selenium, vitamin C and vitamin E in the general population. *Eur J Clin Nutr* 2005; **59:** 1043–48.

84 Verougstraete V, Lison D, Hotz P. Cadmium, lung and prostate cancer: a systematic review of recent epidemiological data. *J Toxicol Environ Health B Crit Rev* 2003; **6:** 227–55.

85 Waalkes MP. Cadmium carcinogenesis in review. *J Inorg Biochem* 2000; **79:** 241–44.

86 Lauwerys RR, Roels HA, Buchet JP, Bernard A, Stanescu D. Investigations on the lung and kidney function in workers exposed to cadmium. *Environ Health Perspect* 1979; **28:** 137–45.

87 Milton AH, Rahman M. Respiratory effects and arsenic contaminated well water in Bangladesh. *Int J Environ Health Res* 2002; **12:** 175–79.

88 Al-Saleh I, Alsabbahen A, Shinwari N, et al. Polycyclic aromatic hydrocarbons (PAHs) as determinants of various anthropometric measures of birth outcome. *Sci Total Environ* 2013; **444:** 565–78.

89 Govarts E, Nieuwenhuijsen M, Schoeters G, et al. Birth weight and prenatal exposure to polychlorinated biphenyls (PCBs) and dichlorodiphenyldichloroethylene (DDE): a meta-analysis within 12 European Birth Cohorts. *Environ Health Perspect* 2012; **120:** 162–70.

90 Harley KG, Chevrier J, Schall RA, Sjodin A, Bradman A, Eskenazi B. Association of prenatal exposure to polybrominated diphenyl ethers and infant birth weight. *Am J Epidemiol* 2011; **174:** 885–92.

91 Kippler M, Tofail F, Gardner R, et al. Maternal cadmium exposure during pregnancy and size at birth: a prospective cohort study. *Environ Health Perspect* 2012; **120:** 284–89.

92 Patandin S, Koopman-Esseboom C, de Ridder MA, Weisglas-Kuperus N, Sauer PJ. Effects of environmental exposure to polychlorinated biphenyls and dioxins on birth size and growth in Dutch children. *Pediatr Res* 1998; **44:** 538–45.

93 Rylander L, Strömberg U, Hagmar L. Lowered birth weight among infants born to women with a high intake of fish contaminated with persistent organochlorine compounds. *Chemosphere* 2000; **40:** 1255–62.

94 Wolff MS, Engel S, Berkowitz G, et al. Prenatal pesticide and PCB exposures and birth outcomes. *Pediatr Res* 2007; **61:** 243–50.

95 Wu T, Buck GM, Mendola P. Blood lead levels and sexual maturation in U.S. girls: the Third National Health and Nutrition Examination Survey, 1988-1994. *Environ Health Perspect* 2003; **111:** 737–41.

96 Joensen UN, Bossi R, Leffers H, Jensen AA, Skakkebaek NE, Jorgensen N. Do perfluoroalkyl compounds impair human semen quality? *Environ Health Perspect* 2009; **117:** 923–27.

97 McAuliffe ME, Williams PL, Korrick SA, Altshul LM, Perry MJ. Environmental exposure to polychlorinated biphenyls and p,p'-DDE and sperm sex-chromosome disomy. *Environ Health Perspect* 2012; **120:** 535–40.

98 Mocarelli P, Gerthoux PM, Needham LL, et al. Perinatal exposure to low doses of dioxin can permanently impair human semen quality. *Environ Health Perspect* 2011; **119:** 713–18.

99 Harley KG, Marks AR, Chevrier J, Bradman A, Sjodin A, Eskenazi B. PBDE concentrations in women's serum and fecundability. *Environ Health Perspect* 2010; **118:** 699–704.

100 Koopman-Esseboom C, Morse DC, Weisglas-Kuperus N, et al. Effects of dioxins and polychlorinated biphenyls on thyroid hormone status of pregnant women and their infants. *Pediatr Res* 1994; **36:** 468–73.

101 Bergman Å, Heindel J, Jobling S, et al. State of the science of endocrine disrupting chemicals 2012. Geneva: World Health Organization (WHO), United Nations Environment Programme (UNEP), Inter-Organization Programme for the Sound Management of Chemicals (IOMC), 2013.

102 Axelrad DA, Bellinger DC, Ryan LM, Woodruff TJ. Dose-response relationship of prenatal mercury exposure and IQ: an integrative analysis of epidemiologic data. *Environ Health Perspect* 2007; **115:** 609–15.

103 Bellinger DC, Stiles KM, Needleman HL. Low-level lead exposure, intelligence and academic achievement: a long-term follow-up study. *Pediatrics* 1992; **90:** 855–61.

104 Chen A, Dietrich KN, Ware JH, Radcliffe J, Rogan WJ. IQ and blood lead from 2 to 7 years of age: are the effects in older children the residual of high blood lead concentrations in 2-year-olds? *Environ Health Perspect* 2005; **113:** 597–601.

105 Dietrich KN, Berger OG, Succop PA, Hammond PB, Bornschein RL. The developmental consequences of low to moderate prenatal and postnatal lead exposure: intellectual attainment in the Cincinnati Lead Study Cohort following school entry. *Neurotoxicol Teratol* 1993; **15:** 37–44.

106 Eskenazi B, Chevrier J, Rauch SA, et al. In utero and childhood polybrominated diphenyl ether (PBDE) exposures and neurodevelopment in the CHAMACOS study. *Environ Health Perspect* 2013; **121:** 257–62.

107 Herbstman JB, Sjodin A, Kurzon M, et al. Prenatal exposure to PBDEs and neurodevelopment. *Environ Health Perspect* 2010; **118:** 712–19.

108 Jacobson JL, Jacobson SW. Intellectual impairment in children exposed to polychlorinated biphenyls in utero. *N Engl J Med* 1996; **335:** 783–89.

109 Jacobson JL, Jacobson SW, Humphrey HE. Effects of in utero exposure to polychlorinated biphenyls and related contaminants on cognitive functioning in young children. *J Pediatr* 1990; **116:** 38–45.

110 Kippler M, Tofail F, Hamadani JD, et al. Early-life cadmium exposure and child development in 5-year-old girls and boys: a cohort study in rural Bangladesh. *Environ Health Perspect* 2012; **120:** 1462–68.

111 Piikivi L, Hänninen H, Martelin T, Mantere P. Psychological performance and long-term exposure to mercury vapors. *Scand J Work Environ Health* 1984; **10:** 35–41.

112 Stewart PW, Reihman J, Lonky EI, Darvill TJ, Pagano J. Cognitive development in preschool children prenatally exposed to PCBs and MeHg. *Neurotoxicol Teratol* 2003; **25**: 11–22.

113 Surkan PJ, Zhang A, Trachtenberg F, Daniel DB, McKinlay S, Bellinger DC. Neuropsychological function in children with blood lead levels <10 microg/dL. *Neurotoxicology* 2007; **28:** 1170–77.

114 Braun JM, Kahn RS, Froehlich T, Auinger P, Lanphear BP. Exposures to environmental toxicants and attention deficit hyperactivity disorder in U.S. children. *Environ Health Perspect* 2006; **114:** 1904–09.

115 Eubig PA, Aguiar A, Schantz SL. Lead and PCBs as risk factors for attention deficit/hyperactivity disorder. *Environ Health Perspect* 2010; **118:** 1654–67.

116 Sagiv SK, Thurston SW, Bellinger DC, Amarasiriwardena C, Korrick SA. Prenatal exposure to mercury and fish consumption during pregnancy and attention-deficit/hyperactivity disorder-related behavior in children. *Arch Pediatr Adolesc Med* 2012; **166:** 1123–31.

117 Sinczuk-Walczak H, Szymczak M, Razniewska G, Matczak W, Szymczak W. Effects of occupational exposure to aluminum on nervous system: clinical and electroencephalographic findings. *Int J Occup Med Environ Health* 2003; **16:** 301–10.

118 Wang HL, Chen XT, Yang B, et al. Case-control study of blood lead levels and attention deficit hyperactivity disorder in Chinese children. *Environ Health Perspect* 2008; **116:** 1401–06.

119 Guilarte TR, Opler M, Pletnikov M. Is lead exposure in early life an environmental risk factor for schizophrenia? Neurobiological connections and testable hypotheses. *Neurotoxicology* 2012; **33:** 560–74.

120 Opler MG, Brown AS, Graziano J, et al. Prenatal lead exposure, delta-aminolevulinic acid, and schizophrenia. *Environ Health Perspect* 2004; **112:** 548–52.

121 Opler MG, Buka SL, Groeger J, et al. Prenatal exposure to lead, delta-aminolevulinic acid, and schizophrenia: further evidence. *Environ Health Perspect* 2008; **116:** 1586–90.

122 Drago D, Cavaliere A, Mascetra N, et al. Aluminum modulates effects of beta amyloid (1–42) on neuronal calcium homeostasis and mitochondria functioning and is altered in a triple transgenic mouse model of Alzheimer's disease. *Rejuvenation Res* 2008; **11:** 861–71.

123 Weisskopf MG, Weuve J, Nie H, et al. Association of cumulative lead exposure with Parkinson's disease. *Environ Health Perspect* 2010; **118:** 1609–13.