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Perfluoroalkyl substances and food allergies in adolescents

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Abstract

Perfluoroalkyl and polyfluoroalkyl substances (PFASs) are a class of organic compounds that are persistent in the environment due to their stable carbon-fluorine backbone, which is not susceptible to degradation. Research suggests these chemicals may exert an immunotoxic effect. The aim of this study is to investigate the associations between four PFASs – perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHxS) –with food sensitization and food allergies in adolescent participants (ages 12–19 years) in the National Health and Nutrition Examination Survey (NHANES) 2005–2006 and 2007–2010, respectively. We performed multivariate logistic regression to analyze the association between individual PFASs with food sensitization (defined as having at least 1 food-specific IgE level ≥ 0.35 kU/L) in NHANES 2005–2006 and food allergies (self-reported) in NHANES 2007–2010. Serum PFOA, PFOS, and PFHxS were statistically significantly associated with higher odds to have self-reported food allergies in NHANES 2007–2010.When using IgE levels as a marker of food sensitization, we found that serum PFNA was inversely associated with food sensitization (NHANES 2005–2006). In conclusion, we found that serum levels of PFASs were associated with higher odds to have self-reported food allergies. Conversely, adolescents with higher serum PFNA were less likely to be sensitized to food allergens. These results, along with previous studies, warrant further investigation, such as well-designed longitudinal studies.

Keywords

Adolescents; Food allergies; NHANES; Perfluoroalkyl compounds

1. Introduction

Perfluoroalkyl and polyfluoroalkyl substances (PFASs) are a class of organic compounds that are persistent in the environment due to their stable carbon-fluorine backbone, which is

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Disclaimer

The findings and conclusion in this report are those of the authors and do not necessarily represent the official position of CDC/ATSDR.

IRB approval: CDC/ATSDR has determined that our research did not meet the criteria for human research as per federal regulation and therefore did not require review.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.envint.2015.12.020.

not susceptible to degradation (ATSDR, 2015). Not only are these compounds found to be resistant to deterioration in the environment, but they are also found to persist within the human body with an average half-life in blood greater than four years (ATSDR, 2015). These compounds can be subdivided into groups including perfluorinated sulfonic acid (PFSA) and perfluorinated carboxylic acid (PFCA), which include the two most widely produced PFASs, perfluorooctane sulfonic acid (PFOS) and perfluorooctanoic acid (PFOA), respectively. This class of compounds has the unique ability to repel water, stains, and grease, leading to their extensive use as surface coatings and protectant formulations in a wide range of products including nonstick coatings on cookware, paper and cardboard, carpets, and other textiles (ATSDR, 2015). There have been large volumes of these chemicals produced since the 1950s, with the most prevalent compounds being PFOA and PFOS. However, recently there have been attempts to reduce the production of these compounds; PFOS was included in Annex B of the 2009 Stockholm Convention on Persistent Organic Pollutants (Wang et al., 2009), and the EPA launched an initiative to voluntarily reduce PFOA emissions in 2006 (EPA, 2013).

The main sources of PFASs exposure for the general population include contaminated drinking water, food products, dust, and consumer products that contain these chemicals. Furthermore, human breast milk provides an important source of exposure for infants (ATSDR, 2015). The toxicity of PFASs is not fully understood; however, these compounds have been linked to health effects including hepatotoxicity, developmental toxicity, hormonal effects, immunotoxicity, and carcinogenic potency (Fromme and Tittlemier, 2009). Recently, research has begun to focus on the immunotoxic effects of these chemicals. It has been shown that exposure to PFASs can lead to altered inflammatory responses, production of cytokines, and adaptive and innate immune responses (DeWitt et al., 2009). Most of the animal studies show exposure to PFASs in mouse models has an immunosuppressive effect resulting in lower IgM production (DeWitt et al., 2008; Peden-Adams et al., 2008; Yang et al., 2000). Additionally, PFASs exposure has been suggested to alter inflammatory responses and affect production of cytokines in laboratory animals (DeWitt et al., 2009).

Furthermore, it has been shown that these effects may occur at exposure levels comparable to human exposure levels in the general population (DeWitt et al., 2012). Several epidemiological studies have investigated the immunotoxic potential of PFASs with varying results. Okada et al. (2014) investigated associations between prenatal exposure to PFASs with self-reported infant allergic disease; they found that several PFASs, including PFOA and perfluorononanoic acid (PFNA) – another compound included in the PFCA group –were associated with lower odds for all allergic diseases in female infants. Similarly, Okada et al. (Okada et al., 2012) found that cord blood immunoglobulin E (IgE) levels “decreased significantly” with high maternal PFOA concentration among female infants. However, no significant associations were observed between maternal PFOS and PFOA levels and cord blood IgE levels among male infants. On the other hand, Wang et al. (Wang et al., 2011) found that cord blood IgE levels were positively correlated with maternal serum PFOA and PFOS in male infants.

Food allergies are adverse immune reactions that affect up to 6% of children and 3–4% of adults (Wang and Sampson, 2009). Epidemiological studies in humans suggest that the

prevalence of food allergies is higher among young children than among adults (Branum and Lukacs, 2008). Children often outgrow their allergies to milk, egg, wheat and soy products; however, nut and shellfish allergies often persist to adulthood (Wang and Sampson, 2009). Recently, it has been suggested that the average time period for children to outgrow these allergies may be increasing, with some allergies continuing into the teenage years rather than subsiding in early school-age (Wang and Sampson, 2009).

PFASs have been associated with asthma. Dong et al. (2013) in a case control study (n cases = 231; n controls = 225) reported that higher level of PFOA and perfluorododecanoic acid (PFDoA) were associated with statistically significant higher odd to have asthma. Furthermore, they found, that among children with asthma, serum IgE were positively associated with PFOS and PFOA. Humblet et al. (2014) analyzing data form NHANES 1999–2008 reported an association of PFOA with higher odd ratio of self-reported diagnosis of asthma and an inverse relationship between PFOS and asthma. However, when the analyses were conducted with sample weight the associations were attenuated and did not reach statistical significance. Recently, Smit et al. (2015) in a prospective study of 1024 mother–child pairs from Greenland and Ukraine from the INUENDO birth cohort reported no association of maternal pregnancy serum perfluoroalkyl substances with reported “ever asthma” in children at age between 5 and 9 years. Whereas, there was an inverse association with current wheeze in the mother–child pairs in the Ukraine cohort, but null finding in the Greenland cohort.

Due to the scarcity of information pertaining to the immunotoxic effects of PFASs, we sought to look at the associations between four main PFASs – PFOS, PFOA, PFNA, and perfluorohexane sulfonic acid (PFHxS) – with food sensitization (defined as having at least 1 food-specific serum IgE ≥ 0.35 kU/L) and self-reported food allergies in adolescent participants (ages 12–19 years) in the National Health and Nutrition Examination Survey (NHANES) 2005–2006 and 2007–2010, respectively.

2. Methods

2.1. Study population

NHANES are cross-sectional, nationally representative surveys of the non-institutionalized civilian population of the United States conducted by the National Center for Health Statistics (NCHS), CDC (Johnson et al., 2013). The survey employs a multistage stratified probability sample based on selected counties, blocks, households, and persons within households (Johnson et al., 2013). Beginning in 1999, the survey was conducted continuously and data was released in 2-year cycles. For our study, we merged publicly available files for NHANES cycles 2007–2008 and 2009–2010 using NCHS recommendations for information on self-reported food allergies (Johnson et al., 2013). We also used NHANES 2005–2006 for analysis on food sensitization, as indicated by food-specific (eggs, milk, peanuts, or shrimp) IgE levels.

The NHANES surveys include data from NCHS-trained professional interviews conducted in participants’ homes as well as extensive physical examinations (including blood and urine collection) conducted at mobile exam centers. All procedures were approved by the NCHS

Research Ethics Review Board (Protocol #2005–2006 http://www.cdc.gov/nchs/nhanes/irba98.htm), and all participants provided written informed consent.

In the 2005–2006, 2007–2008, and 2009–2010 data sets, serum PFASs were measured in a randomly selected one-third subsample of persons 12 years and older by the CDC's National Center for Environmental Health (NCEH), Division of Laboratory Sciences (DLS), which coordinates the National Biomonitoring Program (NBP) to assess nutritional status and the exposure of the U.S. population to environmental chemicals and toxic substances (http://www.cdc.gov/biomonitoring/). For our analysis, we included adolescent (ages 12–19 years) participants who had biological measurements for PFASs. Participants with missing covariates (e.g. serum cotinine, etc.) included in the multivariable-adjusted models were excluded from our analyses.

2.2. PFASs measurement

NCEH/DLS analyzed the serum levels of twelve different PFASs. We included PFOA, PFNA, PFOS, and PFHxS serum sample results in our analyses because they were detected in >95% of the samples. These compounds were measured using automated solid-phase extraction coupled to reverse-phase high-performance liquid chromatography/tandem mass spectrometry (http://www.cdc.gov/nchs/data/nhanes/nhanes_09_10/PFC_F_Polyfluorinated_Compounds_met.pdf). The limit of detection (LOD) was 0.1 ng/mL for PFOA and PFHxS, 0.2 ng/mL for PFOS, and 0.082 ng/mL for PFNA. For concentrations less than the LOD, a value equal to the limit of detection divided by the square root of two was used.

2.3. Outcomes

We investigated the presence of food sensitization (NHANES 2005–2006) and food allergies (NHANES 2007–2010) as the outcomes of interest. The use of these two different outcomes was based on the availability of information in each cycle. For NHANES 2005–2006, serum food specific IgE levels were measured using the ImmunoCAP system and were performed at a central laboratory of Elmhurst Memorial Hospital in Elmhurst, IL. Food sensitization was defined as having at least 1 food-specific serum IgE ≥ 0.35 kU/L. The food-specific IgEs measured in NHANES 2005–2006 included egg, milk, peanuts, and shrimp. Chi-square analyses did not found any significant difference in food sensitization between gender ($p = 0.59$) and between age groups 12–15 years vs 16–19 years ($p = 0.82$) (data not shown). Also, there was not significant difference between specific food IgE between gender and between age groups (data not shown).

For NHANES 2007–2010, IgE levels were not measured. However, the updated questionnaire included information on food allergies; this was ascertained by the response to the self-reported question: "Do you have any food allergies?". We therefore used this question as a binary outcome in our analysis. Also, if the participants s reported food allergy, they were further asked, "What foods are you allergic to?" with options including allergies to wheat, cow's milk, eggs, fish, shellfish, corn, peanuts, other nuts, soy products, and other foods. A discrepancy between self-reported food allergies and confirmed sensitization particularly for self-reported milk and wheat has been reported (Eller et al., 2009). However,

the population-based study by Ben-Shoshan et al. (2010) showed that the prevalence to self-reported allergy to peanut, tree nut, fish or shellfish did not differed with the prevalence of probable food allergy based on self-reported physician diagnosis and a convincing clinical history of an IgE-mediated reaction. Therefore, we also performed analyses restricted to participants that self-reported allergy to peanuts, tree nuts, fish or shellfish and because of the low number of cases we used PFASs as natural log-transformed. Chi-square analyses did not found any significant difference in self-reported food allergy between gender ($p = 0.46$) and between age groups 12–15 years vs 16–19 years ($p = 0.41$) (data not shown). Also, there was not significant difference between specific reported food allergy between gender and between age groups (data not shown).

2.4. Covariates

We adjusted for the following covariates: age, race/ethnicity, sex, body mass index (BMI), and serum cotinine as a biomarker of tobacco smoke. For NHANES 2005–2006, race/ethnicity was categorized in five categories — non-Hispanic white, non-Hispanic black, Mexican-American, other Hispanic, and other. Whereas, for NHANES 2007–2010, race/ethnicity was categorized in four categories — non-Hispanic white, non-Hispanic black, Hispanic (Mexican-American and other Hispanic), and other. This difference in racial/ethnicity classification was due to a change in the NHANES oversampling procedure, starting from NHANES 2007–2008.Serum cotinine was log-natural transformed in the analyses. A sensitivity analysis was conducted using additional adjustment for poverty income ratio (PIR). Poverty income ratio is a measure of socioeconomic status and represents the calculated ratio of household income to the poverty threshold after accounting for inflation and family size; it was categorized in two levels: $PIR \leq 1$ (at or below the poverty level) and $PIR > 1$ (above the poverty level).

2.5. Statistical methods

SAS 9.3 (SAS Institute, Cary, NC) was used for all statistical analyses and SAS-Callable SUDAAN 10 (Research Triangle Institute, Research Triangle Park, NC) was used with weights and survey strata provided with the survey to account for the oversampling, complex sampling methods, and non-response of NHANES. We estimated sampling errors using the Taylor series linearized method. Logistic regression analyses were used to investigate the association of PFCs with food sensitization (defined as having at least 1 food-specific serum $IgE \geq 0.35$ kU/L) in NHANES 2005–2006 and with self-reported food allergies in NHANES 2007–2010. PFCs were categorized as weighted quartiles based on the distribution of serum PFC levels among the study population, resulting in approximately the same weighted number of participants within each quartile. Complementary analyses using log-natural transformed PFASs were evaluated in association with the food allergy outcomes. We also assessed possible interactions between PFASs and gender, but because the interaction was not statistically significant, it was not included in the models. p-Values from Satterthwaite statistics were presented at the significance level < 0.05.

3. Results

Table 1 and Table 2 present the characteristics of the study population. For 2005–2006, the geometric mean (GM) serum PFOA, PFNA, PFOS and PFHxS were 3.59 ng/mL, 0.93 ng/mL, 14.98 ng/mL, and 2.09 ng/mL, respectively (Table 1). For 2007–2010, the geometric mean (GM) serum PFOA, PFNA, PFOS and PFHxS for adolescent participants (12–19 years of age) in NHANES 2007–2010 were 3.27 ng/mL, 1.13 ng/mL, 8.74 ng/mL, and 2.19 ng/mL, respectively (Table 2). The geometric mean age for all cycles was 15 years and approximately 51% of the participants were males. The geometric mean BMI was 22.79 kg/m^2 in NHANES 2005–2006 (Table 1), and it was slightly higher in the later cycles with a GM of 23.19 kg/m^2 (Table 2). Among the adolescent participants, 18.57% had food sensitization (defined as having at least 1 food-specific serum IgE ≥ 0.35 kU/L) (NHANES 2005–2006) (Table 1) and 7.47% had self-reported food allergies (NHANES 2007–2010) (Table 2).

3.1. Food sensitization (NHANES 2005–2006)

Table 3 presents the results of the logistic regression analyses of food sensitization with individual PFASs. Those in the highest quartile of PFNA had a statistically significant negative association with food sensitization (lower odds of occurrence) (OR = 0.51, 95% CI: 0.28, 0.92) compared to the referent, lowest quartile. Furthermore, PFNA showed a non-significant monotonic dose response for increasing quartiles of exposure. No other PFASs were significantly associated with overall food sensitization based on IgE levels (NHANES 2005–2006). Sensitivity analyses including poverty income ratio yielded results similar to those from the primary analyses (data not shown). When looking at food-specific IgE sensitization, we found that the highest quartiles of PFOS, and PFNA were statistically significantly, inversely associated with shrimp sensitization (OR = 0.08, 95% CI: 0.01, 0.66; OR = 0.29, 95% CI: 0.09, 0.93; respectively) compared to the respective, referent quartiles (Supplemental Table 1). Also, individuals in the 3rd quartile of PFHxS were inversely associated with shrimp sensitization (Supplemental Table 1).

Sensitivity analyses using log-natural transformed PFASs did not find any statistically significant associations with food sensitization (IgE level ≥ 0.35 kU/L), indicating that the associations are most likely not linear (Supplemental Table 2). Sensitivity analyses including poverty income ratio yielded results similar to those from the primary analyses (data not shown).

3.2. Self-reported food allergies (NHANES 2007–2010)

Those in the highest quartile of PFOA and PFHxS had statistically significant positive associations with self-reported food allergies (higher odds of occurrence) (OR = 9.09, 95% CI: 3.32, 24.90; and OR = 3.06, 95% CI: 1.35, 6.93, respectively) compared to those in their referent quartiles. Furthermore, PFOA had a statistically significant p-trend ($p < 0.001$) for increasing quartiles associated with food allergies, indicating a dose–response trend. PFHxS did not demonstrate a monotonic dose–response based on the p-value for trend. Participants in the third and fourth quartiles of PFOS had statistically significant positive associations with self-reported food allergies (higher odds of occurrence) (OR = 2.43, 95% CI: 1.05,

5.59; and OR = 2.95, 95% CI: 1.21, 7.24, respectively) compared to the referent quartile; however, the p-value for trend was not statistically significant suggesting that the dose–response may not be linear No statistically significant association was found between PFNA and self-reported food allergies (Table 4). Sensitivity analyses including poverty income ratio yielded results similar to those from the primary analyses (data not shown).

Complementary analyses using log-natural transformed PFASs gave similar results, with the exception of PFHxS, where the statistically significant association was lost (Supplemental Table 2). Analyses restricted to reported food allergy to peanuts, tree nuts, fish or shellfish also showed a positive association with PFOA (Supplemental Table 2). Sensitivity analyses including poverty income ratio yielded results similar to those from the primary analyses (data not shown).

4. Discussion

To our knowledge, this is the first study reporting an association between self-reported food allergies and PFASs in adolescents (ages 12–19 years) using a nationally representative survey, NHANES 2007–2010. Additionally, we build on the current body of research that has looked at PFASs association with food sensitization based on IgE levels, using NHANES 2005–2006.

We found that participants in the highest quartiles of PFOA, PFOS, and PFHxS had statistically significant positive associations with self-reported food allergies. In a recent study, Okada et al. (2012) used a self-reported allergy status to evaluate infant (≤18 months of age) food allergies in a prospective cohort of 343 mother–infant pairs in Japan. They found no statistically significant association between maternal PFOS or PFOA levels with food allergies in the infants. In another study, Okada et al. (2014) investigated associations between prenatal exposure to PFASs with self-reported infant allergic disease; they found that several PFASs, including PFOA and PFNA were associated with lower odds for all allergic diseases in female infants (negative association). The differences between our study results and those observed in other studies could be due to many factors, including study design, covariates included, and exposure measurement. Furthermore, Okada et al. (2014) and Okada et al. (2012) were focused on infant participants, whereas we focused on adolescents due to the exposure assessment present in the NHANES database. As serum PFASs concentration is greatly influenced by prenatal and infant exposure through maternal levels in the placenta and breast milk, the difference in age in the study populations could have affected the outcomes. Furthermore, the use of a self-reported outcome could potentially be subjected to information bias.

In our analyses of NHANES 2005–2006 using IgE levels as a marker of food sensitization (defined as having at least 1 food-specific serum IgE ≥ 0.35 kU/L), we found that PFNA had a statistically significant negative association with food sensitization. Several epidemiological studies have investigated the immunotoxic effects of PFASs using IgE levels rather than presence or absence of food allergies. Wang et al. (2011), in a Taiwanese birth cohort, found that PFOA and PFOS levels positively correlated with cord blood IgE levels. These results were limited to boys after stratification by gender. Okada et al. (2012)

investigated IgE levels in association with PFASs and found that PFOA was statistically significantly inversely associated with IgE levels in female infants (Okada et al., 2012). Recently, Stein et al. (2007) using the NHANES 2005–2006 cohort, reported that adolescents (12–19 years old) in the higher serum PFOS concentration were inversely associated with allergic sensitization. Moreover, in analyses performed using specific allergens, the authors reported that adolescent with higher serum PFOS or PFHxS were inversely associated with allergic sensitization to “cockroach or shrimps” (Stein et al., 2007). These result are in agreement with our finding of an inverse association of serum PFOS with specific allergic sensitization to shrimp. However, we also found that in our analyses, PFNA was inversely associated with specific allergic sensitization to shrimp. The difference between our analyses and those of Stein et al. (2007) lies on the outcome definitions. For example, Stein et al. (2007) defined allergic sensitization based to the total IgE, whereas we restricted allergic sensitization only to those associated to food (milk, eggs, peanuts and shrimp).Moreover, Stein et al. (2007) analyzed the presence of allergy sensitization to “cockroach or shrimps”, whereas we analyzed allergy sensitization to shrimp only.

Our study findings on the association of serum PFASs with self-reported food allergies (NHANES 2007–2010) and food sensitization (using food specific IgE levels as biomarker) (NHANES 2005–2006) may seem contradictory. However, it has been suggested that circulating IgE antibodies may remain undetectable in clinically diagnosed food allergies (Wang and Sampson, 2009). In other words, the specificity of an IgE test may be relatively poor, resulting in a positive IgE test in sensitized subjects without manifested food allergies (Asero et al., 2007). Sensitization is the presence of specific IgE responses occurring after exposure of the immune system to an allergen; whereas, a clinical allergy is the development of symptoms upon consumption of food. It is important to note that food allergy cannot be directly predicted on the basis of sensitization (Asero et al., 2007). Therefore, IgE levels and food allergies may not be consistent within an individual.

The literature on this subject is reflective of the discrepancies between IgE levels and clinical allergies. In a population-based cohort study conducted on children in the UK, researchers conducted a food challenge on 79 children who were peanut-sensitized based on IgE measures. Of the 79 children, only 7 were designated as having a food allergy (Nicolaou et al., 2010). Another study investigating the correlation between skin prick tests for IgE levels and food challenges found that there was a concordance of only around 58% between a positive prick test and positive challenge in 430 children exposed to commercial extracts of food (Rancé et al., 1997). Therefore, the differing results we observed are not inconsistent with those reported elsewhere. Additionally, in our analyses, the use of two different populations to evaluate these outcomes makes comparisons difficult, as we do not have information on both IgE levels and self-reported allergies for any participants.

Overall, we found that around 18.5% of the adolescent participants in NHANES 2005–2006 had food sensitization, while 7.5% of the adolescent participants in NHANES 2007–2010 reported having food allergies. These levels are somewhat higher than reported elsewhere; in 2007, approximately 3.9% of US children under the age of 18 were reported to have a food or digestive issues in the previous year (Branum and Lukacs, 2008).

There are several important limitations to this study. This is a cross-sectional study, which limits the inferences that can be made, since temporality between exposure and outcome cannot be ascertained. Therefore, reverse causation cannot be excluded, where some unknown lifestyle factor might result in people with food allergies being exposed to higher levels of PFASs. Furthermore, our exposure assessment was conducted postnatally in adolescents, rather than prenatally, which represents a more sensitive window of exposure. This is an inherent limitation to the cross-sectional study design, as exposure and outcome are assessed concomitantly. An additional limitation pertains to the use of questionnaires in NHANES, thus there is the possibility of information bias due to a reliance on participants providing accurate information for the self-reported variables. The use of two different outcomes between the different cohorts – sensitivities in NHANES 2005–2006 and allergies in 2007–2010 – make the results not fully comparable between these groups. There is suggestion that there are gender differences in serum PFASs levels and immune response to these exposures (Wang et al., 2011); however, we did not find any statistically significant associations between PFASs and gender. There may have been other potential confounders that affected our results, for example, increasing alcohol consumption has been shown to be associated with increasing PFOS levels (Jain, 2014); however, we did not control for this covariate as our population of interest is not legally allowed to consume alcoholic beverages, thus this information is not available in the public NHANES database. PFASs have a long half-life, thus exposures during the prenatal and infancy period (when breastfeeding) can have an effect on levels of compounds even in adolescents. It would have been beneficial to control for time spent breastfeeding, as this period varies widely in populations, and this is an important route of exposure. Unfortunately, time spent breastfeeding is only available in NHANES for participants 6 years of age and under, so we were not able to control for this variable in our analysis. Another important limitation is the small number of cases which may have decreased the power to detect significant findings.

5. Conclusions

In conclusion, we found that individual PFASs – PFOA, PFOS, and PFHxS – had statistically significant positive associations with self-reported food allergies in NHANES 2007–2010; whereas, PFNA was inversely associated with food sensitization in NHANES 2005–2006. These results should be considered with caution because of the low number of cases and the cross-sectional design of the study. Additional studies, such as well-designed prospective studies to evaluate the effect of PFASs exposure and the risk of developing food allergies or food sensitizations are needed to more fully understand the implications of the findings of this study.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Table 1

Weighted characteristics for adolescent (aged 12–19) participants in NHANES 2005–2006 where presence of food sensitization (IgE levels) was assessed.

	2005–2006
n	637
Serum perfluorooctanoic acid (PFOA) (ng/mL), GM (SE)	3.59 (0.16)
Serum perfluorononanoic acid (PFNA) (ng/mL), GM (SE)	0.93 (0.08)
Serum perfluorooctane sulfonic acid (PFOS) (ng/mL), GM (SE)	14.98 (0.35)
Serum perfluorohexane sulfonic acid (PFHxS) (ng/mL), GM (SE)	2.09 (0.18)
Age (years), GM(SE)	15.33 (0.13)
BMI (kg/m^2), GM (SE)	22.79 (0.27)
Serum cotinine (ng/mL), GM (SE)	0.25 (0.04)
Sex	
Male %	50.93 (2.63)
Female %	49.07 (2.63)
Income	
PIR < =1 (indicating at or below poverty level) % (SE)	18.67 (1.51)
PIR > 1 (above poverty level) % (SE)	81.33 (1.51)
Race	
Non-Hispanic White % (SE)	62.36 (3.76)
Non-Hispanic Black % (SE)	15.07 (3.22)
Mexican American % (SE)	11.57 (1.35)
Other Hispanic % (SE)	4.56 (1.04)
Other %(SE)	6.44 (1.95)
Food sensitization[a]	
IgE ≥ 0.35 kU/L, % (SE)	18.57 (2.23) [n = 150]
IgE < 0.35 kU/L, % (SE)	81.43 (2.23) [n = 487]
Milk sensitization[a]	
IgE ≥ 0.35 kU/L, % (SE)	5.73 (0.76) [n = 42]
IgE < 0.35 kU/L, % (SE)	94.27 (0.76) [n = 595]
Egg sensitization[a]	
IgE ≥ 0.35 kU/L, % (SE)	2.61 (1.19) [n = 21]
IgE < 0.35 kU/L, % (SE)	97.39 (1.19) [n = 613]
Peanut sensitization[a]	
IgE ≥ 0.35 kU/L, % (SE)	11.87 (1.59) [n = 77]
IgE < 0.35 kU/L, % (SE)	88.13 (1.59) [n = 557]
Shrimp sensitization[a]	
IgE ≥ 0.35 kU/L, % (SE)	6.56 (1.51) [n = 57]
IgE < 0.35 kU/L, % (SE)	93.44 (1.51) [n = 577]

[a]Food sensitization defined as having at least 1 food specific serum IgE level ≥ 0.35 kU/L

Table 2

Weighted characteristics for adolescent (aged 12–19) participants in NHANES 2007–2010 where presence of food allergies (self-report) was assessed.

	2007–2010
n	701
Serum perfluorooctanoic acid (PFOA) (ng/mL), GM (SE)	3.27 (0.09)
Serum perfluorononanoic acid (PFNA) (ng/mL), GM (SE)	1.13 (0.05)
Serum perfluorooctane sulfonic acid (PFOS) (ng/mL), GM (SE)	8.74 (0.40)
Serum perfluorohexane sulfonic acid (PFHxS) (ng/mL), GM (SE)	2.19 (0.10)
Age (years), GM(SE)	15.28 (0.10)
BMI (kg/m^2), GM (SE)	23.19 (0.27)
Serum cotinine (ng/mL), GM (SE)	0.17 (0.02)
Sex	
Male %	50.93 (2.58)
Female %	49.07 (2.58)
Income	
PIR ≤ 1 (indicating at or below poverty level) % (SE)	22.70 (2.34)
PIR > 1 (above poverty level) % (SE)	77.30 (2.34)
Race	
Non-Hispanic White % (SE)	59.34 (2.93)
Non-Hispanic Black % (SE)	14.75 (1.38)
Hispanic (Mexican American and Other Hispanic) % (SE)	18.73 (2.40)
Other % (SE)	7.19 (1.24)
Food allergies (self-reported)	
Yes % (SE)	7.47 (1.09) [n = 55]
No % (SE)	92.53 (1.09) [n = 646]

Table 3

Logistic regression[a] (odds ratio and 95% confidence interval) for individual PFAS compounds with food sensitization[b] in adolescent (ages 12–19) participants in NHANES 2005–2006.

	n (cases/controls)	OR (upper-lower 95% CI)
PFOA Q1: ≤2.46 ng/mL	47/136	1.00
PFOA Q2: 2.47–3.78 ng/mL	30/136	0.91 (0.47, 1.76)
PFOA Q3: 3.79–5.36 ng/mL	43/119	1.28 (0.59, 2.76)
PFOA Q4: >5.36 ng/mL	30/96	1.23 (0.57, 2.65)
P-Trend		0.74
PFOS Q1: ≤ 10.65 ng/mL	61/155	1.00
PFOS Q2: 10.66–14.84 ng/mL	30/122	1.21 (0.57, 2.58)
PFOS Q3: 14.85–22.69 ng/mL	40/113	1.35 (0.71, 2.58)
PFOS Q4: >22.69 ng/mL	19/97	0.74 (0.23, 2.40)
p-Trend		0.49
PFNA Q1: ≤ 0.59 ng/mL	32/68	1.00
PFNA Q2: 0.60–0.89 ng/mL	38/157	0.37(0.12,1.16)
PFNA Q3: 0.90–1.36 ng/mL	48/152	0.49 (0.23,1.04)
PFNA Q4: > 1.36 ng/mL	32/110	0.51 (0.28, 0.92)
p-Trend		0.15
PFHxS Q1: ≤1.00 ng/mL	46/139	1.00
PFHxS Q2: 1.01–2.34 ng/mL	43/135	1.11 (0.66,1.88)
PFHxS Q3: 2.35–4.29 ng/mL	30/106	1.46 (0.79, 2.69)
PFHxS Q4: >4.29 ng/mL	31/107	1.17 (0.56, 2.44)
p-Trend		0.72

[a] Adjusted for age, sex, race/ethnicity, BMI, serum cotinine.

[b] Food sensitization defined as having at least 1 food specific IgE level ≥ 0.35 kU/L.

Table 4

Logistic regression[a] (odds ratio and 95% confidence interval) for individual PFAS compounds with food allergies (self-reported) in adolescent (ages 12–19) participants in NHANES 2007–2010.

	n (cases/controls)	OR (upper-lower 95% CI)
PFOA Q1: ≤2.43 ng/mL	8/188	1.00
PFOA Q2: 2.44–3.31 ng/mL	16/176	2.84(0.83, 9.73)
PFOA Q3: 3.32–4.47 ng/mL	10/144	1.70 (0.51,5.65)
PFOA Q4: >4.47 ng/mL	21/138	9.09 (3.32, 24.90)
p-trend		<0.001
PFOS Q1: ≤5.96 ng/mL	12/210	1.00
PFOS Q2: 5.97–9.16 ng/mL	15/157	2.22 (0.85, 5.77)
PFOS Q3: 9.17–13.75 ng/mL	14/147	2.43 (1.05, 5.59)
PFOS Q4: >13.75 ng/mL	14/132	2.95 (1.21, 7.24)
p-Trend		0.27
PFNA Q1: ≤0.79 ng/mL	8/152	1.00
PFNA Q2: 0.80–1.06 ng/mL	13/155	0.83 (0.25, 2.75)
PFNA Q3: 1.07–1.47 ng/mL	19/178	2.09 (0.65, 6.66)
PFNA Q4: >1.47 ng/mL	15/161	1.73 (0.54,5.52)
p-Trend		0.28
PFHxS Q1: ≤ 1.08 ng/mL	12/189	1.00
PFHxS Q2: 1.09–1.88 ng/mL	13/151	1.43 (0.40, 5.14)
PFHxS Q3: 1.89–4.00 ng/mL	14/171	0.99 (0.37, 2.65)
PFHxS Q4: >4.00 ng/mL	16/135	3.06 (1.35, 6.93)
p-Trend		0.11

[a]Adjusted for age, sex, race/ethnicity, BMI, serum cotinine.