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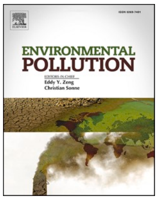

Fetal exposure to organic contaminants revealed by infant hair: A preliminary study in south China☆

Feng-Shan Cai [a,b,f], Bin Tang [b], Jing Zheng [b,c,*], Xiao Yan [b,c], Wei-Keng Luo [b], Mian He [d], Xiao-Jun Luo [a,e], Ming-Zhong Ren [b], Yun-Jiang Yu [b], Bi-Xian Mai [a,e]

[a] *State Key Laboratory of Organic Geochemistry, Guangdong Provincial Key Laboratory of Environmental Protection and Resources Utilization, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, PR China*
[b] *State Environmental Protection Key Laboratory of Environmental Pollution Health Risk Assessment, South China Institute of Environmental Sciences, Ministry of Environmental Protection, Guangzhou, 510655, PR China*
[c] *School of Public Health, Key Laboratory of Environmental Pollution and Disease Monitoring of Ministry of Education, Guizhou Medical University, Guiyang, 550000, PR China*
[d] *Guangdong Provincial Key Laboratory of Digestive Cancer Research, The Seventh Affiliated Hospital of Sun Yat-sen University, Shenzhen, 518107, PR China*
[e] *Guangdong-Hong Kong-Macao Joint Laboratory for Environmental Pollution and Control, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou, 510640, PR China*
[f] *University of Chinese Academy of Sciences, Beijing, 100049, PR China*

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ABSTRACT

Fetal exposure to multiple organic contaminants (OCs) is a public concern because of the adverse effects of OCs on early life development. Infant hair has the potential to be used as an alternative matrix to identify susceptible fetuses, owing to its reliability, sensitivity, and advantages associated with sampling, handling, and ethics. However, the applicability of infant hair for assessing in utero exposure to OCs is still limited. In this study, 57 infant hair samples were collected in Guangzhou, South China, to evaluate the levels and compositions of typical OCs in the fetus. Most of the target OCs were detected in infant hair, with medians of 144 μg/g, 17.7 μg/g, 192 ng/g, 46.9 ng/g, and 1.36 ng/g for phthalate esters (PAEs), alternative plasticizers (APs), organophosphorus flame retardants (OPFRs), polybrominated diphenyl ethers (PBDEs), and organochlorine pesticides (OCPs), respectively. Meanwhile, paired maternal hair (0–9 cm from the scalp) was collected to examine the associations between maternal and infant hair for individual compounds. Low-brominated PBDEs tended to deposit in infant hair, with median concentrations approximately two times higher than those in maternal samples. Levels of PBDEs and 4,4′-dichlorodiphenyldichloroethylene (p,p’-DDE) in paired maternal and infant hair showed strong positive correlations ($p < 0.05$), while most plasticizers (PAEs and APs) were poorly correlated between paired hair samples. Exposure sources were responsible for the variation in correlation between OC levels in the paired infant and maternal samples. Crude relationships between fetal exposure to OCs and birth size were examined using the Bayesian kernel machine regression (BKMR) model. BDE-28 was found to be adversely associated with the birth size. This study provides referential information for evaluating in utero exposure to OCs and their health risks based on infant hair.

Abbreviations: APs, alternative plasticizer; BKMR, Bayesian Kernel Machine Regression; β-HCH, β-hexachlorocyclohexane; BLZ, birth length Z score; BMI, body mass index; BWZ, birth weight Z score; DDT, dichlorodiphenyltrichloroethane; DEHP, bis(2-ethylhexyl)phthalate; DEHT, bis-(2-ethylhexyl) terephthalate; DMP, dimethyl phthalate; DOP, di-n-octyl phthalate; EHDPP, 2-ethylhexyl diphenyl phosphate; HCZ, head circumference Z score; IQR, interquartile range; LOD, limit of detection; LOQ, limit of quantification; OC, organic contaminant; OCP, organochlorine pesticide; OPFR, organophosphorus flame retardant; PAE, phthalate ester; PBDE, polybrominated diphenyl ether; PFAS, poly- and perfluoroalkyl substances; PIP, posterior inclusion probabilitie; SI, supporting information; TDCIPP, tris(1,3-dichloro-2-propyl) phosphate; *p,p'*-DDE, 4,4′-Dichlorodiphenyldichloroethylene; *p,p'*-DDT, 4,4′-dichlorodiphenyltrichloroethane.

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* Corresponding author. State Environmental Protection Key Laboratory of Environmental Pollution Health Risk Assessment, South China Institute of Environmental Sciences, Ministry of Environmental Protection, Guangzhou, 510655, PR China.

E-mail address: zhengjing@scies.org (J. Zheng).

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Main finding of the work

Using hair as a biomonitoring matrix to reveal fetal exposure to OCs, we found higher deposition of lower-brominated PBDEs in infant hair than that in maternal hair, and raise concerns over fetal exposure to BDE-28.

1. Introduction

Pregnant women and fetuses are highly sensitive and vulnerable to organic contaminants (OCs) as the fetal immune and metabolic systems are still in development (Barker, 2007). Although the use of legacy OCs, such as polybrominated diphenyl ethers (PBDEs) and organochlorine pesticides (OCPs), has been banned or restricted for years, environmental exposure to these chemicals will continue owing to their historically extensive applications. Previous studies have reported the extensive detection of PBDEs and OCPs in maternal and infant tissue samples and their health risks, including deficiencies in the fetal and early postnatal life periods (Yin et al., 2019; Fernandez-Cruz et al., 2020; Matovu et al., 2020). Plasticizers, including phthalate esters (PAEs) and their alternatives (i.e., alternative plasticizers, APs) and organophosphorus flame retardants (OPFRs), are widely used in various products as chemical additives and have high detection frequencies in the indoor environments of ordinary residents (Salthammer, 2020; Tang et al., 2020). Epidemiological studies have indicated that maternal exposure to PAEs and OPFRs may have adverse effects on fetal development and birth outcomes (Day et al., 2021; Yao et al., 2021). Owing to the ubiquitous presence of OCs in the environment, an increasing number of studies have focused on exposure biomonitoring and their potential adverse effects on embryonic development and growth (Jin et al., 2020; Kuiper et al., 2020; Luo et al., 2021; Ouidir et al., 2020; Wang et al., 2022; Yao et al., 2021).

Most epidemiological studies have used maternal urine to assess prenatal exposure to plasticizers and OPFRs owing to their relatively rapid elimination in human body (Marie et al., 2015; Vorkamp et al., 2020). Meanwhile, maternal blood, placenta, and cord blood are commonly used to assess prenatal exposure to PBDEs and OCPs (Yin et al., 2019; Matovu et al., 2020). However, intrauterine exposure to certain OCs, such as endocrine disruptors, generally results in long-term cumulative effects with respect to health. OC levels in maternal urine or blood samples can provide information solely regarding recent and acute exposure to OCs. Several studies have revealed that variation in the sampling time of maternal urine (Kuiper et al., 2020; Luo et al., 2021) or blood (Eryasa et al., 2019) significantly affects the comparability of the examining levels of OCs in these matrices. Besides, the cord blood and placenta may have limited applications in biomonitoring owing to the poor deposition of toxicants (Fernandez-Cruz et al., 2020). Therefore, it is essential to employ a biomonitoring matrix that provides a relatively stable long-term window of exposure, which benefits the assessment of dose-effect associations.

Hair samples are preferred as they provide a longer detection window for multiple chemicals (Appenzeller and Tsatsakis, 2012) and have advantages with respect to sampling, pretreatment, and ethical issues. Fetal follicles begin to grow at approximately eight weeks of gestation, and the hair shaft forms at approximately 24–28 weeks of gestation (Furdon and Clark, 2003). Thus, infant hair is a comprehensive terminal biological sample that can be used to directly assess fetal exposure to OCs in relation to the fetal compartment, thereby ensuring reliability and sensitivity (Wabuyele et al., 2018). Recently, infant hair has been used for biomonitoring prenatal exposure to drugs and environmental toxic metals, including mercury, lead, manganese, and arsenic, in utero (Bose-O'Reilly et al., 2020; Gareri and Koren, 2010; Pan et al., 2021; Örün, Yalçın and O. Aykut. 2021; Irizar et al., 2019; Rodrigues et al., 2015). However, limited data are available regarding the assessment of fetal exposure to OCs using infant hair. Further studies are needed to elucidate the feasibility of using infant hair as a biomonitoring matrix for in utero exposure to OC mixtures.

In the present study, infant hair samples were collected from healthy infants in Guangzhou City, South China to provide insights into in utero exposure to OC mixtures. Paired maternal hair samples (0–9 cm) were also collected to investigate the differences and correlations between the maternal and fetal body burdens of OCs, and the associated influencing factors were explored. Furthermore, the crude relationship between hair OC levels and fetal birth size was conservatively estimated. The major objective of this study was to propose infant hair as an alternative biomonitoring matrix to detect fetal OC exposure.

2. Materials and methods

2.1. Chemicals

The target analytes consisted of eight PBDE congeners, eight PAEs, eight APs, fifteen OPFRs, and ten OCPs. Detailed information regarding these analytes is provided in Table S1 of the Supporting Information (SI).

2.2. Study population

A total of 57 pairs of maternal and infant hair samples were collected 1–2 days after delivery in Guangzhou, Guangdong Province, South China, from January to March 2020. Non-dyed hair in the occipital area was excised close to the scalp. Hair samples were wrapped in aluminum foil and stored at −20 °C. Informed consent was obtained from all the participants at recruitment. This study was approved by the Ethics Committees of the Sixth Affiliated Hospital of Sun Yat-sen University. The demographic characteristics of the mothers and their infants are presented in Table 1.

2.3. Sample pretreatment and instrumental analysis

According to the average rate of hair growth of 1 cm per month (Pragst et al., 2006), maternal hair (0–9 cm) from the scalp represents approximately nine months of exposure, covering the entire period of

Table 1
Characteristics of the study population.

Characteristics	Mean ± SD	25th	50th	75th	%
Pregnant women (n = 57)					
Age (years)	29.8 ± 3.87	27	30	32	
Pre-pregnancy body mass index (kg/m^2)	20.9 ± 2.64	19.4	20.8	22.3	
Pregnancy weight gain (kg)	13.5 ± 3.59	11.5	13.0	15.3	
Gestationalage (days)	269 ± 12.0	263	272	277	
Parity					
1	30				52.7
>1	27				47.3
Smoking during pregnancy					
Never	55				96.5
Ever	2				3.5
Alcohol during pregnancy					
Never	52				91.2
Ever	5				8.8
Infants (n = 57)					
Sex					
Male	33				57.9
Female	24				42.1
Birth weight (kg)	3.02 ± 0.44	2.82	3.08	3.32	
Birth length (cm)	49.2 ± 2.26	48	49	51	
Head circumference (cm)	32.6 ± 1.14	32	33	33	

pregnancy. Prior to analysis, the hair samples were rinsed twice with warm Milli-Q water to remove external contaminants (e.g., soil particles, and dust), as reported in our previous study (Zheng et al., 2013). The pretreatment method for determining the target analytes in maternal and infant hair samples was based on the methodology described in our previous study (Tang et al., 2022), with minor modifications, and is described in detail in the SI. Detailed information on the instrumental analysis parameters is provided in the SI.

2.4. Quality assurance and control

The analytical protocol for OCs in hair was validated by analyses of spiked native standards in the matrix (a homogeneous hair sample) at low (10 ng of each chemical) and high (100 ng of each chemical) levels. The recoveries were 73–103% for PBDEs, 69–118% for OPFRs, 75–111% for PAEs, 63–97% for APs, and 87–105% for OCPs for the low-spiked group (n = 3), and 74–120% for PBDEs, 69–114% for OPFRs, 63–121% for PAEs, 63–125% for APs, and 88–103% for OCPs for the high-spiked matrices (n = 3). Instrumental quality control was performed by the regular injection of solvent blanks and mixture of standard solutions. Standard solutions were injected after every 12 hair samples, with inter- and intra-daily relative standard deviations less than 15%, to ensure consistency in the analysis of target chemicals. The recoveries of internal standards were in the range of 75 ± 16% to 102 ± 15% in infant hair samples and 82 ± 12% to 97 ± 19% in maternal hair samples. Detailed information on the recovery of each compound is provided in the SI.

Procedural blank samples were analyzed in parallel with each batch of hair samples to adjust for potential background contamination by the target chemicals. The mean OC levels measured in procedural blanks were subtracted from the sample results. The limits of quantification (LOQs) were estimated as the average levels of target analytes in the procedural blanks plus three times the standard deviation (Tang et al., 2021; Zheng et al., 2015). For chemicals not detected in the procedural blanks, the LOQs were calculated as signal-to-noise ratios of 10. The LOQs for PBDEs, PAEs, APs, OPFRs, and OCPs in hair were in the range of 0.06–0.98, 2.44–758, 6.15–340, 0.04–112, and 0.01–0.21 ng/g, respectively (Table S1).

2.5. Statistical analysis

Hair OC concentrations below the LOD were imputed using LOD/2 for statistical analysis. OCs detected in <50% of samples were not included in the statistical analysis. All OC concentrations were log-transformed to satisfy the requirements for normally distributed residuals. The newborn size calculator from the INTERGROWTH-21st Project was used to calculate the Z scores for gestational age using the following parameters: birth weight Z score (BWZ), birth length Z score (BLZ), and head circumference Z score (HCZ). The correlations among log-transformed OC levels were estimated by calculating the partial (two-tailed) correlation coefficients (*r*), adjusted for maternal age (years, continuous), pre-pregnancy body mass index (BMI) (kg/m^2, continuous), parity (continuous), pregnancy weight gain (kg, continuous), gestational age (days, continuous), and infant sex (male or female). A two-tailed significant p-value was set at 0.05. Considering the possible non-additive and nonlinear associations between OC mixtures and birth size, Bayesian kernel machine regression (BKMR) (Bobb et al., 2015) was implemented to examine the overall association between OC mixture exposure and each of the three birth size Z scores (BWZ, BLZ, and HCZ), and the relative importance of each OC. A series of sensitivity analyses was also performed to investigate the robustness of the primary mixture model. Detailed information for the statistical analysis using the mixture model is provided in the SI. A power analysis was performed to estimate the statistical analysis power of this study, and the results indicated that the sample size met the relevant statistical requirements. A recommended value of effect size of 0.35 was selected according to Cohen's criteria for a large effect size in the linear model (Cohen, 1988). All statistical analyses were performed using the R software version 4.1.0. BKMR models were implemented with the "bkmr" (version 0.2.2) R packages. Power analysis was implemented with the "pwr" (version 1.3–0) R packages.

3. Results and discussion

3.1. OCs in infant and maternal hair

The detection frequency and concentrations of OCs analyzed in 57 infant hair samples are listed in Table S2 and shown in Fig. 1.

The interquartile range (IQR) of ∑PAEs in infant hair was 58.0–292 μg/g (median: 144 μg/g), of which bis(2-ethylhexyl) phthalate (DEHP) showed the highest concentrations, with a median of 49.1 μg/g. The IQR of ∑APs in infant hair ranged from 10.5 to 73.6 μg/g (median: 17.7 μg/g), and bis-(2-ethylhexyl) terephthalate (DEHT) was the predominant AP with a median of 10.2 μg/g. The IQR of ∑OPFRs in infant hair was 45.3–396 ng/g (median: 192 ng/g); 2-ethylhexyl diphenyl phosphate (EHDPP) dominated OPFRs in infant hair with a median of 29.8 ng/g. Few studies have reported plasticizers and OPFR levels in maternal and infant tissues because most of these chemicals are readily metabolized *in vivo* and excreted via urine (Huang et al., 2021; Luo et al., 2020; Luo et al., 2021). However, the residuals of these two types of chemicals can still be detected in human serum or blood (Huang et al., 2014; Koch et al., 2005; Wang et al., 2021; Zhang et al., 2009; Zhao et al., 2017) and can be transported through the human placenta with high transplacental efficiencies (Li et al., 2018; Wang et al., 2021; Zhao et al., 2017). Considering the frequent detection of PAEs, APs, and OPFRs in infant hair in the present study, it can be inferred that infant hair can capture

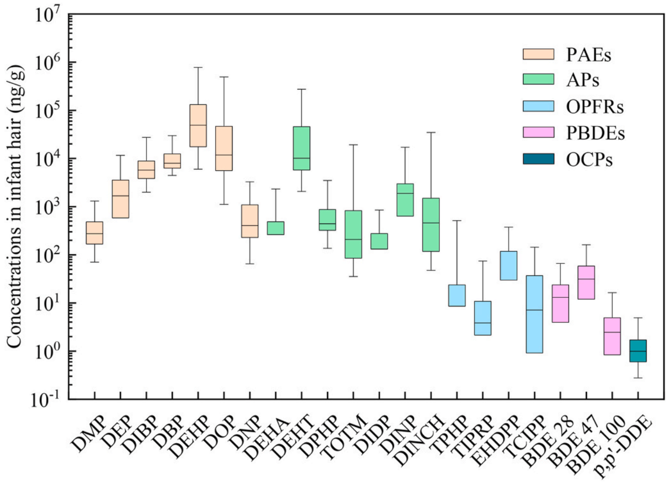

Fig. 1. Concentrations of OCs detected with DFs >70% in the infant hair samples. The upper and lower bounds of the boxes indicate the 75th and 25th percentiles, respectively; the horizontal lines within the boxes indicate median values; the upper and lower limits of the whiskers indicate the 95th and 5th percentiles, respectively. Abbreviations: AP, alternative plasticizers; BDE-28, 2,4,4′-tribromodiphenyl ether; BDE-47, 2,2′,4,4′-tetrabromodiphenyl ether; BDE-100, 2,2′,4,4′,6-pentabromodiphenyl ether; DBP, di-n-butyl phthalate; DEP, diethyl phthalate; DEHA, bis-(2-ethylhexyl) adipate; DEHP, bis(2-ethylhexyl)phthalate; DEHT, bis-(2-ethylhexyl) terephthalate; DIBP, di-iso-butyl phthalate; DIDP, di-iso decyl phthalate; DINCH, 1,2-cyclohexane dicarboxylic acid diisononyl ester; DINP, di-iso nonyl phthalate; DMP, dimethyl phthalate; DNP, dinonyl phthalate; DOP, di-n-octyl phthalate; DPHP, di-(2-propyl heptyl) phthalate; EHDPP, 2-ethylhexyl diphenyl phosphate; OC, organic contaminants; OCP, organochlorine pesticide; OPFR, organophosphorus flame retardant; PAE, phthalate ester; PBDE, polybrominated diphenyl ether; p,p'-DDE, 4,4′-dichlorodiphenyldichloroethylene; TCIPP, tris(2-chloropropyl) phosphate; TIPRP, triisopropyl phosphate; TOTM, tris (2-ethylhexyl) trimetallite; TPHP, triphenyl phosphate.

sporadic exposure to these chemicals with a short half-life. Moreover, continuous exposure to high levels of these chemicals in indoor environments is conducive to their accumulation in utero and deposition in infant hair. DEHT was also the predominant chemical among indoor dust samples from mothers' homes during pregnancy (Hou et al., 2022). Although PAEs still dominate the plasticizer market, increasing AP levels have been observed in indoor dust samples from ordinary residents in Guangzhou (Tang et al., 2020), and their potential environmental pollution and health effects cannot be ignored.

The IQR of $\sum$PBDE in infant hair ranged between 17.4 and 90.6 ng/g (median: 46.9 ng/g). To date, only one study has investigated PBDE levels (0.038–1.01 ng/g) in infant hair ($n = 12$), which were much lower than those in the present study (Aleksa et al., 2012). Moreover, BDE-153 dominated PBDE congeners in infant hair in that study (Aleksa et al., 2012), which was different from the results observed in the present study, with BDE-47 as the major PBDE congener. BDE-47 and -153 have been detected as the dominant congeners in fetal blood collected from Guangzhou in 2006 (Bi et al., 2006). However, several recent studies reported that BDE-47 was the predominant PBDE congener in the meconium (Fernandez-Cruz et al., 2020; Katsikantami et al., 2016) and neonatal urine (Chen et al., 2014), which was consistent with the PBDE compositions found in infant hair in the present study. The difference in the major PBDE found between the present study and the previous study implies a shift in maternal exposure routes to PBDEs. BDE-47 is a major metabolite of BDE-209 in aquatic organisms (e.g., fish) (Roberts et al., 2011) and was found to be the dominant congener in foods with high lipid/fat content (such as fish, chicken, and eggs) (Cai et al., 2018; Hao et al., 2014; Meng et al., 2008), which may be a crucial exposure source for pregnant women and their fetuses. BDE-153 showed the longest residence among PBDE congeners in the human body, with an estimated half-life of 12 years, whereas BDE-47 has a shorter half-life of 3 years (Geyer et al., 2004). Therefore, it can be hypothesized that the dominant BDE-153 in fetal hair (Aleksa et al., 2012) and blood collected decades ago (Bi et al., 2006) was mainly derived from maternal *in vivo* biotransformation of high-brominated PBDEs through external exposure pathways. In the present study, BDE-47 was the dominant congener in the infant hair, probably because of the maternal consumption of aquatic foods with high levels of BDE-47 (i.e., fish).

The IQR of $\sum$OCPs in infant hair was 0.80–2.64 ng/g (median: 1.36 ng/g), of which 4,4′-dichlorodiphenyldichloroethylene (p, p`-DDE) showed the highest concentrations, with a median of 1.00 ng/g. According to previous studies, p,p′-DDE and β-hexachlorocyclohexane (*β*-HCH) are the most abundant OCPs worldwide (Gaspar et al., 2017), and both have been widely detected in cord blood (Choi et al., 2018; Wang et al., 2022) and meconium (Fernandez-Cruz et al., 2020; Jeong et al., 2016), which is consistent with the detection of these two OCPs in infant hair in the present study. The widespread occurrence of these legacy OCs in infant hair indicates their continuous exposure to humans and the need for constant attention to their health effects on early-life development.

The IQRs of $\sum$PAEs, $\sum$APs, $\sum$OPFRs, $\sum$PBDEs, and $\sum$OCPs in maternal hair were 37.7–78.9 μg/g (median: 59.5 μg/g), 6.25–23.5 μg/g (median: 11.4 μg/g), 155–1170 ng/g (median: 455 ng/g), 1.25–5.25 ng/g (median: 2.26 ng/g), and 2.63–11.3 ng/g (median: 6.26 ng/g), respectively (Table S2). Similar to the OC compositions in infant hair, DEHP, DEHT, and *p, p*'-DDE were the most abundant chemicals for PAEs, APs, and OCPs in maternal hair, respectively. Tris(1,3-dichloro-2-propyl) phosphate (TDCIPP) was the dominant OPFR in maternal hair, and BDE-209 (accounting for 44% of the total PBDE) was the dominant PBDE congener in maternal hair, followed by BDE-47 (25%) and −28 (23%), which were different from those in infant hair.

3.2. *Differences and correlations between maternal and infant hair OCs*

The prevalence of target OCs measured in infant hair samples in this study confirmed that these OCs can lead to fetal exposure and accumulation in the intrauterine environment through maternal-fetal transmission. Paired maternal hair (0–9 cm) was collected to examine the association between maternal and infant hairs for compounds (Table S2). Previous studies have compared maternal and infant hair at the chemical level to investigate fetal accumulation and found that the levels of cortisol and cortisone were all markedly higher in infant hair compared with those in the maternal hair (Hollanders et al., 2017; (Stoye et al., 2021)). However, there are still limited details regarding the quantity of infant and maternal hair, which are needed to better interpret the comparisons. For example, infant hair is thinner and more porous than that of adults (Wang and Drummer, 2015). Additionally, we counted the numbers of hair strands in 0.01 g infant hair (approximately 2 cm) and maternal hair (0–9 cm), and found them to be 511 ± 58 and 39 ± 10, respectively, which indicated that there are over 10 times as many infant hairs as maternal hairs of the same weight. Thus, the difference in density between infant and maternal hair may lead to ambiguity in OC levels based on hair weight (i.e., ng/g).

Given that all hair follicles are formed prenatally and new ones are no longer produced postnatally, maternal and infant hair have the same hair follicle initiation and structural development (Gareri and Koren, 2010). Based on this, we assumed that exposure to compounds during pregnancy can be reflected by the total amount of compounds in all hair grown during pregnancy, corresponding to the 0–9 cm portion of maternal hair and the whole strand of infant hair. Thus, the OC levels were converted to pg per hair strand (pg/h, Table S3) to explore the deposition of OCs in infant hair relative to maternal hair. Higher deposition of BDE-28 and -47 was found in infant hair, with median concentrations (pg/h) approximately double higher than those in paired maternal hair (Table S3). Correlation analysis results also suggested chemical-dependent in utero exposure and accumulation, with only five chemicals, BDE-47 ($r = 0.363$, $p = 0.009$), *p,p*'-DDE ($r = 0.397$, $p = 0.004$), DEHP ($r = 0.559$, $p < 0.001$), di-n-octyl phthalate (DOP) ($r = 0.334$, $p = 0.017$), and dimethyl phthalate (DMP) ($r = 0.303$, $p = 0.031$) exhibiting positive correlations between maternal and infant hair (Table S4).

Different exposure sources for maternal and infant hair can be proposed to explain the variation in distribution and general lack of correlation for OCs between maternal and infant hair. Although hair was rinsed twice with Milli-Q water to remove dirt (e.g., dander, grease, dust, etc.) from the hair surface, OCs from exogenous sources (e.g., air and dust) can be incorporated into the growing hair shaft (Qiao et al., 2019). For example, BDE-209 was detected in ≥75% of maternal hair samples; however, it was rarely detected in infant hair samples. In dust samples collected from mothers' homes during pregnancy, only BDE-209 was detected at concentrations at μg/g levels (Hou et al., 2022). BDE-209 in maternal hair may originate from external contamination, including dust. Thus, maternal hair OCs indicate the integration of internal body burden (maternal blood) and external contamination (e.g., air and dust), which could only reflect prenatal exposure to the parent and the environment. In contrast, infant hair OCs are assumed to be endogenously derived during pregnancy from three main sources: 1) fetal circulation, which brings both maternally and fetally unmetabolized OCs to the germinal cells of the hair follicle, 2) steady exchange with amniotic fluid, 3) and fetal metabolism.

Low-brominated PBDEs and DDTs in maternal hair are considered to be deposited through food intake (Wu et al., 2020) and less affected by external sources because of the low detection frequencies in environmental samples (Hou et al., 2022). Therefore, these lipophilic OC levels in infant hair are overall influenced by their levels in the mother. A possible cause for the high levels of low-brominated PBDEs in infant hair is that lower-brominated PBDEs (i.e., BDE-28, -99, and −47) are more likely to pass through the placenta into infants than higher-brominated congeners (i.e., BDE-153 and -209) (Chen et al., 2014; Frederiksen et al., 2010; Zhao et al., 2013). Consistently, low-brominated congeners, including BDE-28, -47, and −100, were detected at higher frequencies and levels than those of high-brominated congeners in infant hair.

Correlation analysis of PBDEs and DDTs between maternal and infant hair was performed to further evaluate their accumulation in infant hair. Positive correlations were found among BDE-28, -47, and −100 in infant hair ($r = 0.692$–0.986, $p < 0.001$, Table 2), implying potentially similar exposure sources and toxicokinetics. Moreover, BDE-28 and -47 in infant hair were positively correlated with BDE-47 and 209 in maternal hair ($r = 0.363$–0.421, $p < 0.05$, Table 2). These results imply that continuous maternal exposure to PBDEs during pregnancy is an important source of low-brominated PBDEs in infant hair. For DDTs, we found positive correlations for *p,p'*-DDE between paired infant and maternal hair ($r = 0.397$, $p = 0.004$) but no correlation between *p,p'*-DDE in infant hair and *p,p'*-DDT in maternal hair (Table 3). These results suggest that *p,p'*-DDE in infant hair originates from the predominated maternal-fetal transmission of *p,p'*-DDE rather than the maternal metabolism of *p,p'*-DDT.

Between developmental weeks 24–28, fetal follicles enter the catagen phase, followed by telogen stages, and then shed to undergo their second life cycle (Gareri and Koren, 2010). Consequently, infant hair OC levels in full-term neonates are thought to provide an index of OC exposure from week 28 of pregnancy to birth (roughly in the last trimester). However, the observed positive correlations of PBDEs and DDTs between maternal and infant hair may support the hypothesis that the detection window reflected by the infant hair sample potentially encompasses a longer period of pregnancy, since 9-cm of maternal hair is considered to cover the entire period of pregnancy. Previous studies have reported that contaminants can pass through the placenta and cause fetal exposure during early pregnancy (Zhao et al., 2017; Li et al., 2018). During early pregnancy, the limited elimination capacity of OCs in the fetus may be conducive to the accumulation of OCs in the fetus and fewer barriers to the diffusion of OCs from fetal blood to the germinal cells (Foster et al., 2011; Zhao et al., 2017). Moreover, constant exposure to amniotic fluid helps and promotes the diffusion of substances into the infant hair matrix (Ramírez Fernández et al., 2022). Therefore, infant hair may retain contaminants in fetal circulation and amniotic fluid during the intact pregnancy exposure period. Data from additional biomonitoring studies and evidence from *in vitro* and *in vivo* investigations are required to better elucidate the detection window of infant hair.

In general, infant hair can provide long-term exposure information for low-brominated PBDEs and *p,p'*-DDE, which is positively associated with maternal hair. Given the limited data on paired maternal and infant hair thus far, the knowledge gaps regarding hair quantity required for comparison, and the recognition of factors that influence the deposition of OCs in infant hair, it is essential to examine whether maternal and infant hair can be used interchangeably to evaluate long-term OC exposure in newborns. Our findings regarding the occurrence, distribution, and accumulation trends of OCs in paired maternal and infant hair represent an initial step in understanding these complex relationships. The higher deposition of low-brominated PBDEs (i.e., BDE-28, -47, and −100) in infant hair than maternal hair indicates that the fetus experienced a high level of exposure, a fact that requires further attention.

Table 2

Partial correlation of log-transformed PBDE concentrations between paired infant and maternal hair.

		BDE-28 [a]	BDE-47 [a]	BDE-100 [a]	BDE-28 [b]	BDE-47 [b]	BDE-209 [b]
BDE-28 [a]	*r*	1.000			.107	378**	.421**
	p				.455	.006	.002
BDE-47 [a]	*r*	.986**	1.000		.068	.363**	.395**
	p	<.001			.636	.009	.004
BDE-100 [a]	*r*	.704**	.692**	1.000	−.055	.183	.388**
	p	<.001	<.001		.702	.200	.005

Partial correlation was adjusted for maternal age, pre-pregnancy body mass index, parity, pregnancy weight gain, gestational age and infant gender. Abbreviations: BDE-28, 2,4,4′-tribromodiphenyl ether; BDE-47, 2,2′,4,4′-tetrabromodiphenyl ether; BDE-100, 2,2′,4,4′,6-Pentabromodiphenyl ether; BDE-209, decabromodiphenyl ether; PBDE, polybrominated diphenyl ether.

**Correlation is significant at the 0.01 level (2-tailed).

[a] Infant hair.

[b] Maternal hair (0–9 cm).

Table 3

Partial correlation of log-transformed DDT concentrations between paired infant and maternal hair.

		p,p'-DDE [a]	p,p'-DDE [b]	p,p'-DDT [b]
p,p'-DDE [a]	*r*	1.000		
	p	.		
p,p'-DDE[b]	*r*	.397**	1.000	
	p	.004	.	
p,p'-DDT[b]	*r*	.168	.484**	1.000
	p	.240	<.001	.

Partial correlation was adjusted for maternal age, pre-pregnancy body mass index, parity, pregnancy weight gain, gestational age and infant gender. Abbreviations: p,p'-DDE, 4,4′-dichlorodiphenyldichloroethylene; p,p'-DDT, 4,4′-dichlorodiphenyltrichloroethane.

**Correlation is significant at the 0.01 level (2-tailed).

[a] Infant hair.

[b] Maternal hair (0–9 cm).

3.3. *Crude relationships between fetal exposure to OCs and birth size*

Although BWZ, BLZ, and HCZ are not specific for fetal dysfunction or disease, these parameters have been promoted as early markers of alterations in fetal development (Luo et al., 2021; Wang et al., 2022). We examined the relationship between OC levels in infant hair and birth size parameters to assess the possible joint effects of OC exposure on fetal development. The results of the BKMR model showed no significant cumulative associations between overall OC mixtures and birth size Z-scores (Fig. S3). BDE-28 in infant hair exhibited a major negative effect on birth size Z-scores when other OCs were set at the 25th, 50th, and 75th percentiles (Fig. S4). The posterior inclusion probabilities (PIPs) ranked BDE-28 (conditional-PIP: 0.554) in infant hair the highest with respect to the inverse association with HCZ (Table S4). These results are robust to sensitivity analyses (detailed descriptions are provided in the SI).

In the present study, high concentrations of BDE-28 in infant hair were associated with lower birth sizes. This result agrees with that of most epidemiological studies in humans that revealed that higher PBDE levels in the plasma (Ouidir et al., 2020), serum (Eick et al., 2020), colostrum (Jin et al., 2020), and dried blood spots (Bell et al., 2019) are generally associated with low birth sizes. Consistent correlations were obtained in different studies using a variety of biomonitoring matrices, probably because of the long half-life of low-brominated PBDEs in available biological matrices. Human Early-Life Exposome is a particularly important period for studying the causes of disease (Vrijheid et al., 2021), and hair analysis can retrospectively reflect the exposure characteristics and potential health effects of OCs in the corresponding time period (Qiao et al., 2019), which provides a solution to the uncertainty of exposure biomonitoring.

Since the time of PBDEs restriction in the electronics industry in China, the concentrations of certain PBDEs in environmental and human samples have declined (Tang et al., 2022). While the levels may have dropped, PBDEs remain ubiquitously present in pregnant women and might affect fetal development, as fetuses are sensitive to even very low doses of xenobiotics (Fernandez-Cruz et al., 2020; Matovu et al., 2020). However, it should be noted that this study was a preliminary exploration of the crude relationship between hair OC levels and birth sizes, owing to the relatively small sample size.

It should be noted that the present study had several limitations. First, owing to missing data, adjustment for dietary intake for exposure to OCs was not available. Aquatic products are major exposure sources of BDE-47, as well as nutrients that promote fetal growth; thus, fish and seafood consumption by pregnant women would induce bias with respect to the association between BDE-47 and birth sizes. Meanwhile, these data are useful in the source analysis of BDE-47 in maternal and infant hair. Second, we cannot rule out the possibility of flame retardants and plasticizers due to the influence of infant hair collection devices, although the effect may be negligible if it occurs. Third, there is a lack of discussion on critical processes in maternal-fetal transmission and their effect on the deposition of OCs in infant hair due to the absence of maternal internal exposure data (such as OC levels in the blood and amniotic fluid). An additional consideration is that several other groups of OCs may also impact fetal growth, such as poly- and perfluoroalkyl substances (PFAS), bisphenol A, and pesticides, but were excluded from our study because of the low sample volume and lack of separate pretreatment methods, especially for infant hair. Finally, the sample size was modest for the exposure study, but small for the regression analysis. The relatively small sample size limits further interpretation of the effects on fetal development and the analysis of the demographic impact on OC levels in hair. Larger sample sizes and more accurate analysis methods in future studies would allow for a deeper investigation of the potential health effects of OCs as revealed by infant hair.

4. Conclusions

For the first time, we analyzed fetal exposure to OCs using infant hair as the biomonitoring matrix. Infant hair can provide long-term exposure information for low-brominated and *p,p*'-DDE, which is positively associated with maternal hair. Low-brominated PBDEs had higher deposition in infant hair and were associated with lower birth size. The results of the present study indicated that infant hair has advantages with respect to providing an index of in-utero exposure to OC mixtures and raise concerns over fetal exposure to these chemicals. However, more studies encompassing the OC deposition process in infant hair and larger sample sizes are needed to further investigate the feasibility of using infant hair to evaluate fetal exposure to OCs.

Credit author statement

Feng-Shan Cai: Methodology, Writing - Original Draft, **Bin Tang**: Methodology, Writing - Review & Editing, **Jing Zheng:** Conceptualization, Funding acquisition, Project administration, Supervision, Writing - Review & Editing, **Xiao Yan:** Validation, Writing - Review & Editing, **Wei-Keng Luo:** Software, Visualization, Writing - Review & Editing, **Mian He:** Software, Formal analysis, Writing - Review & Editing, **Xiao-Jun Luo:** Formal analysis, Writing - Review & Editing, **Ming-Zhong Ren:** Resources, Formal analysis, Writing - Review & Editing, **Yun-Jiang Yu:** Resources, Funding acquisition, Writing - Review & Editing, **Bi-Xian Mai:** Supervision, Writing - Review & Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

Aleksa, K., Carnevale, A., Goodyer, C., Koren, G., 2012. Detection of polybrominated biphenyl ethers (PBDEs) in pediatric hair as a tool for determining in utero exposure. Forensic Sci. Int. 218 (1–3), 37–43.

Appenzeller, B.M.R., Tsatsakis, A.M., 2012. Hair analysis for biomonitoring of environmental and occupational exposure to organic pollutants: state of the art, critical review and future needs. Toxicol. Lett. 210 (2), 119–140.

Barker, D.J.P., 2007. The origins of the developmental origins theory. J. Intern. Med. 261 (5), 412–417.

Bell, G.A., Perkins, N., Louis, G.M.B., Kannan, K., Bell, E.M., Gao, C., Yeung, E.H., 2019. Exposure to persistent organic pollutants and birth characteristics the upstate KIDS study. Epidemiology 30 (2), S94–S100.

Bi, X., Qu, W., Sheng, G., Zhang, W., Mai, B., Chen, D., Yu, L., Fu, J., 2006. Polybrominated diphenyl ethers in South China maternal and fetal blood and breast milk. Environ. Pollut. 144 (3), 1024–1030.

Bobb, J.F., Valeri, L., Claus, H.B., et al., 2015. Bayesian kernel machine regression for estimating the health effects of multipollutant mixtures. Biostat. 16, 493–508.

Bose-O'Reilly, S., Lettmeier, B., Shoko, D., Roider, G., Drasch, G., Siebert, U., 2020. Infants and mothers levels of mercury in breast milk, urine and hair, data from an artisanal and small-scale gold mining area in Kadoma/Zimbabwe. Environ. Res. 184, 109266.

Cai, Y.-M., Ren, G.-F., Lin, Z., Sheng, G.-Y., Bi, X.-H., Sun, S.-Y., 2018. Assessment of exposure to polybrominated diphenyl ethers associated with consumption of market hens in Guangzhou. Ecotoxicol. Environ. Saf. 153, 40–44.

Chen, Z.-J., Liu, H.-Y., Cheng, Z., Man, Y.-B., Zhang, K.-S., Wei, W., Du, J., Wong, M.-H., Wang, H.-S., 2014. Polybrominated diphenyl ethers (PBDEs) in human samples of mother–newborn pairs in South China and their placental transfer characteristics. Environ. Int. 73, 77–84.

Choi, S., Kim, H.-j., Kim, S., Choi, G., Kim, S., Park, J., Shim, S.-s., Lee, I., Kim, S., Moon, H.-B., Choi, K., Lee, J.J., Kim, S.Y., 2018. Current status of organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) exposure among mothers and their babies of Korea-CHECK cohort study. Sci. Total Environ. 618, 674–681.

Cohen, J., 1988. Statistical Power Analysis for the Behavioral Sciences, second ed. Lawrence Erlbaum, Hillsdale, NJ.

Day, D.B., Collett, B.R., Barrett, E.S., Bush, N.R., Swan, S.H., Nguyen, R.H.N., Szpiro, A. A., Sathyanarayana, S., 2021. Phthalate mixtures in pregnancy, autistic traits, and adverse childhood behavioral outcomes. Environ. Int. 147.

Eick, S.M., Hom Thepaksorn, E.K., Izano, M.A., Cushing, L.J., Wang, Y., Smith, S.C., Gao, S., Park, J.-S., Padula, A.M., DeMicco, E., Valeri, L., Woodruff, T.J., Morello-Frosch, R., 2020. Associations between prenatal maternal exposure to per- and polyfluoroalkyl substances (PFAS) and polybrominated diphenyl ethers (PBDEs) and birth outcomes among pregnant women in San Francisco. Environ. Health 19, 100.

Eryasa, B., Grandjean, P., Nielsen, F., Valvi, D., Zmirou-Navier, D., Sunderland, E., Weihe, P., Oulhote, Y., 2019. Physico-chemical properties and gestational diabetes predict transplacental transfer and partitioning of perfluoroalkyl substances. Environ. Int. 130.

Fernandez-Cruz, T., Alvarez-Silvares, E., Dominguez-Vigo, P., Simal-Gandara, J., Martinez-Carballo, E., 2020. Prenatal exposure to organic pollutants in northwestern Spain using non-invasive matrices (placenta and meconium). Sci. Total Environ. 731.

Foster, W.G., Gregorovich, S., Morrison, K.M., Atkinson, S.A., Kubwabo, C., Stewart, B., Teo, K., 2011. Human maternal and umbilical cord blood concentrations of polybrominated diphenyl ethers. Chemosphere 84 (10), 1301–1309.

Frederiksen, M., Thomsen, C., Froshaug, M., Vorkamp, K., Thomsen, M., Becher, G., Knudsen, L.E., 2010. Polybrominated diphenyl ethers in paired samples of maternal and umbilical cord blood plasma and associations with house dust in a Danish cohort. Int. J. Hyg Environ. Health 213 (4), 233–242.

Furdon, S.A., Clark, D.A., 2003. Scalp hair characteristics in the newborn infant. Adv. Neonatal Care: official journal of the National Association of Neonatal Nurses 3 (6), 286–296.

Gareri, J., Koren, G., 2010. Prenatal hair development: implications for drug exposure determination. Forensic Sci. Int. 196 (1–3), 27–31.

Gaspar, F.W., Chevrier, J., Quiros-Alcala, L., Lipsitt, J.M., Barr, D.B., Holland, N., Bornman, R., Eskenazi, B., 2017. Levels and determinants of DDT and DDE exposure in the VHEMBE cohort. Environ. Health Perspect. 125 (7).

Geyer, H.J., Schramm, K.W., Per, O., Darnerud, Mcdonald, T.A., 2004. Terminal elimination half-lives of the brominated flame retardants TBBPA, HBCD, and lower brominated PBDEs in humans. Organohalogen Compd. 66, 3820–3825.

Hao, Q., Sun, Y.-X., Xu, X.-R., Yao, Z.-W., Wang, Y.-S., Zhang, Z.-W., Luo, X.-J., Mai, B.-X., 2014. Occurrence of persistent organic pollutants in marine fish from the Natuna Island, South China Sea. Mar. Pollut. Bull. 85 (1), 274–279.

Hollanders, J.J., van der Voorn, B., Kieviet, N., Dolman, K.M., de Rijke, Y, B., van den Akker, E.L.T., Rotteveel, J., Honig, A., Finken, M.J.J., 2017. Interpretation of glucocorticoids in neonatal hair: a reflection of intrauterine glucocorticoid regulation? Endocr. Connect. 6, 692–699.

Hou, Y., Tang, B., Cai, F.-s., Yan, X., Zheng, J., Wang, J.-l., Zhang, H., 2022. Legacy and novel flame retardants and plasticizers in indoor dust from residents' homes in Guangzhou: pollution status and human exposure assessment. Acta Sci. Circumstantiae. https://doi.org/10.13671/j.hjkxxb.2021.0584 (in Chinese).

Huang, Y., Li, J., Garcia, J.M., Lin, H., Wang, Y., Yan, P., Wang, L., Tan, Y., Luo, J., Qiu, Z., Chen, J.-a., Shu, W., 2014. Phthalate levels in cord blood are associated with preterm delivery and fetal growth parameters in Chinese women. PLoS One 9 (2).

Huang, S., Qi, Z., Ma, S., Li, G., Long, C., Yu, Y., 2021. A critical review on human internal exposure of phthalate metabolites and the associated health risks. Environ. Pollut. 279.

Irizar, A., Gil, F., Lertxundi, A., Martin-Domingo, M.C., Urbieta, N., Molinuevo, A., Ibarluzea, J., Basterrechea, M., Aurrekoetxea, J.J., Jimenez-Zabala, A., Santa-Marina, L., 2019. Manganese levels in newborns' hair by maternal sociodemographic, dietary and environmental factors. Environ. Res. 170, 92–100.

Jeong, Y., Lee, S., Kim, S., Choi, S.-D., Park, J., Kim, H.-J., Lee, J.J., Choi, G., Choi, S., Kim, S., Kim, S.Y., Kim, Y.D., Cho, G., Suh, E., Kim, S.K., Eun, S.-H., Eom, S., Kim, S., Kim, G.-H., Kim, S., Choi, K., Moon, H.-B., 2016. Occurrence and prenatal exposure to persistent organic pollutants using meconium in Korea: feasibility of meconium as a non-invasive human matrix. Environ. Res. 147, 8–15.

Jin, Y., Li, J., Deng, X., Xia, B., Song, Q., Zhao, Y., He, X., Li, Y., Xu, Z., Xie, A., Lin, J., Zhang, Y., Chen, S., 2020. Association between fetal growth restriction and maternal exposure to polybrominated diphenyl ethers. Ecotoxicol. Environ. Saf. 198, 110623.

Katsikantami, I., Sifakis, S., Tzatzarakis, M.N., Vakonaki, E., Kalantzi, O.-I., Tsatsakis, A. M., Rizos, A.K., 2016. A global assessment of phthalates burden and related links to health effects. Environ. Int. 97, 212–236.

Koch, H.M., Bolt, H.M., Preuss, R., Angerer, J., 2005. New metabolites of di (2-ethylhexyl) phthalate (DEHP) in human urine and serum after single oral doses of deuterium-labelled DEHP. Arch. Toxicol. 79 (7), 367–376.

Kuiper, J.R., Stapleton, H.M., Wills-Karp, M., Wang, X., Burd, I., Buckley, J.P., 2020. Predictors and reproducibility of urinary organophosphate ester metabolite concentrations during pregnancy and associations with birth outcomes in an urban population. Environ. Health 19 (1).

Li, X., Sun, H., Yao, Y., Zhao, Z., Qin, X., Duan, Y., Wang, L., 2018. Distribution of phthalate metabolites between paired maternal-fetal samples. Environ. Sci. Technol. 52 (11), 6626–6635.

Luo, D., Liu, W., Tao, Y., Wang, L., Yu, M., Hu, L., Zhou, A., Covaci, A., Xia, W., Li, Y., Xu, S., Mei, S., 2020. Prenatal exposure to organophosphate flame retardants and the risk of low birth weight: a nested case-control study in China. Environ. Sci. Technol. 54 (6), 3375–3385.

Luo, D., Liu, W., Wu, W., Tao, Y., Hu, L., Wang, L., Yu, M., Zhou, A., Covaci, A., Xia, W., Xu, S., Li, Y., Mei, S., 2021. Trimester-specific effects of maternal exposure to organophosphate flame retardants on offspring size at birth: a prospective cohort study in China. J. Hazard Mater. 406.

Marie, C., Vendittelli, F., Sauvant-Rochat, M.-P., 2015. Obstetrical outcomes and biomarkers to assess exposure to phthalates: a review. Environ. Int. 83, 116–136.

Matovu, H., Ssebugere, P., Sillanpaa, M., 2020. Prenatal exposure levels of polybrominated diphenyl ethers in mother-infant pairs and their transplacental transfer characteristics in Uganda (East Africa). Environ. Pollut. 258.

Meng, X.-Z., Yu, L., Guo, Y., Mai, B.-X., Zeng, E.Y., 2008. Congener-specific distribution of polybrominated diphenyl ethers in fish of China: implication for input sources. Environ. Toxicol. Chem. 27 (1), 67–72.

Örün, E., Yalçın, S.S., Aykut, O., 2021. Lead, mercury, and cadmium levels in breast milk and infant hair in the late period of lactation in Ankara, Turkey. Int. J. Environ. Health Res. 1–12.

Ouidir, M., Buck Louis, G.M., Kanner, J., Grantz, K.L., Zhang, C., Sundaram, R., Rahman, M.L., Lee, S., Kannan, K., Tekola-Ayele, F., Mendola, P., 2020. Association of maternal exposure to persistent organic pollutants in early pregnancy with fetal growth. JAMA Pediatr. 174 (2), 149–161.

Pan, W.K., Weinhouse, C., Ortiz, E.J., Berky, A.J., Fixsen, E., Mallipudi, A., Feingold, B.J., Navio, S., Rivera, N.A., Hsu-kim, H., Jaime Miranda, J., 2021. CoNaMad-cohorte de Nacimiento de Madre de Dios/madre de Dios birth cohort to study effects of in-utero trace metals exposure in the southern Peruvian amazon. Annals of Global Health 87 (1).

Pragst, F., Balikova, M.A., 2006. State of the art in hair analysis for detection of drug and alcohol abuse. Clin. Chim. Acta 370 (1–2), 17–49.

Qiao, L., Zheng, X.-B., Zheng, J., Chen, S.-J., Zhong, C.-Q., Chen, J.-H., Yang, Z.-Y., Mai, B.-X., 2019. Legacy and currently used organic contaminants in human hair and hand wipes of female E-waste dismantling workers and workplace dust in South China. Environ. Sci. Technol. 53 (5), 2820–2829.

Ramírez Fernández, M.M., Wille, S.M.R., Yegles, M., Samyn, N., 2022. Evaluation of decontamination procedures for drug testing in undamaged versus damaged hair. Drug Test. Anal. 1–11.

Roberts, S.C., Noyes, P.D., Gallagher, E.P., Stapleton, H.M., 2011. Species-specific differences and Structure−Activity relationships in the debromination of PBDE congeners in three fish species. Environ. Sci. Technol. 45 (5), 1999–2005.

Rodrigues, E.G., Kile, M., Dobson, C., Amarasiriwardena, C., Quamruzzaman, Q., Rahman, M., Golam, M., Christiani, D.C., 2015. Maternal-infant biomarkers of prenatal exposure to arsenic and manganese. J. Expo. Sci. Environ. Epidemiol. 25 (6), 639–648.

Salthammer, T., 2020. Emerging indoor pollutants. International journal of hygiene and. Environ. Health 224, 113423.

Stoye, D.Q., Sullivan, G., Galdi, P., Kirschbaum, C., Lamb, G.J., Black, G.S., Evans, M.J., Boardman, J.P., Reynolds, R.M., 2021. Perinatal determinants of neonatal hair glucocorticoid concentrations. Psychoneuroendocrinology 128, 105223.

Tang, B., Christia, C., Malarvannan, G., Liu, Y.-E., Luo, X.-J., Covaci, A., Mai, B.-X., Poma, G., 2020. Legacy and emerging organophosphorus flame retardants and plasticizers in indoor microenvironments from Guangzhou, South China. Environ. Int. 143, 105972.

Tang, B., Xiong, S.-M., Zheng, J., Wang, M.-H., Cai, F.-S., Luo, W.-K., Xu, R.-F., Yu, Y.-J., 2021. Analysis of polybrominated diphenyl ethers, hexabromocyclododecanes, and legacy and emerging phosphorus flame retardants in human hair. Chemosphere 262, 127807.

Tang, B., Chen, S.-J., Zheng, J., Xiong, S.-M., Yan, X., Luo, W.-K., Mai, B.-X., Yu, Y.-J., 2022. Changes in human hair levels of organic contaminants reflecting China's regulations on electronic waste recycling. Sci. Total Environ. 806.

Vorkamp, K., Castano, A., Antignac, J.-P., Boada, L.D., Cequier, E., Covaci, A., Esteban Lopez, M., Haug, L.S., Kasper-Sonnenberg, M., Koch, H.M., Perez Luzardo, O., Osite, A., Rambaud, L., Pinorini, M.-T., Sabbioni, G., Thomsen, C., 2020. Biomarkers, matrices and analytical methods targeting human exposure to chemicals selected for a European human biomonitoring initiative. Environ. Int. 146, 106082-106082.

Vrijheid, M., Basagana, X., Gonzalez, J.R., Jaddoe, V.W.V., Jensen, G., et al., 2021. Advancing tools for human early lifecourse exposome research and translation (ATHLETE). Project overview 5 (5), e166.

Wabuyele, S.L., Colby, J.M., McMillin, G.A., 2018. Detection of drug-exposed newborns. Ther. Drug Monit. 40 (2), 166–185.

Wang, X., Drummer, O.H., 2015. Review: interpretation of drug presence in the hair of children. Forensic Sci. Int. 257, 458–472.

Wang, X., Chen, P., Zhao, L., Zhu, L., Wu, F., 2021. Transplacental behaviors of organophosphate tri- and diesters based on paired human maternal and cord whole blood: efficiencies and impact factors. Environ. Sci. Technol. 55 (5), 3091–3100.

Wang, S.-S., Lu, A.-X., Cao, L.-L., Ran, X.-F., Wang, Y.-Q., Liu, C., Yan, C.-H., 2022. Effects of prenatal exposure to persistent organic pollutants on neonatal Outcomes:A mother-child cohort (Shanghai, China). Environ. Res. 203, 111767.

Wu, Z., He, C., Han, W., Song, J., Li, H., Zhang, Y., Jing, X., Wu, W., 2020. Exposure pathways, levels and toxicity of polybrominated diphenyl ethers in humans: a review. Environ. Res. 187, 109531.

Yao, Y., Li, M., Pan, L., Duan, Y., Duan, X., Li, Y., Sun, H., 2021. Exposure to organophosphate ester flame retardants and plasticizers during pregnancy: thyroid endocrine disruption and mediation role of oxidative stress. Environ. Int. 146.

Yin, S., Zhang, J., Guo, F., Zhao, L., Poma, G., Covaci, A., Liu, W., 2019. Transplacental transfer of organochlorine pesticides: concentration ratio and chiral properties. Environ. Int. 130.

Zhang, Y., Lin, L., Cao, Y., Chen, B., Zheng, L., Ge, R.-S., 2009. Phthalate levels and low birth weight: a nested case-control study of Chinese newborns. J. Pediatr. 155 (4), 500–504.

Zhao, Y., Ruan, X., Li, Y., Yan, M., Qin, Z., 2013. Polybrominated diphenyl ethers (PBDEs) in aborted human fetuses and placental transfer during the first trimester of pregnancy. Environ. Sci. Technol. 47 (11), 5939–5946.

Zhao, F., Chen, M., Gao, F., Shen, H., Hu, J., 2017. Organophosphorus flame retardants in pregnant women and their transfer to chorionic villi. Environ. Sci. Technol. 51 (11), 6489–6497.

Zheng, J., Yan, X., Chen, S.-J., Peng, X.-W., Hu, G.-C., Chen, K.-H., Luo, X.-J., Mai, B.-X., Yang, Z.-Y., 2013. Polychlorinated biphenyls in human hair at an e-waste site in China: composition profiles and chiral signatures in comparison to dust. Environ. Int. 54, 128–133.

Zheng, X.-B., Xu, F.-C., Chen, K.-H., Zeng, Y.-H., Luo, X.-J., Chen, S.-J., Mai, B.-X., Covaci, A., 2015. Flame retardants and organochlorines in indoor dust from several e-waste recycling sites in South China: composition variations and implications for human exposure. Environ. Int. 78, 1–7.