Dietary predictors of prenatal per- and poly-fluoroalkyl substances exposure

Stephanie M. Eick1, Dana E. Goin1, Jessica Trowbridge1, Lara Cushing2, Sabrina Crispo Smith2, June-Soo Park1,3, Erin DeMicco1, Amy M. Padula1, Tracey J. Woodruff1 and Rachel Morello-Frosch1,4

© The Author(s) 2021

BACKGROUND: Per- and poly-fluoroalkyl substances (PFAS) are commonly detected in a variety of foods and food packaging materials, and also in human breast milk. However, few studies have examined diet as a potential source of PFAS exposure during pregnancy. In the present cross-sectional study, we examined prenatal PFAS levels in relation to self-reported consumption of meats, dairy products, and processed foods during pregnancy.

METHODS: Participants were enrolled in the Chemicals in Our Bodies study, a demographically diverse pregnancy cohort in San Francisco, CA (N = 509). Diet was assessed using a self-reported interview questionnaire administered during the second trimester. Participants were asked on average how many times a day, week, or month they ate 11 different foods since becoming pregnant. Responses were categorized as at least once a week or less than once a week and foods were grouped into three categories: processed foods, dairy products, and meats. Twelve PFAS (ng/mL) were measured in second trimester serum samples. We investigated relationships between consumption of individual dairy products, meats, and processed foods and natural log-transformed PFAS using separate linear regression models adjusted for maternal age, education, race/ethnicity, and nativity.

RESULTS: Seven PFAS were detected in ≥65% of participants. Consumption of dairy milk and cheese at least once per week was moderately associated with elevated levels of perfluorononoic acid (PFNA) and perfluorodecanoic acid (PFDeA) relative to those who ate dairy products less than once week. The strongest associations observed were with PFDeA for dairy milk (β = 0.2, 95% confidence interval [CI] = 0.02, 0.39) and PFNA for cheese (β = 0.22, 95% CI = 0.02, 0.41). Eating fish, poultry, and red meat at least once per week was associated with higher levels of perfluoroundecanoic acid, PFDeA, PFNA, and perfluorooctane sulfonic acid.

CONCLUSIONS: Results indicate that consumption of animal products may contribute to elevated prenatal PFAS levels.

Keywords: Diet; Pregnancy; Per- and poly-fluoroalkyl substances; Nutrition

INTRODUCTION

Per- and poly-fluoroalkyl substances (PFAS) are environmental chemicals that are widely used in commerce due to their oil and water repellent properties. PFAS are commonly found in non-stick cookware, food containers, and some drinking water [1], leading to ubiquitous human exposure [2]. Environmental studies have shown that increasing concentrations of some PFAS, particularly perfluorooctanoic acid (PFOA) and perfluorooctane sulfonic acid (PFOS), are associated with an increased risk of developing certain cancers and pregnancy-induced hypertension [3, 4]. Of all PFAS in the United States (US), PFOA and PFOS have been historically produced in the largest amounts and concerns regarding adverse health effects associated with these chemicals have led to voluntary phase outs by industry in the early 2000s [5]. While PFOA and PFOS levels in the US population have subsequently declined following these phase outs, they are still widely detected, indicating that they can persist in the environment and in humans for many years [6]. In addition, newer PFAS that are structurally similar to PFOA and PFOS are being phased in and we have a limited understanding of their toxicity [7].

Given the long half-life and persistence of PFAS, identifying their exposure sources is critical to inform strategies that can reduce exposures and body burden. PFAS are magnified in the food web, and diet has been implicated as a major route for PFAS exposure [1]. In addition to humans, PFOS has been detected in polar bears in the Arctic and other wildlife in remote regions [8]. Furthermore, PFAS have been detected in animals, such as fish and poultry, which are subsequently consumed by humans [9, 10], and studies have observed positive relationships between fish and poultry consumption and PFAS levels [11–14]. PFAS are also used in food packaging materials due to their oil and water-repellent properties. PFAS can latch onto foods via migration from food packaging materials, such as

1Program on Reproductive Health and the Environment, Department of Obstetrics, Gynecology and Reproductive Sciences, University of California, San Francisco, San Francisco, CA, USA. 2Department of Environmental Health Sciences, Fielding School of Public Health, University of California, Los Angeles, Los Angeles, CA, USA. 3Environmental Chemistry Laboratory, Department of Toxic Substances Control, California Environmental Protection Agency, Berkeley, CA, USA. 4Department of Environmental Science, Policy and Management and School of Public Health, University of California, Berkeley, Berkeley, CA, USA. *email: stephanie.marie.eick@emory.edu; rmf@berkeley.edu

Received: 23 April 2021 Revised: 7 September 2021 Accepted: 10 September 2021
Published online: 6 October 2021
microwave popcorn bags and take-out pizza boxes [15, 16], and previous studies have indicated that individuals who eat foods packaged in these materials, such as pizza and salty snacks, have elevated levels of many PFAS relative to those who report never eating these foods [17]. Data from the National Health and Nutrition Examination Survey (NHANES) has also shown that consumption of fast food, pizza, and microwave popcorn is associated with higher levels of PFOA and perfluoronoronic acid (PFNA) [18].

Prior studies conducted in pregnant people have consistently shown a positive relationship between fish consumption and PFAS levels [12, 19, 20]. However, we have a limited understanding of the relationship between PFAS and other dietary predictors during pregnancy. This is particularly concerning, as many PFAS, including PFOA and PFOS, are easily transferred to the fetus via the placenta [21, 22] and have been detected in 99% of pregnant people [23]. Elevated levels of PFAS prenatally have also been associated with adverse reproductive health outcomes, such as preeclampsia, preterm birth, and reduced fetal growth [24–27]. In the present study, we examined relationships between self-reported consumption of foods and food packaging materials and serum PFAS levels in a demographically diverse cohort of pregnant people in San Francisco.

METHODS

Study population

Participants included in this analysis were enrolled in the Chemicals in Our Bodies (CIOB) cohort. CIOB was designed to examine the cumulative effects of environmental chemical and non-chemical stressors in pregnancy and is described in detail elsewhere [26, 28]. Briefly, pregnant people were recruited during their second trimester of pregnancy at three University of California, San Francisco (UCSF) hospitals beginning in 2014. Participants recruited from Moffitt Long and Mission Bay Hospitals were economically diverse, and the majority had private health insurance. Those recruited from the Zuckerberg San Francisco General Hospital were primarily lower income and enrolled in Medi-Cal (California’s Medicaid program). Eligibility for CIOB included: ≥18 years of age, singleton pregnancy, and English or Spanish speaking. As part of the study, mothers consented to study staff accessing their medical records and all participants provided written, informed consent prior to participating. The Institutional Review Boards at UCSF (13-12160) and the University of California, Berkeley (2010-05-04) approved CIOB.

Diet

Dietary factors were assessed using a self-reported interview questionnaire adapted from prior studies examining dietary sources of PFAS [14, 29, 30], which was administered during the second trimester (see Supplementary Material). Participants were asked how many times a day, week, or month they ate certain foods since becoming pregnant. We focused our analyses on three groups of foods and food packaging sources that have been identified as potential sources of PFAS exposure in the literature: meats, processed foods, and dairy products [1, 14, 18]. Poultry, fish, shellfish, and red meats (beef, pork, lamb, goat) were included as meats. Processed foods included take-out or delivered pizza, fast food or take-out food, food from a restaurant that is packaged in paper or cardboard, food purchased from a store that comes in paper or cardboard, French fries, microwave popcorn, and movie theater popcorn. Lastly, dairy milk, cheese, and yogurt were included as dairy products. Microwave and movie theater popcorn were combined into a single popcorn category, and fish and shellfish were combined into a single fish category. Fast food or take-out food and food from a restaurant packaged in paper or cardboard were also combined into a single take-out food category. Responses to all questions were converted to the number of times consumed per week and categorized as at least once a week or less than once a week. We categorized popcorn as less than once a month or at least once a month as very few participants reported eating popcorn at least once a week. While we examined other categories (such as never, more than once to but less than once a month, more than once a month to less than once a week, at least once a week), we focused on binary measures in our main analysis as the number of participants across groups was small.

PFAS exposure

Twelve PFAS were measured in second trimester maternal serum samples (range 12–28 weeks’ gestation), at the Environmental Chemical Laboratory at the California Department of Toxic Substances Control (DTSC). Prior to analysis, serum samples were frozen at ~8 °C. PFAS were quantified by injection onto an automated online solid phase extraction method coupled to liquid chromatography and tandem mass spectrometry. Additional details regarding the analysis of PFAS are available elsewhere [22, 28]. We restricted our analysis to PFAS detected in ≥65% of samples, which included: PFOA, PFOS, PFNA, perfluorohexanesulfonic acid (PFHxS), methyl-perfluorooctane sulfonamide acid (Me-PFOSAcOH), perfluorodecanoic acid (PFPeA), and perfluoroundecanoic acid (PFUnDA).

RESULTS

There were 509 participants included in our analysis. Of this group, nearly 40% were 30 years of age or older and had a graduate degree. Most participants were white (38%) or Latina (34%) and half had a normal pre-pregnancy BMI. Roughly 34% of participants experienced financial strain and 15% were food insecure (Table 1).

Of the processed foods, take-out food was consumed the most frequently with 76.6% of participants reporting consumption of take-out food at least once a week. Take-out or delivered pizza was the least commonly consumed (11.6% at least once a week on average). Nearly all participants reported consuming dairy products at least once a week on average. Cheese was the most common (86.4%), followed by dairy milk (80.1%), and yogurt (76%). Among the meats, 85.9% and 70.1% reported eating
poultry and red meat on average at least once a week, respectively (Table 2).

All seven PFAS included in our analysis had machine readable values available for >90% of samples (Table 3). Of these, PFOA and PFOS were detected at the highest concentrations, with median values of 0.8 and 2.0 ng/mL, respectively. Four PFAS were detected in <65% of samples (PFDoA, PFOSA, PFBS, Et-PFOSA-AcOH, PFHpA; Table 3).

Elevated levels of PFNA, PFOA, and PFOS were observed among those who reported eating cheese at least once a week in unadjusted models (Fig. 1 and Supplementary Table S1). Only the relationship between cheese and PFNA remained relatively unchanged after adjusting for covariates ($\beta = 0.23$, 95% CI $= 0.04, 0.42$). In adjusted models, drinking dairy milk at least once a week was modestly associated with elevated levels of PFOA ($\beta = 0.11$, 95% CI $= -0.05, 0.27$), PFOS ($\beta = 0.08$, 95% CI $= -0.08, 0.25$),

### Table 1. Distribution of demographic characteristics in the Chemicals in Our Bodies Study Population ($N = 509$).

| Maternal age at enrollment (years) | N (%) |
|-----------------------------------|-------|
| <25                               | 54 (11) |
| 25–29                             | 76 (15) |
| 30–34                             | 182 (36) |
| ≥35                               | 196 (39) |
| Missing                            | 1 (0.2) |

| Maternal education                | N (%) |
|-----------------------------------|-------|
| <High school                      | 60 (12) |
| High school degree or some college| 138 (27) |
| College degree                    | 116 (23) |
| Graduate degree                   | 186 (37) |
| Missing                            | 9 (1.8) |

| Maternal race/ethnicity           | N (%) |
|-----------------------------------|-------|
| White                             | 191 (38) |
| Black                             | 37 (7) |
| Asian/Pacific Islander            | 85 (17) |
| Latina                            | 173 (34) |
| Other                             | 14 (3) |
| Missing                            | 9 (1.8) |

| Nativity                          | N (%) |
|-----------------------------------|-------|
| Foreign born                      | 213 (42) |
| US born                           | 419 (82) |
| Missing                            | 33 (6.5) |

| Parity                            | N (%) |
|-----------------------------------|-------|
| No prior births                   | 246 (48) |
| One or more prior births          | 254 (50) |
| Missing                            | 9 (1.8) |

| Marital status                    | N (%) |
|-----------------------------------|-------|
| Married                           | 337 (66) |
| Living together                   | 103 (20) |
| Single                            | 59 (12) |
| Missing                            | 10 (2.0) |

| Pre-pregnancy body mass index (kg/m²) | N (%) |
|---------------------------------------|-------|
| Underweight (<18.5)                  | 12 (2) |
| Normal (18.5–24.9)                    | 240 (47) |
| Overweight (25–29.9)                  | 129 (25) |
| Obese (≥30)                           | 90 (18) |
| Missing                               | 38 (7.5) |

| Financial strain                   | N (%) |
|-----------------------------------|-------|
| Yes                                | 190 (37) |
| No                                 | 274 (54) |
| Missing                            | 45 (8.8) |

| Food insecurity                    | N (%) |
|-----------------------------------|-------|
| Yes                                | 78 (15) |
| No                                 | 419 (82) |
| Missing                            | 12 (2.4) |

### Table 2. Distribution of self-reported consumption of foods in the Chemicals in Our Bodies Study ($N = 509$).

| Processed foods                  | N (%) |
|----------------------------------|-------|
| Pizza                            | 435 (85.5) |
| ≥1/week                          | 59 (11.6) |
| Missing                          | 15 (2.9) |

| Take-out food                    | N (%) |
|----------------------------------|-------|
| <1/week                          | 101 (19.8) |
| ≥1/week                          | 390 (76.6) |
| Missing                          | 18 (3.5) |

| Store bought food                | N (%) |
|----------------------------------|-------|
| <1/week                          | 394 (77.4) |
| ≥1/week                          | 96 (18.9) |
| Missing                          | 19 (3.7) |

| Dairy products                   | N (%) |
|----------------------------------|-------|
| Dairy milk                       | 80 (15.7) |
| ≥1/week                          | 410 (80.6) |
| Missing                          | 19 (3.7) |

| Cheese                           | N (%) |
|----------------------------------|-------|
| <1/week                          | 51 (10.0) |
| ≥1/week                          | 440 (86.4) |
| Missing                          | 18 (3.5) |

| Yogurt                           | N (%) |
|----------------------------------|-------|
| <1/week                          | 105 (20.6) |
| ≥1/week                          | 387 (76.0) |
| Missing                          | 17 (3.3) |

| Meats                             | N (%) |
|----------------------------------|-------|
| Poultry                          | 58 (11.4) |
| ≥1/week                          | 437 (85.9) |
| Missing                          | 14 (2.8) |

| Fish and shellfish               | N (%) |
|----------------------------------|-------|
| <1/week                          | 169 (33.2) |
| ≥1/week                          | 319 (62.7) |
| Missing                          | 21 (4.1) |

| Red meat                         | N (%) |
|----------------------------------|-------|
| <1/week                          | 137 (26.9) |
| ≥1/week                          | 357 (70.1) |
| Missing                          | 15 (2.9) |
PFDeA (β = 0.20, 95% CI = 0.02, 0.39), and PFUdA (β = 0.19, 95% CI = −0.02, 0.39) (Fig. 1 and Supplementary Table S2). Eating yogurt at least once a week was associated with higher levels of PFOA, PFHxS, and PFUdA in unadjusted models only.

Compared to those who ate fish or shellfish less than once a week, consuming fish or shellfish at least once a week was associated with elevated levels of PFNA, PFOS, PFDeA, and PFUdA in adjusted models (Fig. 2 and Supplementary Table S2). The strongest associations observed were with PFUdA (β = 0.58, 95% CI = 0.42, 0.74) and PFDeA (β = 0.25, 95% CI = 0.10, 0.40). Eating poultry and red meat at least once a week, compared to less than once a week, was also modestly associated with increasing PFOS, PFDeA, and PFUdA levels (Fig. 2).

Overall, PFAS levels were not associated with higher consumption of any of the processed foods after adjusting for covariates (Fig. 3). In unadjusted models, eating take-out food at least once a week was associated with slightly higher levels of PFOS (β = 0.13, 95% CI = −0.03, 0.29) and PFHxS (β = 0.13, 95% CI = −0.01, 0.35) relative to less than once a week. Eating microwave or movie theater popcorn at least once a month, compared to less than once a month, was moderately associated with lower levels of PFUdA (β = −0.26, 95% CI = −0.43, −0.08) and PFDeA (β = −0.12, 95% CI = −0.27, 0.02) (Fig. 3 and Supplementary Table S1). Additional adjustment for food insecurity did not noticeably change point estimates (Supplementary Table S3).

In models stratified by food insecurity, the relationships between red meat, fish consumption and PFNA, PFOS, PFDeA, and PFUdA were modestly stronger among those who were not food insecure compared to those who experienced food insecurity (Supplementary Fig. S2). Similar patterns were observed when stratifying by financial strain. In particular, PFOS, PFDeA, and PFUdA were elevated in relation to red meat and fish consumption only among those who did not experience financial strain (Supplementary Fig. S3).

### Table 3. Distribution of second trimester PFAS concentrations (ng/mL) in maternal serum in the Chemicals in Our Bodies Study (N = 509).

|       | MDL  | % above MDL | % readable | Selected percentiles |
|-------|------|-------------|------------|----------------------|
|       |      |             |            | 5th      | 50th     | Maximum |
| PFNA  | 0.06 | 98.8        | 99.6       | 0.1      | 0.3      | 18.7     |
| PFOA  | 0.13 | 99.8        | 100        | 0.3      | 0.8      | 32.2     |
| PFHxS | 0.01 | 100         | 100        | 0.1      | 0.3      | 4.9      |
| PFOS  | 0.07 | 100         | 100        | 0.5      | 1.9      | 14.5     |
| Me-PFOSA-AcOH | 0.01 | 98.8 | 99.8 | 0.02 | 0.05 | 0.8 |
| PFDeA | 0.05 | 69.4 | 92.3 | 0.02 | 0.1 | 3.9 |
| PFUdA | 0.08 | 72.3 | 95.5 | 0.02 | 0.1 | 1.3 |
| PFDoA | 0.20 | 2.2  | 58.4 | 0.01 | 0.02 | 0.5 |
| PFOSA | 0.02 | 2.4  | 45.6 | 0.001 | 0.02 | 0.1 |
| PFBS  | 0.03 | 0.8  | 54.4 | 0.001 | 0.02 | 0.1 |
| Et-PFOSA-AcOH | 0.01 | 10.6 | 69.7 | 0.001 | 0.01 | 0.1 |
| PFHpA | 0.05 | 12.0 | 68.0 | 0.003 | 0.02 | 0.5 |

To calculate percentiles, machine read values were used for observations below the MDL when available and if a machine read value was unavailable, values were replaced with the MDL/√2.

MDL method detection limit.

---

**Fig. 1** Linear regression coefficients and 95% confidence intervals indicating the mean change in natural log-transformed PFAS concentrations (ng/mL) in maternal serum in association with self-reported consumption of dairy products greater than once a week relative to less than once a week. Models adjusted for maternal age, maternal race/ethnicity, education, and nativity. CI confidence interval.

---

**Fig. 3** Change in log(PFAS) (95% CI) in association with self-reported consumption of dairy products greater than once a month compared to less than once a month. (Supplementary Fig. S3).
DISCUSSION
In a large, demographically diverse pregnancy cohort in San Francisco, we observed that serum PFAS levels were positively associated with the consumption of dairy milk, cheese, fish or shellfish, red meat, and poultry after adjusting for age, race/ethnicity, education, and nativity. Furthermore, processed foods, including take-out food, French fries, and pizza, were not associated with prenatal PFAS levels in our study population. Our results suggest that animal products may be important sources of PFAS exposure during pregnancy.

Our finding that fish and shellfish consumption are associated with higher levels of long-chain PFAS, specifically PFNA, PFOS, PFDeA, and PFUdA, is supported by prior studies [11, 19, 39]. For example, in a pregnancy cohort in Spain, eating at least 5.6 servings of fish and shellfish a week was associated with elevated PFOS, PFOA, and PFNA compared to those who ate between 0 and 3.59 servings a week [40]. Similarly, in the NHANES population, consumption of fish and shellfish within the last week was positively associated with PFOA, PFNA, PFOS, and PFUdA [18, 41]. In these studies, the strongest effects observed were with PFUdA [18, 41], which is consistent with our findings and may be due to the high concentrations of PFUdA detected in fish relative to other PFAS [42]. We also observed that PFAS levels were modestly elevated among individuals who ate poultry and red meat at least once a week. This is consistent with previous studies conducted among pregnant populations in China and Spain [19, 40].

Foods that come from animals, particularly fish, have been identified as a primary source of PFAS exposure [1] and detectable levels of PFAS have been found in blood and tissue samples obtained from fish, chicken, and beef [43]. PFAS may be accumulating in fish and other animal products due to contaminated habitats, as PFAS released into the environment have been detected in drinking water for livestock, and in bays, lakes, and rivers that are home to many fish species [43, 44]. PFAS have also been detected in liver, muscle, and blood of dairy cows [45], which is consistent with our finding that levels of five PFAS were elevated among those who drank dairy milk and ate cheese at least once a week. PFAS can accumulate and bind to serum proteins in birds and fish [46] and the associations we observed with meat, seafood, and dairy products may be reflective of this. Acknowledging that there are health benefits associated with eating fish [47] and that red meat and poultry consumption is increasing globally [48], it will be important to consider seafood and white meat, as well as other animal products, as a potential source of PFAS exposure moving forward.

We observed that the relationships between fish and shellfish, red meat, and PFAS were generally stronger among individuals who did not experience food insecurity or financial strain. This is consistent with prior work in the NHANES study population showing the association between PFAS and fish and shellfish consumption was modified by household income [41]. In that study, associations were stronger among individuals with higher annual household incomes. These differences could be the result of different exposure patterns among higher SES individuals, as they may have sufficient income to purchase fish and red meat more frequently [37].

In contrast to prior findings [18], microwave popcorn and other processed foods were not a major source of PFAS exposure in our study population. Prior work shows that daily consumption of microwave popcorn is associated with elevated levels of PFAS [18], possibly due to increased contact with microwave popcorn bags, which often contain PFAS [49]. Relatively few participants in our study reported eating popcorn more than once a week, which could be why we did not observe associations between eating popcorn and PFAS levels. In our study, consumption of popcorn was analyzed as less than or equal to once a month and other studies that used similar categorizations found no association between popcorn consumption and PFAS levels. For example, in the Child Health and Development Studies, ever versus never eating microwave popcorn was not associated with PFAS levels among adult women [30]. Similarly, among children in the HOME cohort, ever versus never eating microwave popcorn in the past year was not associated with PFAS levels [11]. In contrast, the study that observed a positive association between popcorn and PFAS levels assessed diet using a 24-h recall and 12-month food frequency questionnaire, with 86% of individuals consuming popcorn within the last 12 months [18]. In addition, only 11% of participants in our study reported eating pizza on average at least once a week, and our limited sample size could be why we observed no associations between pizza consumption and PFAS levels. While not observed in our study, prior research has shown that PFAS are found in food contact paperboard (e.g., pizza boxes) [16] and that eating food from a fast food or pizza restaurant

![Linear regression coefficients and 95% confidence intervals indicating the mean change in natural log-transformed PFAS concentrations (ng/mL) in maternal serum in association with self-reported consumption of meats greater than once a week relative to less than once a week. Models adjusted for maternal age, maternal race/ethnicity, education, and nativity. Fish includes fish and shellfish. CI confidence interval.](image-url)
within the last 7 days is associated with elevated levels of PFOA [18]. These studies indicate that contaminated food contact materials, such as pizza boxes and microwave popcorn bags, are likely important sources of PFAS exposure on the population level. Given that PFAS are readily detected in these processed foods and packaging materials, removing PFAS from food contact materials is warranted.

An important strength of our study is that we examined numerous foods and food packaging materials in relation to PFAS exposure that are understudied, such as cheese and yogurt. In addition, our cohort included measurements of several PFAS that have not been as widely studied as PFOA and PFOS. The CIOB cohort also includes participants from diverse racial, ethnic, and socioeconomic backgrounds and our results provide important information on dietary predictors of PFAS exposure among understudied populations. We also acknowledge our limitations. Our questionnaire did not specifically ask if participants were vegetarian or vegan and prior research shows an inverse association between vegetable intake and PFAS levels [50, 51]. We attempted to estimate the number of vegetarians, but only 12 participants reported not eating any meat products. Our questionnaire was also restricted to dietary patterns during pregnancy, which may not be predictive of PFAS levels over time as PFAS bioaccumulate and diets may change more frequently. However, this exposure misclassification is likely non-differential and would bias our results toward the null. Shorter-chain PFAS were detected at low concentrations in our study and prior research has suggested that shorter-chain PFAS, such as PFBS, can bioaccumulate in the liver of fish [52]. In humans, PFAS tend to accumulate in substantial amounts across various tissues, including the lung and liver [53]. This may suggest that the serum PFAS levels in our study underestimate total bodily exposures.

Drinking water contamination is considered an important source of PFAS exposure in many communities, and people with contaminated drinking water have elevated PFAS in their blood [54, 55]. However, local San Francisco Bay Area water systems are not likely a significant source of PFAS exposure for CIOB participants; municipal water systems in the locations where most study participants live were tested for PFAS under the Environmental Protection Agency's Unregulated Contaminant Monitoring Rule in 2016; tests of San Francisco Public Utilities Commission water sources between 2012 and 2018 did not find measurable levels of several PFAS in San Francisco or surrounding community municipal water systems [56, 57]. PFAS are also found in consumer products and building materials, representing additional exposure sources that we were unable to measure. Thus, our results may be subject to residual confounding by these factors. In addition, diet was assessed based on a self-report questionnaire asking about certain foods and foods in certain food packaging materials, which may be subject to measurement error as participants may not accurately recall frequency of all foods eaten during pregnancy. Our study had a relatively small sample size, which limited our statistical power and ability to examine certain dietary categories, including fish and shellfish, with more granularity. This imprecision is also reflected in some of the wide CIs, particularly in our analyses stratified by food insecurity and financial strain. Furthermore, we did not make any adjustments for multiple comparisons, which may increase the likelihood of chance findings. Importantly, adjusting for multiple comparisons is not always necessary in exploratory observational studies [58, 59], as it may increase the probability of type II error due to low statistical power. We did focus the interpretation of our results on identifying consistent patterns, rather than specific point estimates. Lastly, our study is cross-sectional as PFAS levels and diet were both assessed at the same second trimester visit. However, given the long half-life of PFAS, it is unlikely that our results would be subject to reverse causality.

**CONCLUSIONS**

In the CIOB study population, we found that individuals who reported drinking milk and eating cheese, fish, red meat, and poultry at least once a week, compared to less than once a week, had elevated levels of PFNA, PFOS, PFDeA, and PFUeA. Processed foods, including take-out foods, pizza, and popcorn, were not associated with PFAS levels in our study. While our results contrast...
with prior work indicating that contact with food packaging materials may be a source of PFAS exposure, our findings may be attributed to the low level of consumption of processed foods in this population. In our study population, animal products are the main dietary source of PFAS. Given the rise of animal consumption worldwide [48], it is important to consider this source as an important dietary route of PFAS exposure during pregnancy.

REFERENCES

1. Sunderland HM, Hu XC, Dassuncao C, Tokranov AK, Wagner CC, Allen JG. A review of the pathways of human exposure to poly- and perfluoralkyl substances (PFASs) and present understanding of health effects. J Expo Sci Environ Epidemiol. 2019;29:131–47.
2. Calafat AM, Wong LY, Kuklenyk Z, Reidy JA, Needham LL. Perfluorooalkyl chemicals in the U.S. population: data from the National Health and Nutrition Examination Survey (NHANES) 2003–2004 and comparisons with NHANES 1999–2000. Environ Health Perspect. 2007;115:1596–602.
3. Barry V, Winquist A, Steenland K. Perfluorooctanoic acid (PFOA) exposures and incident cancers among adults living near a chemical plant. Environ Health Perspect. 2013;121:1313–8.
4. Darrow LA, Stein CR, Steenland K. Serum perfluorooctanoic acid and perfluorooctane sulfonate concentrations in relation to birth outcomes in the Mid-Ohio Valley, 2005-2010. Environ Health Perspect. 2013;121:1207–13.
5. United States Environmental Protection Agency. Technical Fact Sheet – perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA). 2017. https://www.epa.gov/sites/production/files/2017-12/documents/factsheet_contaminants_pfos_pfoa_11-20-17_508_0.pdf. Accessed 15 Mar 2021.
6. Dong Z, Wang H, Yu YY, Li YB, Naidu R, Liu Y. Using 2003–2014 U.S. NHANES data to determine the associations between per- and polyfluoralkyl substances and children’s health and immunotoxicity. J Expo Sci Environ Epidemiol. 2019;17:461–8.
7. Wang Z, DeWitt JC, Higgins CP, Cousins IT. A never-ending story of per- and polyfluoralkyl substances (PFASs)? Environ Sci Technol. 2015;51:2508–18.
8. Giesy JP, Kannan K. Global distribution of perfluorooctane sulfonate in wildlife. Environ Sci Technol. 2001;35:1339–42.
9. Fair PA, Wolf B, White ND, Arnott SA, Kannan K, Karthikraj R, et al. Perfluoralkyl substances (PFASs) in edible fish species from Charleston Harbor and tributaries, South Carolina, United States: Exposure and risk assessment. Environ Res. 2019;171:266–77.
10. Jogsten IE, Perelló G, Llebaria X, Bigas E, Martí-Cid R, Kärrman A, et al. Exposure to perfluorinated compounds in Catalonia, Spain, through consumption of various raw and cooked foodstuffs, including packaged food. Food Chem Toxicol. 2009;47:1577–83.
11. Kingsley SL, Elliot MN, Kelsey KT, Calafat AM, Ehrlich S, Lanphear BP, et al. Variability and predictors of serum perfluoralkyl substance concentrations during pregnancy and early childhood. Environ Res. 2018;165:247–57.
12. Shu H, Lindh CH, Wikström S, Bornehag C-G. Temporal trends and predictors of perfluoralkyl substances serum levels in Swedish pregnant women in the SELMA study. PLoS One. 2018;13:e0209255.
13. Zhou W, Zhao S, Zhou Y, Liu X, Yuan T, et al. Dietary intake, drinking water ingestion and plasma perfluoralkyl substances concentration in reproductive aged Chinese women. Environ Int. 2019;127:487–94.
14. Trowbridge J, Gerona RR, Lin T, Rudel RA, Bessonneau V, Buren H, et al. Exposure to perfluoralkyl substances in a cohort of women firefighters and office workers in San Francisco. Environ Sci Technol. 2020;54:3363–74.
15. Yuan G, Peng H, Huang C, Hu J. Ubiquitous occurrence of fluorotelomer alcohols in eco-friendly paper-made food-contact materials and their implication for human exposure. Environ Sci Technol. 2016;50:942–50.
16. Schiødt LA, Balan SA, Blum A, Andrews QO, Strynar MJ, Dickinson ME, et al. Fluorinated compounds in U.S. fast food packaging. Environ Sci Technol Lett. 2017;4:105–11.
17. Park SK, Peng Q, Ding N, Mukherjee B, Harlow SD. Determinants of per- and polyfluoralkyl substances (PFAS) in midlife women: evidence of racial/ethnic and geographic differences in PFAS exposure. Environ Res. 2019;175:186–99.
18. Susmann Herbert P, Schlaider Laurel A, Rodgers Kathryn M, Ruel Ruthann A. Dietary habits related to food packaging and population exposure to PFASs. Environ Health Perspect. 2019;127:107003.
19. Tian Y, Zhou Y, Mao M, Wang Z, Yuan W, Liu X, et al. Determinants of plasma concentrations of perfluoralkyl and polyfluoralkyl substances in pregnant women from a birth cohort in Shanghai, China. Environ Int. 2018;119:165–73.
20. Wang B, Chen Q, Shen L, Zhao S, Pang W, Zhang J. Perfluorooalkyl and polyfluoralkyl substances in cord blood of newborns in Shanghai, China: implications for risk assessment. Environ Int. 2016;97:7–14.
REFERENCES

45. Vestergren R, Orata F, Berger U, Cousins IT. Bioaccumulation of perfluoroalkyl acids in dairy cows in a naturally contaminated environment. Environ Sci Pollut Res. 2013;20:7959–69.

46. Jones PD, Hu W, De Coen W, Newsted JL, Giesy JP. Binding of perfluorinated fatty acids to serum proteins. Environ Toxicol Chem. 2003;22:2639–49.

47. Hosomi R, Yoshida M, Fukunaga K. Seafood consumption and components for health. Glob J Health Sci. 2012;4:72–86.

48. González N, Marquès M, Nadal M, Domingo JL. Meat consumption: which are the current global risks? A review of recent (2010–2020) evidences. Food Res Int. 2020;137:109341.

49. Zabaleta I, Negreira N, Bizkarguenaga E, Prieto A, Covaci A, Zuloaga O. Screening and identification of per- and polyfluoroalkyl substances in microwave popcorn bags. Food Chem. 2017;230:497–506.

50. Lin P-ID, Cardenas A, Hauser R, Gold DR, Kleinman KP, Hivert M-F, et al. Dietary characteristics associated with plasma concentrations of per- and polyfluoroalkyl substances among adults with pre-diabetes: cross-sectional results from the Diabetes Prevention Program Trial. Environ Int. 2020;137:105217.

51. Halliderson T, Fei C, Olsen J, Lipworth L, McLaughlin JK, Olsen SF. Dietary predictors of perfluorinated chemicals: a study from the Danish National Birth Cohort. Environ Sci Technol. 2008;42:8971–7.

52. Goeritz I, Falk S, Stahl T, Schäfers C, Schlechtriem C. Biomagnification and tissue distribution of perfluoroalkyl substances (PFASs) in market-size rainbow trout (Oncorhynchus mykiss). Environ Toxicol Chem. 2013;32:2078–88.

53. Pérez F, Nadal M, Navarro-Otage A, Fábrega F, Domingo JL, Barceló D, et al. Accumulation of perfluoroalkyl substances in human tissues. Environ Int. 2013;59:354–62.

54. Hu XC, Andrews DQ, Lindstrom AB, Bruton TA, Schaeider LA, Grandjean P, et al. Detection of poly- and perfluoroalkyl substances (PFASs) in U.S. drinking water linked to industrial sites, military fire training areas, and wastewater treatment plants. Environ Sci Technol Lett. 2016;3:344–50.

55. Hurley S, Houtz E, Goldberg D, Wang M, Park J-S, Nelson DO, et al. Preliminary associations between the detection of perfluoralkyl acids (PFAAs) in drinking water and serum concentrations in a sample of California women. Environ Sci Technol Lett. 2016;3:264–9.

56. US EPA. Occurrence data for the unregulated contaminant monitoring rule. 2021. https://www.epa.gov/dwucmr/occurrence-data-unregulated-contaminant-monitoring-rule. Accessed 1 June 2021.

57. San Francisco Public Utilities Commission. Screening and recommended actions for health. Glob J Health Sci. 2012;4:72–86.

58. Wrenn JM, withdrawal and publication of certain under the Origin of Human and Animal Tissue rule. Environ Sci Technol. 2020;54:1604–12.

59. Tufekci A, Seckin O, Ceylan C, Dikici Y, Avci Z, et al. Maternal phthalate and phthalate alternative metabolites and urinary biomarkers of estrogens and testosterone across pregnancy. Environ Int. 2021;155:106676.

ACKNOWLEDGEMENTS

We would like to thank Dimitri Panagopoulos Abrahamsson for reviewing this manuscript, our clinical research team for collecting the data, the study participants who participated in the CIOB study, and the DTSC biomonitoring team for the laboratory analysis of PFAS in serum.

AUTHOR CONTRIBUTIONS

SME was responsible for data cleaning and analysis, interpretation of results, writing—original draft, revisions, and editing. DEG contributed to data analysis, interpretation of results, writing—reviewing and editing. JT contributed to data analysis, interpretation of results, writing—reviewing and editing. LC contributed to data analysis, interpretation of results, writing—reviewing and editing. SCS was responsible for the measurement of PFAS in maternal serum. J-SP oversaw the PFAS method development and measurement analysis and was responsible for writing—reviewing and editing. ED was responsible for administration of research design, recruitment, and study protocol implementation, writing—reviewing and editing. AMP contributed to data analysis, interpretation of results, writing—reviewing and editing. TJW was responsible for funding acquisition, project administration, writing—reviewing and editing. RM-F was responsible for funding acquisition, design of CIOB study protocols, oversight of statistical analysis, interpretation of results, project administration, writing—original draft, revisions, and editing.

FUNDING

This work was supported by grants R01ES023272 and R01ES023272 from the National Institute of Environmental Health Sciences, and UG3OD023272 and UH3OD023272 from the National Institutes of Health Environmental influences on Child Health Outcomes (ECHO) program. LC’s participation was supported by the JPB Environmental Health Fellowship.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41370-021-00386-6.

Correspondence and requests for materials should be addressed to Stephanie M. Eick or Rachel Morello-Frosch.

Reprints and permission information is available at http://www.nature.com/reprints

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2021