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Maternal-Child Exposures to Persistent Organic Pollutants in Dhaka, Bangladesh

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Abstract

Information about the human burdens of persistent organic pollutants (POPs) in low- and middle-income countries is limited. In particular, studies often include only a small subset of POPs. To address this data gap, we aimed to assess maternal-child exposures to POPs in Dhaka, Bangladesh. We quantified 16 organochlorine pesticides, 12 polychlorinated biphenyls, 21 brominated flame retardants, 18 per- and polyfluorinated alkyl substances, 2 polycyclic aromatic hydrocarbons, and short-chain chlorinated paraffins in 18 pooled samples of human cord blood from 90 mother–infant pairs living in Dhaka, Bangladesh (2014–2015). In all pooled samples, we detected high levels of *p*,*p*′-DDT (median 81.6 ng/g lipid) and its metabolites *p*,*p*′-DDE and *p*,*p*′-DDD (median 551 and 10.7 ng/g lipid, respectively), where the *p*,*p*′-DDE/*p*,*p*′-DDT ratio ranged from 2.9 to 9.8 indicating recent dichlorodiphenyltrichloroethane (DDT) exposure. We also detected acenaphthene, decabromodiphenyl ethane, *o*,*p*′-DDT, *o*,*p*′-DDE, hexachlorobenzene, β-hexachlorocyclohexane, hexabromobenzene, and perfluorooctanoic acid in a subset of samples. For the other 59 target compounds, concentrations were below the limits of detection, despite using ultra-trace analytical methodology. No trends were observed when stratifying the analyses of detected POP concentrations by maternal age, maternal body mass index, or large fish consumption. These findings highlight recent DDT exposure in Dhaka, but the overall POP burden was otherwise low in this sample of pregnant women/newborns. Future monitoring efforts should focus on newly detected POPs for which burdens may be increasing due to ongoing industrialization in Bangladesh.

Keywords Child exposure/health · Flame retardants · Perfluorinated chemicals · Pesticides · Polycyclic aromatic hydrocarbons · Analytical methods

Introduction

Persistent organic pollutants (POPs) are a broad class of synthetic chemicals developed for industrial, agricultural, and/or commercial applications that have known or suspected human toxicity, based on a growing body of animal and epidemiological studies (Baillie-Hamilton 2002; Di Renzo et al.

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2015; Diamanti-Kandarakis et al. 2009; Elobeid and Allison 2008; Grant et al. 2014; Liu and Peterson 2015; Loomis et al. 2015; Newbold et al. 2008; Schug et al. 2011; Tang-Péronard et al. 2011). They can last for years before degrading into less dangerous forms, travel long distances (e.g., through air, water, exported food, commercial products), and bioaccumulate in higher-order animals present in many diets, such as fish which tend to easily enrich POPs in their tissues (Geyer et al. 2000; United Nations Environmental Programme 2005). For these reasons, measures to reduce and/or eliminate the production and use of POPs were initiated in many countries from the 1970s and onwards, and international regulations like the Stockholm Convention came into place. Although these measures have led to declining human concentrations of many POPs in many high-income countries (Kong et al. 2014), there is scant knowledge of the human burden of exposures in low- and middle-income countries (LMICs), where heavy industrialization and permissive environmental regulations are widespread today.

The Organisation for Economic Co-operation and Development (OECD) has classified hazardous chemicals and waste as a 'red-light' issue (i.e., requiring urgent attention) based on their future projections of environmental trends to 2030 (OECD 2008). Academic societies and international expert workshops have called for further investments into not only the identification of pollutant exposures, but also research on their health effects (Di Renzo et al. 2015; Grandjean et al. 2015). Recent reviews and commentaries have suggested that human exposure to POPs is adversely linked with a diverse array of outcomes that span the life-course, including childhood growth and development (Di Renzo et al. 2015; Liu and Peterson 2015; Tang-Péronard et al. 2011), fertility (Di Renzo et al. 2015), pregnancy (Di Renzo et al. 2015), diabetes (Grant et al. 2014), and cancer (Loomis et al. 2015). To date, most epidemiologic studies have focused on 'legacy POPs' including the polychlorinated biphenyls (PCBs) and organochlorine pesticides (OCPs) such as dichlorodiphenyltrichloroethane (DDT), whereas other pollutant groups have not been evaluated in terms of exposure patterns or associations with disease outcomes (World Health Organization 2012), with a notable lack of data from LMICs.

Identifying the relative burden of POPs in populations will help to inform the design of future epidemiologic studies of environmental etiologies of endocrine/metabolic dysregulation and chronic disease. Thus, the specific objectives of this study were to determine the concentrations of OCPs, PCBs, brominated flame retardants (BFRs), per- and polyfluorinated alkyl substances (PFASs), polycyclic aromatic hydrocarbons (PAHs), and short-chain chlorinated paraffins (SCCPs) in umbilical cord blood from a cohort in Dhaka, Bangladesh, and to examine POP concentrations stratified by maternal age, body mass index (BMI), and large fish consumption. Here, umbilical cord blood was the preferred matrix for assessment of maternal-child exposures due to the efficiency of transplacental transmission of POPs (Butler Walker et al. 2003; Covaci et al. 2002; Mazdai et al. 2003; Needham et al. 2011); that is, cord blood concentrations would be indicative of exposures experienced by the mother, as well as by the fetus in utero, a period of particular vulnerability to POP exposures.

Materials and Methods

Study Area

This study was based on cord blood samples collected in the Maternal Vitamin D for Infant Growth (MDIG) study trial of 1300 pregnant women in Dhaka, Bangladesh, which has been previously described (Roth et al. 2015). Briefly, the MDIG trial is a randomized, placebo-controlled, dose-ranging trial of maternal vitamin D supplementation during pregnancy and lactation on infant length at 1 and 2 years of age. The trial area includes Kamrangirchar, Azimpur, Lalbagh, and Hazaribag, where most of the participants reside in Kamrangirchar—a densely populated group of urban and peri-urban communities located along the Buriganga River in Dhaka.

Participant Selection and Sample Collection

Of the 1300 pregnant women who were enrolled and actively followed throughout pregnancy in the MDIG trial, 90 were randomly selected for inclusion in this study. Umbilical cord blood collection occurred between July 2014 and October 2015, where from each participant, samples were collected at delivery and stored in 250 µl aliquots at the International Center for Diarrhoeal Disease Research, Bangladesh (icddr,b; Dhaka, Bangladesh), then shipped to the Hospital for Sick Children (Toronto, Canada) for specimen processing, and then to the Norwegian Institute for Air Research (Tromsø and Kjeller, Norway) for laboratory analyses. Specimens were shipped on dry ice and stored at − 70 °C or colder.

Analytical Methodology

All analyses were performed at the laboratories of the Norwegian Institute for Air Research (NILU). Cord serum samples were extracted and analyzed for OCPs, PCBs, BFRs, PFASs, PAHs, and SCCPs. A complete list of the individual compounds is provided in Online Resource, Table S1.

Sample Pooling

Five aliquots of 250 µl were pooled (total 1.25 ml per pool) according to selected maternal characteristics believed to influence POP concentrations (Agudo et al. 2009; Ampleman et al. 2015; Axelrad et al. 2009; Bachelet et al. 2011; James et al. 2002; Laden et al. 1999; Pavuk et al. 2014; Quinn and Wania 2012; Sjödin et al. 2014; Tee et al. 2003): maternal age, maternal BMI, and large fish consumption (Table 1). Maternal age was obtained through self-report (tertiles: 18–20, 21–25, 26–40 years), maternal BMI was calculated using maternal weight and height measured at enrolment in the second trimester of pregnancy (tertiles: < 21.5, 21.5–25.1, > 25.1 kg/m^2), and regular large fish consumption (i.e., at least once per week) was determined using data from the MDIG food frequency questionnaire administered at enrolment (Online Resource, Table S2). The primary reason for a pooled analysis was efficiency of stored biological sample use, as it reduced the serum volume requirement from each mother–child pair, allowing for a larger panel of analytes to be performed on all samples than would have been feasible had we analyzed each individual specimen separately.

Extraction and Clean Up

From each pooled sample ($n = 18$), 0.225 ml was used for PFAS extractions and the remaining 1.025 ml was used for extractions of all other POPs. The analyses employed the internal standard method for quantification and isotope labeled standards were initially added (Online Resource, Table S3). Briefly, the PFAS analyses were performed using sonication-facilitated liquid–liquid extraction in methanol and activated carbon clean up. Extraction was performed using a method that has been previously described (Hanssen et al. 2013), but with two modifications: (1) the volume methanol (1000 µl) added, and (2) the amount of branched perfluorodecanoic acid (br-PFDA) recovery standard (20 µl of 0.102 ng/µl).

For the lipid-soluble POPs, the pooled sample was extracted using a method previously described (Nøst et al. 2013). Briefly, deionized water saturated with ammonium sulfate (1 ml), methanol (2 ml), and hexane (6 ml) was added to the sample prior to vortexing and shaking for 1 h. The supernatant organic phase was pipetted off and the extraction protocol was repeated with 6 ml of hexane. The hexane supernatants were combined and evaporated to 0.2 ml in a heated vacuum evaporation unit. The vials were allowed to dry overnight, followed by weighing the next day for gravimetric lipid determination (i.e., lipid % = dry weight/wet weight * 100). The residue was resuspended with 0.6 ml hexane by vortexing, before subsequent clean up using Florisil (1 g, deactivated). The samples were eluted from Florisil columns as described previously (Nøst et al. 2013), evaporated to 0.2 ml, transferred to a GC-vial, and further reduced to ~ 30 µl by gentle nitrogen flow. Recovery standards (1,2,3,4-tetrachloronaphthalene, carbon-C^{13} labeled PCB-159, as well as deuterium labeled biphenyl-d_{10}, fluoranthene-d_{10}, perylene-d_{12}) were then added.

Instrumental Analysis

PFASs were analyzed and quantified by ultrahigh-pressure liquid chromatography triple-quadrupole mass spectrometry as previously described (Hanssen et al. 2013; Nøst et al. 2014). The instrumental details for analyses of OCPs, PCBs, BFRs using gas chromatography combined with mass spectrometry have been previously described (Nøst et al. 2013) with the adaption of a large-volume-injection method of 5 µl and the application of a 15 m GC column for DDTs and PBDE/DBDPE (decabromodiphenyl ethane), allowing for optimal sensitivity. Corresponding details for analyses of PAHs and SCCPs are presented in Online Resource, Table S4.

Table 1 Pooling scheme for umbilical cord serum samples ($n = 90$) according to maternal age, maternal body mass index (BMI), and large fish consumption

Maternal characteristics	Irregular/no large fish consumption			Regular large fish consumption		
	BMI < 21.5 kg/m^2	BMI 21.5–25.1 kg/m^2	BMI > 25.1 kg/m^2	BMI < 21.5 kg/m^2	BMI 21.5–25.1 kg/m^2	BMI > 25.1 kg/m^2
Age 18–20 years	Pool 1	Pool 2	Pool 3	Pool 10	Pool 11	Pool 12
Age 21–25 years	Pool 4	Pool 5	Pool 6	Pool 13	Pool 14	Pool 15
Age 26–40 years	Pool 7	Pool 8	Pool 9	Pool 16	Pool 17	Pool 18

Each pool is composed of five 250 µl cord blood serum aliquots (total 1.25 ml in each pool). Age was categorized into tertiles: 18–20, 21–25, and 26–40 years. BMI was categorized into tertiles: < 21.5, 21.5–25.1, > 25.1 kg/m^2. Large fish consumption was categorized into two groups: regular (at least once per week) and irregular/no consumption (less than once per week or no consumption)

Quality Assurance and Quality Control

To assess laboratory-derived sample contamination and method accuracy and reproducibility, blanks ($n=4$) and standard reference materials [SRMs 1958 ($n=4$), National Institute of Standards and Technology, Gaithersburg, MD, USA] were processed along with samples. Results for SRMs indicated analytical uncertainties within 60–102% of assigned values for PCBs, OCPs, BFRs, and within 88–120% for perfluorooctanoic acid (PFOA) and PFOS. The laboratories at the Norwegian Institute for Air Research routinely participate in the international AMAP ring test for POPs in human serum, and perform well (within ± 20% of assigned values). For PAHs and SCCPs (i.e., compounds that have not been previously assessed in human tissue), SRMs do not exist for quality assurance/quality controls (QA/QCs); and thus, the concentrations should be regarded with some uncertainty.

Recoveries of internal standards were 72–76, 43–86, 78–115, 40–102, and 12–69% for DDTs, OCPs other than DDTs, PCBs, BFRs, and PAHs, respectively. Compounds for which the recoveries were below 30% were excluded from the presented results. The limits of detection (LODs) were either software-generated and corresponded to signal-to-noise ratios of 3, or represented three times the concentrations found in blank samples.

Statistical Analysis

Descriptive summaries of analyte concentrations were presented if the analyte was detected in at least one pooled sample. For analytes detected in at least 9 (50%) of the samples, median (minimum, maximum) values were estimated and further examined by strata defined by maternal age groups (tertiles), maternal BMI category (tertiles), and regular large fish consumption (at least once per week). All statistical analyses were conducted using Stata version 13 (College Station, Texas).

Results

Characteristics of the participants included in this study are presented in Table 2. Eleven of the 70 compounds were detected in at least one of the 18 pooled umbilical cord blood samples (Table 3). Concentrations of analytes detected in at least 9/18 (50%) samples, expressed as pg/ml and ng/g lipid, are presented in Table 3. In all samples, we detected high levels of *p*,*p*′-DDT (median 81.6 ng/g lipid) and its metabolites *p*,*p*′-DDE and *p*,*p*′-DDD (median 551 and 10.7 ng/g lipid, respectively), where the *p*,*p*′-DDE/*p*,*p*′-DDT ratio (indicator of recent DDT exposure) ranged from 2.9 to 9.8. Furthermore, in some samples, we detected acenaphthene (3/18, 17%), DBDPE (6/18, 33%), *o*,*p*′-DDT (9/18, 50%), *o*,*p*′-DDE (8/18, 44%), hexachlorobenzene (HCB) (6/18, 33%), β-hexachlorocyclohexane (β-HCH) (15/18, 83%), hexabromobenzene (HBB) (1/18, 6%), and PFOA (13/18, 72%, Table 3). No trends were observed among compounds detected in at least half the samples when stratifying by maternal age, maternal BMI, and regular large fish consumption (Fig. 1). Most of the target compounds (59/70, 84%) were not detected (< LOD) in any of the 18 pooled samples (Online Resource, Table S5).

Table 2 Characteristics of study participants

Maternal characteristics[a]	Included participants ($n=90$)
Age (years)	24 (18, 35)
Weight (kg)	53.9 (33.1, 81.4)
Height (m)	1.51 (1.39, 1.64)
BMI (kg/m^2)	23.1 (16.1, 35.5)
Regular large fish consumption[b], *n* (%)	45 (50.0)

[a]Characteristics are summarized as median (min, max) unless otherwise stated

[b]Regular consumption refers to self-reported consumption at least once per week at the time of enrolment (second trimester of pregnancy)

Discussion

We detected *p*,*p*′-DDT and its metabolite *p*,*p*′-DDE (median 81.6 and 551 ng/g lipid, respectively) in all cord blood samples collected from a recent cohort of mother–infant pairs in Dhaka, Bangladesh. Detection of these compounds was expected, but concentrations were at the lower end of the spectrum of those that have been previously reported in Bangladesh (Bergkvist et al. 2012; Haque et al. 2017; Linderholm et al. 2011; Zamir et al. 2009), where the highest concentrations of *p*,*p*′-DDT and *p*,*p*′-DDE have been previously found in mothers in the rural area of Matlab (median 707 and 2123 ng/g lipid, respectively) (Bergkvist et al. 2012) and garment industry workers in Dhaka (2300 and 2900 ng/g lipid, respectively) (Zamir et al. 2009). Cross-country comparisons highlight that concentrations in the present cohort are still lower than other countries that endorse DDT use by indoor residual spray to combat malaria, such as South Africa (2788 and 4092 ng/g lipid) (Channa et al. 2012); however, they are still magnitudes higher than those observed in Europe and North America, where production and use of DDT has been eliminated through international regulations like the Stockholm Convention. For example, the median concentrations of *p*,*p*′-DDT and *p*,*p*′-DDE in breast milk from various regions of Norway were 3 and 41 ng/g lipid, respectively (Polder et al. 2009), while those in North

Table 3 Concentrations of detected persistent organic pollutants in pooled umbilical cord blood samples ($n = 18$) in Dhaka, Bangladesh

Compounds	> LOD[a] (%)	< LOD-max (pg/ml)	Wet weight concentration[b] (pg/ml)		Lipid corrected concentration[b] (ng/g lipid)	
			Median	Min, max	Median	Min, max
OCPs						
p,p′-DDT	18 (100.0)	15–632	312	91.9, 632	81.6	22.5, 204
p,p′-DDE	18 (100.0)	9–4130	2010	739, 4130	551	142, 1210
p,p′-DDD	18 (100.0)	12–111	47.9	21.1, 111	10.7	4.2, 34.7
o,p′-DDT	9 (50.0)	10–21.3	7.6	5, 21.3	2.4	0.6, 7.3
o,p′-DDE	8 (44.4)	7–14.2	–	–	–	–
p,p′-DDE/*p,p′*-DDT[c]	–	–	6.8	2.9, 9.8	6.8	2.9, 9.8
HCB	6 (33.3)	19.3–24.6	–	–	–	–
β-HCH	15 (83.3)	15.1–100	33.8	7.6, 100	9.4	1.0, 23.9
BFRs						
HBB	1 (5.6)	28–61	–	–	–	–
DBDPE	6 (33.3)	134–312	–	–	–	–
PAHs						
Acenaphthene	3 (16.7)	1830–2240	–	–	–	–
PFASs						
PFOA	13 (72.2)	37–233	61	18.5, 233	15	2.4, 80.3

[a]Number of samples in which the concentration was above the limit of detection (LOD)

[b]Values below the LOD were treated as LOD/2

[c]Ratio of *p,p′*-DDE to *p,p′*-DDT

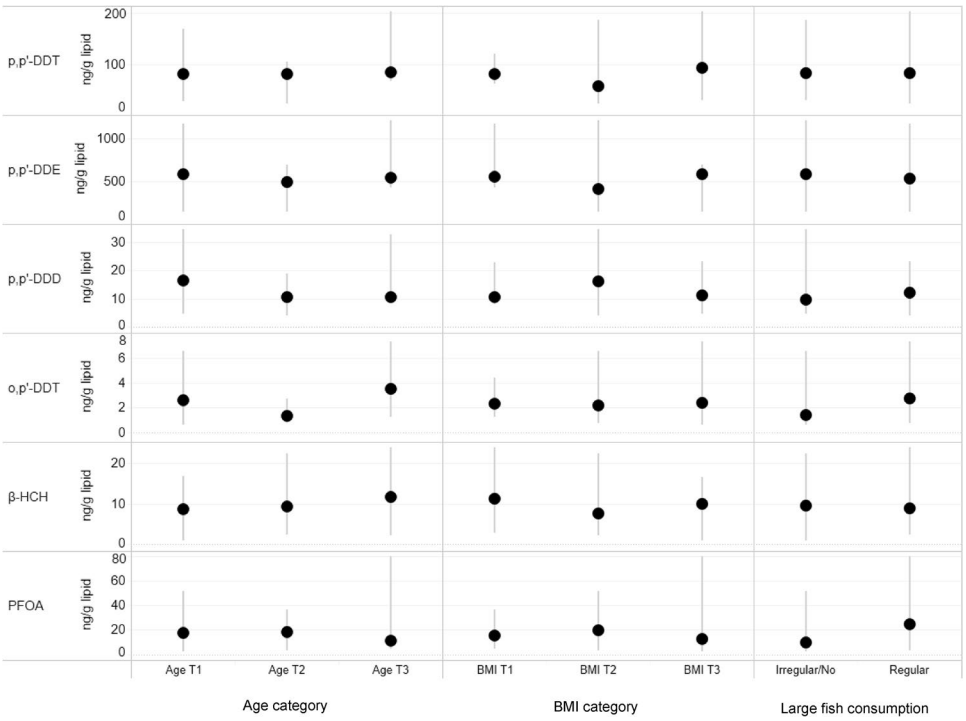

Fig. 1 Trends by maternal age (tertiles), maternal BMI (tertiles), and large fish consumption (regular vs. irregular/no consumption) for analytes detected in at least 9 (50%) of the samples, where values below the LOD were treated as 0.5 × LOD. Points represent the median concentration (ng/g lipid) in each stratum, and gray bands represent the range of concentrations in each stratum. Age tertiles were T1: 18–20 years, T2: 21–25 years, and T3: 26–40 years. BMI tertiles were T1: < 21.5 kg/m^2, T2: 21.5–25.1 kg/m^2, T3: > 25.1 kg/m^2. Large fish consumption was dichotomized into two groups: regular (at least once per week) and irregular/no consumption (less than once per week or no consumption)

Carolina were 5 and 121 ng/g lipid, respectively (Pan et al. 2010).

In the present study, the ratio of *p,p′*-DDE/*p,p′*-DDT ranged from 2.9 to 9.8, suggesting that exposure to DDT is either recent or ongoing. For comparison, the median ratio of *p,p′*-DDE/*p,p′*-DDT was 55 from recent samples in northern Norway, where DDT use has long been phased out (Nøst et al. 2013); while the ratio of *p,p′*-DDE/*p,p′*-DDT

ranged from 1.4 to 2.1 in malaria-endemic regions of South Africa, where the use of DDT is still encouraged for malaria control (Channa et al. 2012). Recent reports have indicated that Bangladesh still has not disposed of their DDT supplies from the 1980s, where improper storage in warehouses has allowed for the contamination of the nearby environment (Illius 2016). Furthermore, DDT continues to be used in Dhaka for the preservation of fish due to its insecticidal properties (Chowdhury et al. 2010), and a recent study showed that the major routes of intake in Bangladesh were food items, particularly beef and fish, as well as house dust (Haque et al. 2017).

We also detected acenaphthene, a by-product of incomplete combustion of organic materials such as natural gas and tobacco (e.g., traffic pollution, cooking, smoking)—exposures that are expected to be widespread in Dhaka. Yet, the findings were perplexing as we detected acenaphthene in only three samples, albeit at high concentrations (> 520 ng/g lipid in three samples) and we cannot exclude analytical uncertainties as the sampling and analyses were not tailored to PAHs in blood. In comparison, a study in Hong Kong reported a median concentration of acenaphthene of 50.3 ng/g lipid and 67.3 ng/g lipid in adult men and women, respectively (Qin et al. 2011). Furthermore, we did not find any other PAHs (common co-exposures such as acenaphthylene) in our samples, which could suggest that acenaphthene exposure is inequitably distributed, and perhaps attributable to specific locations within Dhaka or individual behaviors rather than a ubiquitous exposure (e.g., air pollution).

To our knowledge, no prior study of human samples in South Asia has measured DBDPE, a relatively new BFR. Here, we detected DBDPE in six samples (> 28 ng/g lipid), at levels comparable to those in other industrialized settings. In Guangzhou, one of the largest industrial cities in China, the median concentration of DBDPE in hair samples was found be 17.8 ng/g lipid (Zheng et al. 2011). In contrast, DBDPE was not detected in human tissue in Canada, New Zealand, and the USA (Mannetje et al. 2013; Petreas et al. 2012; Zhou et al. 2014). The levels observed in some samples in this cohort should be not surprising given that Dhaka is the industrial epicenter of Bangladesh, where it is likely that DBDPE is currently being used as a replacement for decabromodiphenyl ether and octabromodiphenyl ether mixtures—BFRs that are facing increasing regulation and are starting to be phased out of the commercial market due to concerns for environmental and human health (Luo et al. 2010). Given the inconsistent findings (i.e., concerning concentrations in some sample pools, but undetectable in others), further assessment of exposures to brominated compounds should be undertaken in a larger study population in Dhaka.

In addition, we also detected low concentrations of PFOA (surfactant), HCB (pesticide), β-HCH (insecticide), and HBB (flame retardant) in a subset of samples. PFOA and HCB concentrations were similar to those found in India, but much lower than those found in Europe, North America, and South America (Devanathan et al. 2009; Kannan et al. 2004). β-HCH concentrations (median 9.4 ng/g lipid) were much lower than previous studies conducted in developed countries such as Germany and Russia, where the median concentrations were found to be 40 and 167 ng/g lipid, respectively (Lam et al. 2013; Schade and Heinzow 1998). HBB was only detected in one of the pooled samples (the other 17 had values below the LOD), but this finding is difficult to contextualize as we lack data regarding HBB from prior studies in Bangladesh or other countries.

The absence of discernable trends in analyses stratified by maternal age, maternal BMI, and large fish consumption was likely due to a combination of at least five factors: (1) generally low or undetectable concentrations of most of the POPs, (2) sample pooling averaged across five individuals' pollutant concentrations in each stratum, where between-individual heterogeneity may have been greater than the between-strata variation, (3) interactions among the three factors (e.g., trends by BMI may differ by age group), (4) lack of consideration of other potentially important predictors of body burden (e.g., beef consumption, concentrations in house dust, Haque et al. 2017), and (5) narrow distributions in maternal age and BMI in our cohort, such that there were only small differences across the strata (Fig. 1).

Overall, several chemicals were detected at low concentrations and in only a subset of samples (with the exception of DDT/DDE), and the majority of compounds we attempted to measure were not detected (< LOD) in any of the pooled samples, suggesting that the overall human burden of POPs is low in this study population. However, environmental exposures are likely to change due to heavy industrialization in response to growing international trade (Zhang et al. 2017), and poorly regulated management of waste and recycling in Bangladesh. As an example, despite the low levels of PCBs reported in this and other studies in Bangladesh (Bergkvist et al. 2012; Linderholm et al. 2011; Zamir et al. 2009), PCB use in the Bangladeshi energy sector is still widespread (e.g., as coolants/insulating fluids in transformers) (Environment and Social Development Organisation 2005), where the improper disposal or recycling of such electrical equipment may potentially represent future elevated human exposure.

A key strength of this study was the demonstration of the feasibility of measuring a wide array of POPs in relatively small amounts of cord blood (1.25 ml) using state-of-the-art methods to investigate human exposure status in a population for which there is little prior POP data. By revealing the blood burden of a wide range of POPs in this cohort, future pollutant studies in this context can target selected POPs for further examination in large

population-based studies of these exposures to enable epidemiologic analyses. However, several limitations of this study should be acknowledged. First, the pooling of umbilical cord blood samples did not allow for individual-level analyses or stratification by variables other than the three we selected prior to pooling (e.g., we could not post hoc consider whether DDT exposure differed by levels of consumption of dried/preserved fish). Second, the ability to detect these chemicals in small sample volumes is limited by the available technology; laboratory methods for some compounds were not tailored for PAHs and SCCPs in human blood and QA/QCs do not include reference materials for these compounds and therefore cautious interpretation of PAH and SCCP concentrations is warranted. Thus, although we may have not detected low background concentrations, we would have captured generally high concentrations in the population. Third, we only considered pollutants that are persistent in the environment, and did not measure other organic pollutants that may be relevant to human health (e.g., Bisphenol A).

In conclusion, our findings confirm that DDT exposure is an ongoing public health concern for mothers and their children in Dhaka, but the overall human burden of the other targeted POPs is low or variable. However, continued monitoring of environmental exposures to POPs will be important as the industrialization of Bangladesh continues. Future research should focus on methods to identify potential sources, environmental transport processes, and routes of uptakes in humans, so that prevention and remediation strategies can be proactively developed to positively impact the population of Bangladesh and other countries similarly undergoing rapid economic development.

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Compliance with Ethical Standards

Conflict of interest The authors declare no conflict of interest.

Ethical Approval All procedures performed in studies involving human participants were in accordance with the Ethical Standards of the Institutional and/or National Research Committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standard. For this type of study, formal consent is not required. Analyses of umbilical cord blood specimens were approved by the Research Ethics Board at the Hospital for Sick Children (Canada), and was exempt from Institutional Ethical Review at the Norwegian Institute for Air Research (Norway) and the International Centre for Diarrhoeal Disease Research, Bangladesh (Bangladesh). Data collection and analyses for the original MDIG trial were approved by The Hospital for Sick Children (Canada) and the International Centre for Diarrhoeal Disease Research, Bangladesh (Bangladesh).

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