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Perfluoroalkyl acids in children and their mothers: Association with drinking water and time trends of inner exposures—Results of the Duisburg birth cohort and Bochum cohort studies

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ABSTRACT

Background: Perfluoroalkyl acids (PFAAs) are widely distributed in the environment and humans are globally exposed with them. Contaminated drinking water can considerably contribute to the inner exposure levels.
Objectives: We report the results of a human biomonitoring study with mother–child pairs living in two German cities, one city with PFAA contaminated drinking water in the sub μg/l-range (Bochum) and the other one without contamination (Duisburg). Furthermore, we studied time trends of exposure levels within the Duisburg cohort study.
Methods: We measured seven PFAAs (PFOS, PFOA, PFHxS, PFNA, PFBS, PFDeA, PFDoA) in blood samples by high performance liquid chromatography and tandem mass spectrometry. Samples were taken during pregnancy, from umbilical cord blood (2000–2002), 6–7 years (5th follow-up) and 8–10 years after birth (7th follow-up). The consumption of drinking water was recorded by a standardized questionnaire. Statistical analyses were calculated with multiple linear regression models.
Results: Children and mothers from Bochum showed higher PFOS and PFOA plasma concentrations than from Duisburg. The median concentrations (μg/l) for children were: PFOS 4.7 vs. 3.3; PFOA 6.0 vs. 3.6 μg/l ($p \leq 0.05$). Consumption of >0.7 l (children) and >0.9 l (mothers) drinking water/day was associated with 13–18% higher PFOS, PFOA and PFHxS concentrations in children ($p \leq 0.01$), and 22% higher PFOA in mothers ($p \leq 0.05$). Within the Duisburg cohort, PFAA levels in children peaked in the 5th follow-up study (medians (μg/l): cord plasma: 2.7 (PFOS); 1.9 (PFOA); 5th follow-up: 3.6 (PFOS); 4.6 (PFOA); 7th follow-up: 3.3 (PFOS); 3.6 (PFOA)). PFOS concentrations in mothers declined from pregnancy to the 5th follow-up (medians: 8.7 vs. 4.0 μg/l).
Conclusion: Residents exposed to PFOS and PFOA through drinking water showed significantly higher PFOS and PFOA concentrations in blood plasma. Although PFAA concentrations in the children slightly decreased from the 5th to the 7th follow-up, we detected increasing exposure trends with increasing age in the 7th follow-up.

Introduction

Surface active perfluoroalkyl acids (PFAAs) have been produced since the late 1940s (Schultz et al., 2003) and are used in a large number of industrial and consumer product applications. They are globally distributed in the environment and can be detected in many environmental media, such as surface water, soil, sediment, sludge from wastewater treatment plants, ambient and indoor air, and house dust (Fromme et al., 2009; Paul et al., 2009; Lau, 2012). Due to the strong carbon-fluorine bond, these chemicals are extremely persistent against degradation, and some PFAAs have the potential for bioaccumulation in organisms and will only slowly be eliminated (Olsen et al., 2007; Mariussen, 2012; Olsen et al., 2012). The elimination rate of PFAAs is dependent on the chain length of the alkyl acids and is faster for short chain PFAAs ($C \leq 8$), with the

Abbreviations: PFOS, perfluorooctane sulfonate; PFOA, perfluorooctanoate; PFHxS, perfluorohexane sulfonate; PFBS, perfluorobutane sulfonate; PFNA, perfluorononanoate; PFDeA, perfluorodecanoate; PFDoA, perfluorododecanoate.

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exception of PFHxS (Lau, 2012; Zhang et al., 2013). Urinary excretion is the major elimination route for short chain PFAAs, but for PFOS and PFHxS, other routes of excretion are likely contribute to the overall elimination (Lau, 2012; Zhang et al., 2013).

In addition to gestational exposure and breastfeeding, infants are exposed to PFAAs (among others) by migration from food packaging into food, drinking water and house dust (Liu et al., 2011; Lau, 2012). PFAAs are well-known drinking water contaminants (Emmett et al., 2006; Lange et al., 2007; Hölzer et al., 2008; MDH, 2009). Critical reviews were published by Post et al. (2012) Lau et al. (2007), and Lau (2012). One contaminated site is located in the Federal State of North Rhine Westphalia (NRW), Germany: PFAA-contaminated industrial waste was mixed into a soil improver by a recycling company and spread by farmers on agricultural land, which led to substantial environmental pollution, particularly to the Möhne River and subsequently drinking water. The Möhne River enters the Ruhr River approximately 45 km downstream the contamination site, and therefore the Ruhr River was affected, too. This case became evident in 2006 (Skutlarek et al., 2006; Wilhelm et al., 2008a, 2010). Because the cities Bochum and Duisburg are strung along the Ruhr River (Bochum is downstream of the contamination site; Duisburg is downstream of Bochum), we examined blood plasma PFAA levels in mother–child pairs living in the two cities. The drinking water for Bochum originates from the surface water of the Ruhr River, but the drinking water for Duisburg is from other sources (for a geographical overview of the Rhine-Ruhr district, the rivers and their water works see Wilhelm et al., 2008a). Additionally, we used the chance to study time trends of PFAA exposures in mothers and children from our Duisburg cohort study, reaching from pregnancy and cord plasma to school-age children, although not initially planned.

Materials and methods

Study area and population

The study was undertaken in the cities of Duisburg and Bochum, North Rhine Westphalia, Germany. The populations of Duisburg and Bochum are 500,000 and 400,000 inhabitants, respectively. The first enrollment of participants was completed in 2002 for Duisburg. Initially, 232 pregnant women from Duisburg took part in the study. During this time we focused on the human biomonitoring of polychlorinated biphenyls (PCBs), dibenzo-*p*-dioxins and dibenzofurans (PCDD/Fs) (Wittsiepe et al., 2007) and their influences on early developmental outcomes of the children (Cao et al., 2008; Wilhelm et al., 2008b). Since 2006 new follow-up studies were funded by the Federal Environment Agency of Germany with the focus on the human biomonitoring of PFAAs and other chemicals with endocrine disrupting properties (e.g. phthalates). In 2010 we recruited additional 359 mother–child pairs from Bochum. Details of the Bochum study are described in Kasper-Sonnenberg et al. (2014). All children were born between 1999 and 2002. Up to now, we conducted a total of 11 examinations within the Duisburg birth cohort and four examinations within the Bochum cohort (starting in parallel with the 7th follow-up study of Duisburg). The examinations regarding the PFAA analyses are named as follows:

- Duisburg cohort: Pregnancy (maternal blood samples between weeks 28–43 of gestation with a median of 32 weeks from 2000 and 2002);
- Duisburg cohort: 1st follow-up study (samples from umbilical cord blood at birth);
- Duisburg cohort: 5th follow-up study (blood samplings and examinations from 2007 to 2008);
- Duisburg and Bochum cohort: 7th follow-up study (blood samplings and examinations from 2009 to 2010).

The mothers and their children were invited by letter to participate in the follow-up examinations. All parents gave their written consent. The study was reviewed and approved by the Ethical Commission of the Medical Facilities at the Ruhr—University Bochum, Germany (Registry no. 1478; 3220-08; 3486-09).

Blood sampling and chemical analysis

Standard materials for venipuncture and blood sampling were used. The collection and processing of maternal and cord blood in the years 2000–2002 is described in Cao et al. (2008). In short, maternal blood was collected at gestational weeks 28–43 and then cord blood was collected at delivery using two different sampling tubes (whole cord blood and plasma samples). Blood samples at the 5th and 7th follow-up were kept and transported at 4–7 °C without interruption of the cooling chain until transfer to a laboratory where centrifugation and separation of plasma took place. All samples were stored at −20 °C and transported frozen to the analytical-toxicological laboratories in Munich, Germany (holding a certificate of accreditation according to German and international normative standards – DIN ISO 17025).

We measured seven most detectable PFAAs (PFOS, PFOA, PFHxS, PFNA, PFBS, PFDeA, PFDoA) in blood by solid phase extraction, high performance liquid chromatography (HPLC), and tandem mass spectrometry (MS/MS) using internal isotope-labeled standards. Whole blood samples were measured in the same manner as the plasma samples. The limits of quantifications (LOQs) were 0.4 μg/l for PFOA, PFNA, PFDeA, PFDoA, and PFBS. For PFOS the LOQ was 0.1 μg/l and for PFHxS 0.2 μg/l. The means of relative recoveries ranged from 84 to 112%, depending on the PFAAs and the lower and higher concentrations. Analyses were performed after the complete collection of the samples. All samples were analyzed in duplicates with coefficients of variation <20%. Twenty samples were measured in each analytical series, for each measuring a calibration line with two quality standards. The accuracy of the standards was 100% ± 20%. Details of the analytical procedure are described in Mosch et al. (2010).

Data collection and anthropometric measures

Baseline questionnaires (administered in the years of enrollment) and questionnaires administered in the follow-up studies were used for the collection of additional information, such as socio-demographic or lifestyle information. The average consumption of drinking water per day and dietary intake for children and mothers were determined by personal interviews with trained staff during the 7th follow-up study using a questionnaire that was previously used in the Arnsberg study (Hölzer et al., 2008). Drinking water consumption was separately recorded for the times staying at home and times at work (mothers) or at day nursery (children), respectively. Participants were excluded: who changed their water consumption behavior since the PFAA contamination became known ($N = 28$), who did not receive the drinking water from the public drinking water supplier ($N = 2$), and whose places at work/day nursery were located outside the district of the places of residence ($N_{mothers} = 308$; $N_{children} = 88$). These restrictions reduced the sample sizes to a relatively great proportion but we aimed to calculate the amount of drinking water that only originated from the known drinking water suppliers. Consumption of vegetables, fruit, meat, milk, milk products, sweets, eggs, and fish (fish bought from the supermarket and fish caught from local waterways) were recorded as meals per week. More than 84% (Duisburg) and 86% (Bochum) of the mothers were born in Germany; thus, we grouped