·综述·

无序电子垃圾拆解对人群健康的影响

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【摘要】 日益增多的电子垃圾已成为困扰全球环境和人群健康的重大问题。无序电子垃圾拆解回收过程中,铅、溴化阻燃剂等重金属和有机物进入空气、土壤、灰尘、水等环境介质中,造成的环境污染威胁着当地居民的身体健康。本文以广东省某电子垃圾拆解区为例,综述了我国重点电子垃圾拆解区人体重金属和有机物暴露水平及所造成的人群健康效应的研究进展。该地区电子垃圾拆解活动已造成重金属和有机物污染,当地人群体内处于重金属和有机物高负荷状态,对人体生理功能造成了一定的影响,集中拆解区的建立可以有效降低多种污染物负荷水平。

【关键词】 电子垃圾; 金属,重; 危害物质; 有机污染物; 人体健康

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Impact of informal e-waste recycling on human health

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【Abstract】 Increasing e-waste has become a major problem for global environment and public health. In the process of dismantling and recycling of disordered electronic waste, heavy metals such as lead and brominated flame retardants and organic substances are released into environmental media such as air, soil, dust and water, which is harmful to the health of local residents. Taking an e-waste dismantling area in Guangdong Province as an example, this paper reviews exposure levels of heavy metals and organic matters in e-waste recycling areas in China, as well as the health effects of local residents. Previous studies have found that e-waste recycling activities led to serious environmental pollution and high exposure levels of heavy metals and organic matters in local residents, which has a certain impact on the physiological functions of various human systems. The establishment of a centralized dismantling zone can effectively reduce the load level of various pollutants.

【Key words】 Electronic waste; Metals, heavy; Hazardous substances; Orangnic pollutant; Human health

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随着全球科技的发展,电子产品更新换代速度很快,各类电子废料已经成为增长最快的固体废弃物之一。电子废弃物又称电子垃圾,包括所有废旧淘汰的电子、电器产品,如废旧冰箱、电视机和手机等。电子垃圾含有铜、铁、铅、镍、锌、铬等金属材料,以及各种塑料、溴代阻燃剂等。无序电子垃圾拆解如手工拆解、烘烤电路板、强酸洗金、露天焚烧等处置方式,使得电子垃圾本身所含以及拆解过程产生的有害物质污染环境并危害人类健康[1-4]。日益增多的电

子垃圾已成为困扰全球环境和健康的重大问题[5-6]。全球每年大约产生2 000万吨～5 000万吨电子垃圾，其中50%～80%输出到亚洲和非洲发展中国家，造成的环境污染威胁着当地居民的身体健康。除中国之外，印度、尼日利亚等发展中国家的电子垃圾污染状况也令人堪忧。20世纪80年代，广东已发展成为著名的废旧五金电器电子产品回收处理中心[1-5]，每年拆解百万吨的电子垃圾。回收拆解产生的污水随意倾倒，所在练江流域从20世纪90年代至今都是劣五类水质。空气、土壤、灰尘及沉淀物等环境介质已经受到了严重的污染[7-13]。工人在最低或者没有任何健康和安全保护的条件下进行回收拆解，居民区内众多的家庭作坊更使得孕妇、新生儿、儿童等敏感人群遭受着污染物暴露相关健康风险[1,14-25]。因此，本文以广东省某电子垃圾拆解区为例，综合分析电子垃圾拆解污染对人群健康的影响。

一、电子垃圾拆解区人体暴露水平

（一）胎盘与脐带组织

人体胎盘是一种非常特殊的器官，作为胎儿和母体循环之间的媒介，胎盘促进发育中的胎儿的营养和废物交换，被认为是最复杂的人体组织。在流行病学和实验研究中，发现重金属和有机物可以到达胎盘、脐带、羊水和胎儿，并且高暴露剂量的重金属和有机物与出生体重减轻，妊娠期长度减少和早产风险增加有关。多项研究发现，电子垃圾拆解区新生儿胎盘铅、镉水平高于参照组，镍水平低于参照组[14,26-29]；电子垃圾拆解区胎盘、脐带多溴联苯醚（polybrominated biphenyl ether，PBDE）水平高于参照组，其中，脐带组织总PBDE浓度甚至高出参照组5倍[30-31]。

（二）脐带血

多项脐带血重金属研究发现，电子垃圾拆解区新生儿脐带血铅、镉、铬水平在多年的研究中均高于参照组，25.61%的新生儿脐带血镉水平高于WHO规定的安全阈值（5 μg/L）[26,32-36]。脐带血有机污染物研究发现，电子垃圾污染区新生儿脐带血7种多环芳烃（polycyclic aromatic hydrocarbon，PAH）总水平及3种致癌性PAHs（䓛、苯并芘和二苯蒽）水平均高于参照组，总PBDE及七种PBDE同系物浓度，多氯联苯（polychlorinated biphenyl，PCB）和双酚A（bisphenol A，BPA）浓度均高于参照组[15,17-18,37]。同一研究现场的后续实验再次验证，广东省该电子垃圾拆解区新生儿脐带血16种PAH总浓度、12种PAH同系物浓度、8种PBDE总浓度及PBDE同系物浓度均高于参照组[38]。

（三）静脉血

2004—2017年儿童静脉血铅水平的研究发现，电子垃圾拆解区儿童的血铅水平、血铅超标率（>5 μg/dl）每年都高于参照组[1,16,39-46]。儿童的血铅水平在2009年及2012年后明显下降，与2009年金融危机作坊关闭、2012年前后电子垃圾集中拆解区建立有关[47-48]。有研究还发现儿童血铅水平有随年龄增长而增加的趋势，儿童2004、2006、2008年的血铬水平均高于参照组[1,49-50]，2004、2006、2009、2011、2012年血镉水平高于参照组[39-41,51-53]。儿童血汞均高于5.8 μg/dl，血汞超标（>10 μg/dl）率为62.11%[54]。2008年8~13岁儿童血锰、血清镍水平明显高于参照组，3~7岁儿童静脉血中锰、铜、锌水平高于参照组，砷、镉、硒水平低于参照组[50,55]。

电子垃圾拆解区儿童静脉血中16种PAH总浓度、7种致癌性PAH总浓度以及12种PAH同系物浓度均高于参照组，按年龄和性别分组后该差异依然具有统计学意义；PAH同系物中贡献率最高的是茚并芘，其次是苯并芘、苯并荧蒽和菲[56]。电子垃圾拆解区4~6岁儿童静脉血中8种PBDE同系物的贡献率依次为BDE-209（占总PBDE含量的70%）、BDE-153（20%）、BDE47和BDE28[57]。电子垃圾拆解工人、电子垃圾拆解区居民血浆中14种PBDE水平高于参照组居民，其中高溴代同系物（如七溴到十溴联苯醚）是参照组的11~20倍[58]。一项针对18~81岁人群的研究发现，电子垃圾拆解区居民静脉血清中6种PBDE总浓度和BDE-209浓度均高于参照组，且BDE-209浓度是其他文献报道职业暴露人群血液浓度的50～200倍[59]。电子垃圾拆解区人群28种PCB同系物总水平明显高于参照组[17,20,37,59]。孕妇血清全氟辛酸（perfluorooctanoic acid，PFOA）水平明显高于参照组与中国其他地区[19]。居民血清双环辛烷（六氯环戊二烯）水平显著高于参照组，而六氯环己烷、滴滴涕水平低于参照组[59-60]。

（四）尿、头发和乳汁

人尿中的重金属和有机物水平可能与特定时间的身体负担水平相关，并且是健康风险分析中的重要指标[61]。该电子垃圾拆解区孕妇尿镉浓度高于参照组，怀男婴孕妇尿镉水平高于怀女婴孕妇[62]。孕妇尿BPA、4-叔辛基苯酚（4-t-octylphenol，4-t-OP）水平高于参照组，其中BPA水平高于其他国家和地区[63]。头发可用于评估人体重金属、有机物暴露水平[61]。有研究发现，该拆解区居民头发锑、汞浓度显著高于参照组[64-65]。

母乳中的重金属和有机物水平则可以反映母体的负担和婴儿的产后暴露水平[61]。有研究发现，污染区产妇母乳中的总PCB浓度为9.50 ng/g，PCB毒性当量浓度为0.93 pg TEQ/g脂肪，其中PCB TEQ浓度的优势单体同系物是PCB 105和157，其浓度占总的PCB毒性当量的80%以上[66]。

二、电子垃圾所造成的人群健康效应

（一）对呼吸系统的影响

有研究发现，在高浓度或长期暴露于较低浓度的情况下，几种类型的重金属都会对气道产生不利影响。该电子垃圾拆解区5~8岁儿童的用力肺活量（forced vital capacity，FVC）和第一秒用力肺活量（forced expiratory volume in the first second，FEV_1）均低于参照组，而咳嗽、呼吸困难、咳痰和喘息的发生率均高于参照组；血铅>5 μg/dl是哮喘的危险因素，镉暴露是咳嗽的危险因素，锰暴露是喘息的危险因素[43,51]。高浓度的锰、镍暴露可能通过氧化损伤途径降低8~9岁儿童的FVC，使其肺功能受损[50]。

（二）对心血管的影响

有研究表明，重金属、有机物暴露与高血压、内皮损伤或功能障碍、动脉硬化等心血管疾病的后续发展之间存在关联[67-69]。该电子垃圾拆解区多种空气污染物（PM_{10}、$PM_{2.5}$、NO_2、SO_2和CO）水平及儿童心率、血浆去甲肾上腺素水平高于参照组，提示电子垃圾空气污染可通过激活交感-肾上腺髓质系统（sympatho-adrenomedullary, SAM）增加心血管疾病风险[7]。儿童的血压、血脂、血管炎症标志物水平异常：收缩压、脉压差和高密度脂蛋白水平低于参照组，甘油三酯和血管炎症标志物脂蛋白相关磷脂酶A2（lipoprotein-associated phospholipase A2, Lp-PLA2）、白细胞介素（interleukin, IL）-6、IL-8浓度高于参照组，提示电子垃圾拆解区铅暴露可通过血管炎症干扰儿童血压、血脂，从而增加心血管疾病风险[46]。

（三）对免疫系统的影响

重金属和有机物对人体有免疫毒性[70-71]。电子垃圾拆解区重金属暴露可干扰儿童的适应性免疫功能。电子垃圾拆解区儿童乙型肝炎表面抗体滴度以及麻疹、腮腺炎、风疹疫苗抗体滴度均低于参照组，且与血铅水平相关，提示铅暴露可降低儿童对乙型肝炎、麻疹、腮腺炎、风疹病毒的免疫应答，增加儿童罹患上述传染性疾病的风险[72-73]。另一项研究发现电子垃圾暴露儿童较低的白喉、百日咳、破伤风、乙脑、脊髓灰质炎、麻疹疫苗抗体滴度与血液铜、锌、铅水平负相关，提示电子垃圾拆解区铜、锌、铅暴露均可降低儿童对多种病毒的免疫应答[55]。血铅浓度还与儿童较高的$CD4^+$中央记忆性T细胞百分数呈正相关，提示铅暴露可能通过选择性地刺激$CD4^+$中央记忆性T细胞发育来干扰儿童细胞免疫[74]。

电子垃圾拆解区重金属暴露可干扰儿童的固有免疫。电子垃圾拆解区儿童静脉血单核细胞计数、嗜酸性粒细胞计数、中性粒细胞计数、嗜碱性粒细胞计数高于参照组，NK细胞百分比低于参照组，与铅、镉暴露相关，提示铅、镉暴露可干扰儿童白细胞免疫[41,44]。儿童红细胞参数改变、红细胞表面Ⅰ型补体受体（erythrocyte complement receptor 1, CR1）表达量降低与铅暴露相关，提示高水平铅暴露可能通过干扰红细胞数量、形态和受体来干扰红细胞免疫[45]。

（四）对神经系统的影响

铅、汞、镉、砷、铝等重金属具有神经发育毒性。重金属暴露可干扰中枢神经系统发育。该电子垃圾拆解区新生儿行为神经学评分（neonatal behavioral neurological assessment, NBNA）低于参照组，且与胎粪铅水平负相关，提示产前铅暴露可增加新生儿行为神经学发育迟缓风险[32]。儿童的活动水平、趋避性、适应性得分高于参照组，且与血铅水平正相关，提示电子垃圾铅暴露可影响儿童气质[16]。儿童的认知评分、语言评分低于参照组，且与血铅水平负相关，提示电子垃圾铅暴露可干扰儿童智力发育[75]。儿童注意缺陷与多动障碍（attention-deficit/hyperactivity disorder, ADHD）发生率为18.6%，铅暴露可能参与了儿童的行为问题和反社会行为等行为异常[76]。另一项研究发现儿童ADHD发生率为12.8%，与血铅水平正相关，提示铅暴露可能增加儿童ADHD风险[77]。

重金属暴露可干扰外周神经系统发育，包括听力与嗅觉记忆功能。该电子垃圾拆解区儿童听力损失发生率、双耳纯音传导平均听阈、低频率平均听阈、高频率平均听阈均高于参照组，且血铅水平是儿童听力损失的风险因素（OR=1.24，95% CI：1.029~1.486），提示铅暴露可能增加儿童听力损失风险[78]。儿童15 min、5 h和24 h嗅觉记忆得分低于参照组，高血铅组儿童（血铅浓度>5 μg/dl）的嗅觉记忆得分低于低血铅组，提示铅暴露可降低儿童嗅觉记忆功能[79]。

（五）对甲状腺功能的影响

环境内分泌干扰物能干扰青少年和成人中的甲状腺激素水平并造成甲状腺功能缺陷[80]。学龄前儿童PBDEs内暴露水平与儿童促甲状腺激素（thyroid-stimulating hormone, TSH）水平正相关，与三碘甲状腺原氨酸（free triiodothyronine, FT3）和四碘甲状腺原氨酸（free thyroxine, FT4）水平负相关，提示PBDE暴露是儿童甲状腺功能紊乱的危险因素[57]。另一项研究发现电子垃圾拆解区儿童较高的血清游离甲状腺素、促甲状腺激素水平与血铅水平正相关，提示铅暴露也是儿童甲状腺功能紊乱的危险因素[53]。

（六）对生殖功能的影响

电子垃圾拆解区成年男性精子质量明显低于参照组，其精子质量与暴露时间、血铅浓度负相关[20]。

（七）对生长发育的影响

电子垃圾拆解区新生儿不良出生结局与重金属暴露有关。电子垃圾地区新生儿更高的不良出生结局（死胎，低出生体重、低足月出生体重）比率和更低的Apgar评分、出身体重与铅暴露相关[34]。另一项研究发现与参照组相比，贵屿孕妇有更高的胎盘铅、镉水平，更低的出生身长以及更大的胎龄，胎盘镉水平与新生儿出生身长与体重呈负相关[27]。暴露区新生儿出生体重、头围、体重指数（body mass index, BMI）、Apgar评分较低，与母亲孕期尿镉浓度负相关（尤其是女婴），提示产前镉暴露与新生儿不良出生结局有关，可能对其生长发育有不良影响[62]。但是也有一些研究显示重金属与出生结局存在不同的关联性：有研究发现胎盘铅、镉和铬与新生儿身高、体重及胎龄没有相关性，而胎盘镍与胎龄负相关，还有研究发现脐带血铬与新生儿身高及体重没有相关性[14, 36]。

电子垃圾拆解区新生儿不良出生结局与有机物暴露有关。拆解区新生儿脐带血总PCB浓度高于参照组，脐带血中部分PCB同系物含量与新生儿的身长、体重、Apgar评分、胎龄以及体重指数呈负相关，另有研究发现脐带血中PCB含量与新生儿出生体重呈负相关，与出生身长和胎龄呈正相关，上述研究均提示产前PCB暴露参与了新生儿不良出生结局的发生[17, 37]。脐带血、脐带组织及胎盘中PBDE含量与新生儿出生体重、BMI以及Apgar评分呈负相关[18,30-31]。不良出生结局新生儿脐带血中的苯并蒽、䓛、苯并芘含量高

于正常出生结局新生儿，且脐带血苯并蒽、䓛、苯并芘含量与新生儿出生身长、胎龄负相关[15]。脐带血六环PAH水平与孕周和新生儿体重正相关[36]，脐带血 BDE-100 和 BDE-154与孕周正相关[38]。孕妇静脉血PFOA水平与新生儿胎龄、体重、身长以及5分钟Apgar评分负相关[19]。

电子垃圾拆解区儿童生长发育迟缓与重金属、有机物暴露有关。居住在电子垃圾拆解区的儿童血锰、血清镍、血铅与血镉水平高于参照组，而BMI、身高、胸围和体重低于参照组；血锰与身高、体重呈负相关，血清镍与身高、体重以及BMI呈负相关，血铅与身高、体重、BMI、头围以及胸围呈负相关，血镉与BMI呈负相关[50, 52]。PAH暴露与儿童身高、胸围、负相关[56]。

为探明电子垃圾拆解区污染物暴露干扰生长发育的机制，有研究进行了蛋白组学和表观遗传学分析。胎盘蛋白组学分析显示，32种差异表达蛋白主要参与能量代谢、蛋白质转运和细胞骨架结构，提示镉暴露导致胎盘线粒体氧化呼吸链异常是胎儿生长受限的重要机制[29]。大通量脐带蛋白组学结果显示，697种差异表达蛋白主要参与抗氧化、细胞凋亡、细胞结构、代谢等生理过程，提示PBDEs暴露通过细胞氧化应激、细胞凋亡来参与新生儿不良出生结局[31]。脐带血DNA甲基化谱差异研究发现，电子垃圾拆解区和参照组之间的125个甲基化差异的CpG位点主要参与神经系统发育、胚胎发育等生理过程，提示铅、镉、铬暴露通过影响生长发育相关基因甲基化来干扰儿童生长发育[81]。

三、展望

电子垃圾拆解区有毒污染物暴露重金属以铅为主，有机物从早期PCB为主转变为目前PBDE为主[1, 14-18, 31,37]。污染物暴露水平高低与电子垃圾拆解作坊营业状态、集中拆解区的建立密切相关；集中拆解区建立后污染物水平明显下降[1, 39-46]。污染物暴露可造成新生儿基因甲基化和蛋白表达差异，与新生儿出生不良结局相关[29, 31, 81]。污染物可通过影响机体神经-内分泌-免疫调节，造成机体功能紊乱[53, 74, 78]。污染物暴露可造成机体慢性炎症状态，后者是重大慢病发生发展的前期基础/物质基础[41, 44, 82]。

即便集中拆解区建立后污染物水平有所降低，但在园区内还是各自为政的小作坊原有的粗放拆解方式，仍然会影响当地的环境生态和人群健康。因此，对于电子垃圾拆解导致的环境和人体效应研究也是一个长期的系统工程，虽然我国研究人员在此方面已经做出了深入探索，但目前电子垃圾拆解区人群健康的研究还存在一些不足：(1)目前主要的研究类型为横断面研究，缺乏电子垃圾区人群队列研究，以探讨电子垃圾暴露与人群健康效应如慢性疾病之间的因果关系。(2)缺乏多中心研究，未来需要开展多地区的联合研究，以便得到更加精确的结论。(3)缺乏二次污染物如二噁英等持久性有机污染物在电子垃圾区人群中年代变化趋势的研究。因此，未来进一步开展相关研究十分必要。

在中国，政府在电子废物回收系统的规划、管理和监测中发挥着核心作用，逐步制定了一系列相关的法规法案来引导规范电子垃圾拆解活动，这些法规和措施加强了电子垃圾拆解活动的管理以及降低电子垃圾拆解所造成的环境污染[83-84]。尤其是2017年中国全面禁止洋垃圾进口，大幅度降低了电子垃圾的来源[85]。本综述回顾总结电子垃圾拆解区人群健康的研究工作，希望能为相关政府部门制定有关政策法规和治理措施、为预防环境污染所造成的相关疾病提供科学依据[86-87]。

利益冲突　所有作者均声明不存在利益冲突

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·文献速览·

2019年WHO关于5岁以下婴幼儿中接种肺炎球菌结合疫苗的立场文件

WHO. Pneumococcal conjugate vaccines in infants and children under 5 years of age: WHO position paper-February 2019 [EB/OL]. [2019-03-06]. http://apps.who.int/iris/nitstream/handle/10665/310968/WER9408.pdf? ua=1.

肺炎球菌感染可导致严重疾病，如脑膜炎、菌血症和肺炎，同时也诱发某些常见疾病，如鼻窦炎和中耳炎等。此WHO立场文件取代2012关于立场文件，主要聚焦于5岁以下儿童使用的肺炎球菌结合疫苗（PCV），总结了2017年6月以来发表的关于PCV10和PCV13的效果研究证据，特别强调接种程序、产品选择和5岁以下儿童的补种。PCV显示良好的安全性和有效性，使用3剂接种程序（2p+1或3p+1）或4剂接种程序（3p+1），均有直接（对于受种者）和间接（对于与受种者居住于同一社区的未接种者）的效果。对于婴儿接种PCV的免疫程序，WHO建议使用3剂次程序，分别为2p+1或3p+0，最早从6周龄开始接种；不同地区选择接种程序时，应考虑接种及时性和期望的接种率等。如可行，特别是在较高疾病负担和死亡率的情况下，在引入PCV时应开展补种，以加速其对1至5岁儿童的预防效果。此外，WHO建议建立肺炎球菌疾病的综合监测系统，持续、高质量开展哨点监测和以人群为基础的监测，定期开展鼻咽部肺炎球菌携带情况调查，监测分析PCV的流行病学影响。

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