Health risks of dietary exposure to perfluorinated compounds

José L. Domingo *

Laboratory of Toxicology and Environmental Health, School of Medicine, Rovira i Virgili, Sant Llorenç 21, 43201 Reus, Catalonia, Spain

ARTICLE INFO

Article history:
Received 19 May 2011
Accepted 1 August 2011
Available online 23 August 2011

Keywords:
Perfluorinated compounds
Food analysis
Human exposure
Dietary intake
Health risks

ABSTRACT

Perfluorinated compounds (PFCs) form a diverse group of chemicals with surface-active properties manufactured for over 50 years. In recent years, a number of studies have reported the ubiquitous distribution of PFCs in human tissues and wildlife. Although the relative importance of the routes of human exposure to these compounds is not well established yet, it has been suggested that food intake and packaging, water, house dust, and airborne are all potentially significant sources. However, dietary intake is probably the main route of exposure to these compounds, including perfluorooctane sulfonate (PFOS) and perfluorooctanoic acid (PFOA), the most extensively investigated PFCs. This paper reviews the state of the science regarding the concentrations of PFCs in foodstuffs, human dietary exposure to these compounds and their health risks. The influence of processing, cooking and packaging on the PFCs levels in food is also discussed. Because of the rather limited information about human dietary exposure, studies to determine exposure to PFCs through the diet for the general population of a number of countries are clearly necessary. The correlation of PFCs body burdens and dietary intake of PFCs should be also established.

© 2011 Elsevier Ltd. All rights reserved.

1. Introduction

Perfluorinated compounds (PFCs) form a diverse group of chemicals with surface-active properties manufactured for over 50 years. The perfluorooctyl acids and their salts, such as perfluorooctyl sulfonates, perfluorooctyl carboxylates, and telomer alcohols, have wide consumer and industrial applications, including protective coatings for fabrics and carpets, paper coatings, insecticides, paints, cosmetics, and fire-fighting foams. In recent years, a number of studies have reported the ubiquitous distribution of PFCs in humans and wildlife (Ahrens, 2011; Fromme et al., 2009; Haug et al., 2011; Kovarova and Svobodova, 2008; Liu et al., 2009, 2010; Paul et al., 2009; Wilhelm et al., 2008, 2010). Among the perfluorooctyl acids, perfluorooctane sulfonate (PFOS), followed by perfluorohexanesulfonate (PFHxS) and perfluorooctanoic acid (PFOA), have been the most extensively studied. These compounds are extremely persistent, bioaccumulative, and of toxicological concern (D’Hollander et al., 2010; Fuentes et al., 2007a; Jensen and Leffers, 2008; Kovarova and Svobodova, 2008; Olsen et al., 2009). In fact, the Conference of the Parties of the Stockholm Convention on Persistent Organic Pollutants (POPs), at its fourth meeting held in May 2009, listed nine additional chemicals as POPs (new POPs), PFOS and its salts, as well as perfluorooctane sulfonyl fluoride are among these new POPs.

Accumulation and trends of PFCs are not largely known yet. However, it is well established that in contrast to the classical more lipophilic POPs such as polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs) or polychlorinated biphenyls (PCBs), PFCs do not typically accumulate in lipids. In humans, exposure levels and pathways leading to the presence of PFCs have been better characterized by monitoring these chemicals in blood. In recent years, the concentrations of various PFCs in human blood have been determined in individuals from a number of regions and countries (see reviews by Angerer et al. (2007) and Fromme et al. (2009)). Although the relative importance of the various potential routes of exposure to these compounds still remains unknown, it has been suggested that food and food packaging, water, house dust, and airborne sources may all be significant (see reviews by D’Hollander et al., 2010; Kantiani et al., 2010; Trudel et al., 2008). With respect to PFOS and PFOA, the most widely investigated PFCs, chronic exposure to both compounds is probably the result of the intake of contaminated foods, including drinking water (Ericson et al., 2008a,b, 2009). However, recent investigations have shown that the indoor environment may also be an important contributor to human exposure to these PFCs (D’Hollander et al., 2010; Fromme et al., 2009; Goosney and Harrad, 2011; Haug et al., 2011). In contrast, consumer products would cause a minor portion of human exposure to PFOS and PFOA. Among these, impregnation sprays, treated carpets in homes, and coated food contact materials could lead to consumer exposure to PFOS and PFOA (Trudel et al., 2008).

Because PFCs are persistent and widely dispersed in the environment, Directive 2006/122/EC placed restrictions on the marketing and use of PFOS. There are also voluntary reductions on PFOA although it is still manufactured. The EU is currently assessing PFOA and, while there are no restrictions in place in the EU at present, a ban could be imposed in the future. However, these substances have been extensively used in...
the built environment and therefore, could represent a significant, long-term diffuse input into wastewater and sludge (Clarke and Smith, 2011).

In recent years, a rather limited number of studies over the world have measured the concentrations of various PFCs in foodstuffs. In addition, in a few studies the dietary intake of some PFCs (mainly PFOS and PFOA) by the general population of certain countries was estimated. It is important to note that in most surveys on the dietary intake of PFCs, food analyses were performed in unprocessed/uncooked/raw products. Notwithstanding, it is well established that the physicochemical and nutritional qualities of a number of foods can be widely modified by cooking processes (Domingo, 2011).

This paper presents an overview on the available scientific information on the levels of PFCs in a number of foods, the human exposure to PFCs through dietary intake, the influence of processing and cooking some foods on the concentrations of PFCs, as well as the dietary health risks for the general population based on the criteria recommended by various international organisms. The scientific literature has been reviewed using the PubMed (http://www.ncbi.nlm.nih.gov/sites/entrez?db=pubmed) and Scopus (http://www.scopus.com/scopus/home.url) databases. Specific reports (EFSA, USEPA, etc.) have also been utilized.

2. Food and PFCs: human exposure in a number of countries

2.1. European countries

2.1.1. Denmark

Halldorsson et al. (2008) investigated in 1076 pregnant women, the association between dietary variables and plasma levels of PFOS and PFOA. Diet was assessed at mid-pregnancy by a food-frequency questionnaire. PFOS levels were significantly and positively associated with intake of red meat, animal fats, and snacks (e.g., popcorn, potato chips), whereas intake of vegetables and poultry was inversely associated. Similar but weaker associations were also observed for PFOA. Furthermore, a comparison between women reporting low red meat and high vegetable intake and women reporting low vegetable and high red meat intake resulted in differences in plasma PFOS and PFOA concentrations (31% and 18% of mean levels, respectively). These data indicate that intakes of red meat, animal fats and snacks are important predictors of plasma levels of PFOS and to lesser extent PFOA. The results for red meat would be compatible with the potential binding of PFOS to proteins in blood, while the observed association with intake of snacks would reflect leaching from food packaging. The influence of food processes, including packaging and cooking, is extensively reviewed in the present paper.

2.1.2. Poland

Falandyz et al. (2006) quantified the levels of 19 PFCs in human blood in some marine food resources from the region of the Gulf of Gdansk at the Baltic Sea south coast. In addition to PFOS and PFOA, 8 other PFCs bioaccumulated in humans. It was noted that food chain was an important route of exposure for all 10 PFCs detected in non-occupationally exposed subjects. It was also observed that those individuals reporting a high fish intake in their diet (mainly Baltic fish) contained, on average, the highest load of all 10 PFCs, when compared with the other human subpopulations. Baltic seafood was found to highly influence human body burden of perfluorohexanesulfonate (PFHxS), PFOS, perfluorooctanesulfonamide (PFOSA), perfluorohexanoic acid (PFHxA), perfluorheptanoic acid (PFHpA), perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUnDa), and perfluorododecanoic acid (PFDoDA), and to a lesser extent PFOA.

2.1.3. Spain

In 2006, we initiated a wide program aimed at investigating various issues concerning toxicity and health risks of exposure to PFCs. The program included experimental studies in rodents (Fuentes et al., 2006, 2007a,b,c; Ribes et al., 2010), the assessment of exposure to PFCs in the population of Catalonia (Spain), as well as the relationship between PFCs exposure and human tissue accumulation (Ericson et al., 2007; Kärrman et al., 2010). Human exposure to PFCs was assessed by determining the contribution of drinking water (Ericson et al., 2008a, 2009) and the diet (Ericson et al., 2008b; Ericson-Jogsten et al., 2009).

The levels of 14 PFCs were determined in 36 composite samples of foodstuffs randomly purchased in 2006 in various locations of Tarragona County (southern Catalonia) (Ericson et al., 2008b). Dietary exposure to PFCs was estimated for various age/gender groups. Among the analyzed PFCs, only PFOS, PFOA, and PFHpA could be detected. On average, for a standard adult man (70 kg body weight), the dietary intake of PFOS was estimated to be 62.5 or 74.2 ng/day (assuming ND = 0 or ND = 1/2 LOD, respectively). Fish, followed by dairy products and meats, were the main contributors to PFOS intake. Although the results suggested a correlation between dietary intake and blood levels of PFOS (Ericson et al., 2007), those results did not justify that dietary intake might be the main route of exposure governing blood concentrations of other PFCs in the population of Catalonia. While in blood, 7 of the analyzed PFCs could be detected (Ericson et al., 2007), only PFOS, PFOA and PFHpA were found in foodstuffs. An important pending issue of that initial dietary survey was to establish the potential role that food processing and packaging could play as a source of dietary PFCs. Therefore, in a subsequent study we assessed the role that some food processes might play as a dietary source of PFCs (Ericson-Jogsten et al., 2009). In addition, certain foodstuffs which, although not being widely consumed by the people living in the area under evaluation, could be potentially expected to contain high PFC levels (e.g., liver of lamb), were also included in that survey. In 2008, food samples were acquired in local markets, supermarkets and grocery stores from Tarragona County. The levels of PFCs were determined in composite samples of veal steak (raw, grilled, and fried), pork loin (raw, grilled, and fried), chicken breast (raw, grilled, and fried), black pudding (uncooked), liver of lamb (raw), marinated salmon (home-made and packaged), lettuce (fresh and packaged), pate of pork liver, foie gras of duck, “Frankfurt” sausages, chicken nuggets (fried), and common salt. Among the 11 PFCs analyzed, only PFHxA, PFOS, PFHpA, and PFOA were detected in at least one composite sample. All levels of the remaining PFCs (perfluorobutane sulfonic acid (PFBS), PFHpA, PFNA, PFDA, PFUnDa, and PFDoDa) were under their respective detection limits. PFOS was the most frequently detected PFC, being found in 8 of the 20 food items analyzed, while PFHpA was detected in samples of raw veal, chicken nuggets, “Frankfurt” sausages, and packaged lettuce. The results were not sufficiently clear to establish if cooking with non-stick cookware, or packaging some foods, could contribute to a higher dietary exposure to PFCs. These results, together with those of our previous food survey (Ericson et al., 2008b), did not explain the presence of some PFCs (PFOSA, PFDA and PFUnDa) found in blood samples of the Catalan population. This would indicate that there are other important sources of human exposure to PFCs, which have not been clearly detected yet. We are currently processing new experimental data concerning additional fish and drinking water samples, as well as outdoor and indoor air samples, including dust, collected in the same area (unpublished data).

The results of another recent study also performed in Catalonia (Ilorca et al., 2010), in which infant exposure to 6 PFCs was assessed by measuring their levels in breast milk and commercial baby food are next summarized. With respect to commercial baby food, the 6 PFCs were detected in all brands of milk infant formulas and cereal baby foods analyzed, being PFDA, PFOS, PFOA and PFNA the compounds detected at higher concentrations (up to 1289 ng/kg). It was suggested that PFCs presence could be associated to possible migration from packaging and containers during production processes. PFOS and PFOA daily intakes and risk indexes (RI = DI/TDI) were estimated for the firsts 6 month of life. RIs calculated for breast milk samples and baby foods were below 1, with exception of one breast milk
sample. Therefore, according to the criteria used for the estimation, just in one case a certain degree of toxicological risk could be considered.

2.1.4. Norway

Haug et al. (2010a) determined the levels of 16 PFCs (PFBA, PFPeA, PFHxS, PFHpA, PFOA, PFNA, PFDA, PFUnDa, PFDoDA, PFTrDa, PFTeDa, PFHxDA, PFODA, PFBS, PFHxS and PFOS) in 21 samples of selected food and beverages such as meat, fish, bread, vegetables, milk, drinking water and tea from the Norwegian market collected between October 2008 and January 2009. Up to 12 different PFCs could be detected. PFOA and PFOS were found at concentrations similar to, or even lower than those found in other studies worldwide. Differences in the relative proportion of PFOA and PFOS between samples of animal origin and samples of non-animal origin were noted. It supported that PFOS has a higher bioaccumulation potential in animals than PFOA. Based on those measurements and consumption data for the general Norwegian population, the total dietary intake of PFCs was estimated in around 100 ng/day. PFOA and PFOS contributed to about 50% of the total intake. When dividing the population according to gender and age groups, estimated intakes were decreasing with increasing age, being higher in males than in females. The authors noted that the estimated intakes of PFOS and PFOA in that study were lower than those reported in surveys performed in Spain, Germany, United Kingdom, Canada and Japan (data also reviewed in the present paper). In a subsequent study of the same research group, the relationship between reported consumption of habitual food intakes with particular focus on fish and shellfish, and serum PFC concentrations in Norwegian adult men and women were investigated (Haug et al., 2010b). Individual dietary intakes of PFCs were also estimated and food groups of main influence were identified. Concentrations of 19 PFCs were determined in serum from 175 participants in the Norwegian Fish and Game Study and evaluated with respect to food consumption using multiple linear regression analysis. PFC concentrations in serum were significantly associated with the consumption of lean fish, fish liver, shrimp and meat, as well as age, breastfeeding history, and area of residence. The estimated dietary intakes of PFOA, PFUnDa and PFOS were 0.60, 0.34 and 1.5 ng/kg/day, respectively. Fish and shellfish was the major dietary source contributing 38% of the estimated dietary intakes of PFOA, 93% of PFUnDa, and 81% of PFOS. The estimated dietary intakes of these three selected PFCs were significantly associated with the corresponding serum PFC concentrations. It was concluded that consumption of fish and shellfish was a major determinant of serum PFC concentrations. This study showed for the first time significant relationships between estimated dietary intakes and serum concentrations of PFCs.

Rylander et al. (2010) assessed the impact of self-reported dietary habits and lifestyle on the plasma concentration of selected PFCs in a representative group of 315 middle-aged Norwegian women (48–62 years of age). The women taking part in the study were all participants collected daily duplicate diet samples during 7 consecutive days. The maximum concentration observed in that study was 118 ng/g ww for PFOA. However, most concentrations of the analyzed PFCs were less than 0.1 ng/g ww. The LODs of PFOS, PFOA, PFHxS, PFHxA, and PFOSA were 0.05–0.1, 0.1, 0.1, 0.2, and 0.2 ng/g, respectively. The median dietary intakes of PFOS and PFOA were 1.4 ng/kg/day and 2.9 ng/kg/day, respectively. PFHxS and PFHxA could be detected only in some samples, with median intakes of 2.0 and 4.3 ng/kg/day, respectively. For calculations, values below the LOD were assigned half of the LOD. However, for the interpretation of these data, it has to be kept in mind that PFHxS and PFHxA were detected only in few samples. PFOSA could not be detected above the limit of detection. These results demonstrated that although the German adult population was exposed to PFOS and PFOA, the median dietary intake did not exceed the recommended tolerable daily intake (TDI). Moreover, the biomonitoring data obtained in this same study (blood samples collected once during the sampling period) predicted an exposure in a comparable range, especially for PFOS. The intakes of PFOS and PFOA using a pharmacokinetic model were estimated in 1.6 and 0.5 ng/kg/day, respectively. It was concluded that in Germany, normally food intake was the main source of exposure of the general population to PFOS and PFOA (Fromme et al., 2007, 2009).

Schuetze et al. (2010) determined the levels of PFOS and PFOA in wild fish caught from different German waters with no, low, medium and high portions of treated municipal sewage discharges. The investigated fish filet samples included 51 wild eels, 44 bream, 5 herring, 5 mackerel, 3 carp and 4 trout. PFOA was not found in any of the investigated samples (LOQ 0.27 μg/kg ww), whereas PFOS was found in the filet samples caught from densely populated regions at levels between 8.2 and 225 μg/kg ww. In samples from marine or remote locations, PFOS was not detected or only detected at levels up to 50.8 μg/kg ww. The detected residues of PFOS found in 33 out of 112 examined fish samples might be classified as potential risks for the health of consumers with elevated fish consumption, based on the EFSA (2008) recommendation for PFOS (TDI of 150 ng/kg of body weight/day).

2.1.6. United Kingdom

In a total diet study performed in 2004, composite food samples from various groups were analyzed for a number of PFCs (UK FSA, 2006). PFOS was detected in only 4 of 20 different analyzed food groups, being individual PFC intakes from multiple exposure sources were recently assessed by Haug et al. (2011) in a group of 41 Norwegian women. Intakes were estimated using measured PFC concentrations in indoor air and house dust, as well as information from food frequency questionnaires and PFC concentrations in Norwegian food. Food was generally the major exposure source, representing 67–84% of the median total intake for PFOA and 88–99% for PFOS, using different dust ingestion rates and biotransformation factors of precursor compounds. However, on an individual basis, the indoor environment accounted for up to around 50% of the total intake for several women. Significant positive associations between concentrations of PFCs in house dust and the corresponding serum concentrations underlined the importance of indoor environment as an exposure pathway for PFCs. The estimated intakes were confirmed by comparing serum concentrations of PFOA and PFOS calculated using pharmacokinetic models, with the corresponding concentrations measured in serum. Although in general terms food intake would be the major source of exposure for PFCs, the authors showed that the indoor environment might also be an important contributor to human exposure to these compounds.
found at concentrations (given in parentheses) above the limit of detection in potatoes (10 ng/g ww), canned vegetables (2 ng/g ww), eggs (1 ng/g ww), and sugars and preserves (1 ng/g ww). In turn, PFOA was detected only in potatoes (1 ng/g ww). Although other PFCs were detected only occasionally, 10 different PFCs were found in potatoes. The estimated average adult dietary intake for PFOS was 100 ng/kg/day. In turn, the high-level dietary intake of this compound, also for adults, was 200 or 30 ng/kg/day (upper or lower bound values, respectively). In a subsequent study (UK FSA, 05/2009), PFOS, PFOA and other related fluorinated chemicals were analyzed in individual retail (on sale in the UK) samples of fish, offal, meat, eggs, milk, dairy products, bread, cereals, popcorn, vegetables and jams. PFOS was found most frequently and at the highest concentrations in fish, liver and kidney. However, it was not detected in meat, dairy products, potatoes, potato products, popcorn and other cereals, as well as in vegetable or fish oils. PFOS was found mainly at low concentrations in crab and liver. Based on those results, the average adult dietary intakes were estimated in 0.01 μg/kg/day for PFOS, and 0.01 μg/kg/day for PFOA (upper bound levels of PFOS and PFOA were considered). The respective high level adult dietary intakes were 0.02 and 0.02 μg/kg body weight/day. These are well below the TDIs set by the EFSA (2008) of 0.15 and 1.5 μg/kg body weight/day for PFOS and PFOA respectively. The results of this UK survey did not raise any concerns for consumer’s health.

Recently, Clarke et al. (2010) reported the results of a survey in which 252 food samples, purchased during 2007 and 2008 from a variety of retail outlets in the UK, were analyzed for the presence of PFOS, PFOA and nine other PFCs. All the targeted PFCs were detected in 75 individual food items. In 70% of the samples, including all meat other than offal, none of the analytes was present above the LOD. The highest detected levels were 59 μg/kg for PFOS and 63 μg/kg for total PFCs (Σ PFCs) in an eel sample, and 40 μg/kg for PFOS (62 μg/kg Σ PFCs) in a whitebread sample. The highest level in an offal sample was 10 μg/kg in a wild roe deer liver. There were six samples with Σ PFCs > 15 μg/kg (fish, shellfish, crustaceans), seven samples with Σ PFCs ranging 11–15 μg/kg (including liver), nine samples with Σ PFCs ranging 6–10 μg/kg (fish and livers), 31 samples with Σ PFCs in the range 2–5 μg/kg (including kidneys, popcorn and processed peas) and a further 22 samples with Σ PFCs close to the LOD of 1 μg/kg (including eggs and potatoes). These concentrations indicated that UK consumers were being exposed to a low level of PFC contamination from food. The estimated upper bound dietary intake of 10 ng/kg/day of PFOS for average adult consumers was clearly lower than the 150 ng/kg TDI set by the EFSA (2008). It was concluded that it would be unlikely for any UK consumer, even an extreme consumer of the most contaminated foods, to exceed the TDI for PFOS or PFOA.

2.1.7. Czech Republic

Hradkova et al. (2010) determined the concentrations of PFOA, PFOS and perfluorooctanesulfonamide (FOSA) in 35 imported canned fish and seafood products (tuna, sardine, and cod liver) purchased in 2009 from the Czech retail market. PFOS was the dominating PFC, ranging from 0.7 μg/kg to 12.8 μg/kg, while PFOA levels were in the range of 1.2 μg/kg to 5.1 μg/kg. FOSA was detected only at trace levels in two samples. Several products originated in the Baltic Sea were the most contaminated within the sample set. According to the results, it would be possible to speculate on a higher incidence of PFOS in the products containing fish species from the Baltic such as cod livers, sardines and sprats, which could reasonably contribute to TDI. However, a similar trend was not observed for PFOA.

2.1.8. Sweden

Berger et al. (2009) analyzed the levels of 11 PFCs in muscle tissue from edible fish species caught in the second largest freshwater lake of that country, Lake Vättern (LV), and in the brackish water Baltic Sea (BS). PFOS was the predominant PFC found, being its concentration higher in LV (medians 2.9–12 ng/g ww) than in BS fish (medians 1.0–2.5 ng/g ww). Moreover, LV fish was more contaminated with several other PFCs than BS fish. Human exposure to PFOS via fish intake was calculated for three study groups, based on consumption data from the literature. The groups consisted of individuals who reported moderate or high consumption of BS fish or high consumption of LV fish, respectively. The results showed that PFOS intake strongly depended on individual fish consumption, as well as the fish catchment’s area. Median PFOS intakes were estimated to 0.15 and 0.62 ng/kg/day for the consumers of moderate and high amounts of BS fish, respectively. For the group with high consumption of LV fish, a median PFOS intake of 2.7 ng/kg/day was estimated. Fish consumption varied considerably within the consumer groups, with maximum PFOS intakes of 4.5 (BS fish) or 9.6 ng/kg bw/day (LV fish). These results showed that PFC levels of fish caught in waters affected by anthropogenic pollution were generally higher than concentrations in fish from open oceans. Therefore, fish caught in polluted freshwater systems of Sweden could be a significant source of dietary human PFOS exposure.

2.2. American countries

2.2.1. Canada

Information on concentrations of PFCs in foodstuffs and the dietary intake of these pollutants by the Canadian population has been basically reported by the group of Tittlemier et al. In a first survey (Tittlemier et al., 2006), Canadian Total Diet Study (TDS) composite samples (n = 151) collected from 1992 to 2004 were analyzed for five perfluorooctanesulfonamides. These compounds were detected in the pg/g to low ng/g of ww range in all food groups: tested-baked goods, candy, dairy, eggs, fast food, fish, meat, and foods to be prepared in packaging. The highest concentrations of total perfluorooctanesulfonamides were observed in fast food composites. Concentrations of N-ethylperfluorooctanesulfonamide (N-EtPFOA) appeared to decrease over the sampling period (1992–2004) in French fries and other fast food composites. However, a similar trend was not apparent in freshwater fish, marine fish, and shellfish composites. The basic estimate of dietary exposure to perfluorooctanesulfonamides suggested that Canadians (>12 years old) were exposed to approximately 73 ng/person/day from these foods. The authors remarked that the most significant dietary sources of perfluorooctanesulfonamides were foods that had been packaged in paper products, which were often treated with perfluoralkyl compounds for oil resistance, such as French fries and pizza. In another survey carried out at the same laboratory (Tittlemier et al., 2007), 54 solid food composite samples collected as part of the Canadian TDS were analyzed for perfluorocarboxylates and PFOS. Foods analyzed included fish and seafood, meat, poultry, frozen entrées, fast food, and microwave popcorn collected from 1992 to 2004 and prepared as for consumption. Nine composite samples contained detectable levels of PFCs: four meat-containing, three fish and shellfish, one fast food, and one microwave popcorn. PFOS and PFOA were the most frequently detected, with concentrations ranging from 0.5 to 4.5 ng/g. The average dietary intake of total perfluorocarboxylates and PFOS for Canadians was estimated to be 250 ng/day, using results from the 2004 TDS composites. A comparison with intakes of perfluorocarboxylates and PFOS via other routes (air, water, dust, treated carpeting, and apparel) suggested that diet was an important source of these compounds (Tittlemier et al., 2007). Recently, Ostertag et al. (2009a) reanalyzed the dietary PFC exposure for Canadians using recent dietary intake information. It allowed comparing these new data with the dietary exposure from the late 1990s and 2004 (Tittlemier et al., 2006, 2007). Another objective of that study was to identify key food items contributing to PFC exposure. PFCs were detected in 8 samples including processed meats, pre-prepared foods and peppers, with a range of concentrations from 0.48 to 5.01 ng/g ww. Mean daily PFC exposure estimates ranged from 1.5 to 2.5 ng/kg body weight. Perfluorinated carboxylates (PFCA C(7)–C(11)) contributed more to PFC exposure than either PFOS or 6:2 fluorotelomer unsaturated carboxylate.
PFOA was detected in 17 of 31 food types (range, 0.02–1.8 ng/g ww), with the highest concentration (0.85 ng/g ww) corresponded to milk purchased in Pensacola, FL. The location of a 3 M PFOA production plant, while the highest level of PFOA (2.35 ng/g ww) was detected in an apple purchased in Decatur, AL. Most samples had levels below the detection limit (0.012 ng/g ww). PFOS was the predominant compound in viscera and muscle of farmed pigs and chickens. In addition, a strong linear correlation (r=0.932) was observed between the concentrations of PFOS and PFUnDA in pig liver (Wang et al., 2010b). Based on these results, the authors indicated that there was little potential risk of exposure to PFCs via the consumption of these products in Beijing. Moreover, a preliminary human health risk assessment of milk and dairy products calculated from the samples analyzed in that study, was compared with estimated daily intake of PFCs reported from the concentrations in drinking water, fish and seafood from China. The calculations indicated that dietary sources accounted for the overwhelming proportion of (>99% for PFOS and 98% for PFOA) total daily intake in adults. The foodstuffs analyzed in that study (meat, meat products and eggs) were not the major contributors to dietary exposure to PFOA, while meat was the primary contributor to dietary exposure to PFOA.

Wang et al. (2010a,b) reported the levels of 11 PFCs in samples of milk, milk powder and yogurt purchased in 2008–2009 from Chinese markets, as well as in samples of viscera and muscle of farmed pigs and chickens in Beijing (China). In milk, PFHpA and PFNA were detected in 68% of samples, while in milk powder samples, PFOS, PFOA and PFNA were the only detected PFCs. None of these was observed in more than 35% of samples. In yogurt, PFOA was the most frequently detected (69% of samples) PFC. The mean concentrations of total PFCs were 178 pg/g ww in milk, 98 pg/g (dw) in milk powder and 42 pg/g ww in yogurt. The authors noted that the concentrations of total PFCs were significantly different among three kinds of milk packaging (Wang et al., 2010a). In tissue samples from farmed pigs and chickens (n = 143), the highest total PFC mean concentration was found in pig liver (3.438 ng/g ww), followed by pig kidney (0.508 ng/g ww), pig heart (0.167 ng/g ww), chicken liver (0.098 ng/g ww), chicken heart (0.050 ng/g ww), pork loin (0.018 ng/g ww), and chicken breast (0.012 ng/g ww). PFOS was the predominant compound in viscera and muscle of farmed pigs and chickens. In addition, a strong linear correlation (r = 0.932) was observed between the concentrations of PFOS and PFUnDA in pig liver (Wang et al., 2010b). Based on these results, the authors indicated that there was little potential risk of exposure to PFCs via the consumption of these products in Beijing. Moreover, a preliminary human health risk assessment of milk and dairy products

The same research group (Ostertag et al., 2009b) performed also a specific study on dietary exposure to PFCs, which was based on traditional foods among Inuit in Nunavut (northern Canada). PFOS, PFCAs (C(7)–C(11)) and fluoroacetol ununsaturated carboxylic acids (FTUCA) (6,2:8,2 and 10:2 FTUCA) were measured in 68 traditional foods collected in Nunavut between 1997 and 1999. Total PFC concentrations were highest in caribou liver (6.2 ng/g), ringed seal liver (minimum, maximum: 7.7, 10.2 ng/g), polar bear meat (7.0 ng/g), and beluga meat (minimum, maximum: 5.8, 7.0 ng/g). To calculate PFOA exposure, Inuit food intake data from 24 h recalls conducted in Nunavut between 1997 and 1999 were used. Mean dietary exposure was estimated between 210 and 610 ng/person/day (0.6–8.5 ng/kg body weight/day). Dietary exposure to PFCs was significantly higher in men in the 41–60 year age group than younger men (<40 years old) and women from the same age group. Caribou meat contributed 43–75% of daily PFC dietary exposure. Health risks associated with these estimated exposure levels should be minimal based on current toxicological information available from animal feeding studies. Based on these results, it was concluded that the contamination of the Arctic with PFCs resulted in dietary exposure of Inuit in Nunavut to PFCs at levels comparable to the Canadian and European populations. In relation to this issue, the relationship between PFOA exposure and plasma lipid levels in the Inuit population of Nunavik (Northern Quebec, Canada) was also assessed (Château-Degat et al., 2010). In that population, PFOA exposure (as well as omega-3 polyunsaturated fatty acids, n-3 PUFAs) intake was found to be related to traditional food consumption. The results showed a relationship between PFOA and plasma lipid levels in an environmentally exposed human population.

2.2. USA

In USA, scientific reported data concerning human dietary exposure to PFCs seem to be limited to the recent study by Schecter et al. (2010), who measured the concentrations of 11 PFCs in composite samples of 31 different types of food (310 individual foods samples) purchased in 2009 from supermarkets in Dallas, TX. Only PFOA, perfluorobutane sulfonate (PFBS), and PFHxS were detected. Concentrations of PFOS and the remaining PFCs (excluding PFOA, PFBS, and PFHxS) were below the detection limit for all foods. Concentrations of PFOS reported in the US National Health and Nutrition Examination Survey (NHANES) using a first-order 1-compartment pharmacokinetic model. Total PFOA intake was also assessed (Château-Degat et al., 2010). In that population, PFOS and the remaining PFCs (excluding PFOS and PFOA) were the only detected PFCs. None of these was observed in any food group. In dairy products, PFOA was only detected in butter (1.07 ng/g ww), while it ranged from 0.02 in ham, chicken breast, and canned chili to 1.80 ng/g ww in olive oil. PFBS and PFHxS were only found in cod at 0.12 and 0.07 ng/g ww, respectively. According to Schecter et al. (2010), a 3 M-sponsored survey was the only previous study of PFC contamination in US foods. In that 3 M study, PFOA, PFOS and PFOSA were measured in individual food samples of green beans, apples, pork, milk, chicken, eggs, bread, hot dogs, catfish, and ground beef (3M, 2001). Most samples had levels below the detection limit (0.5 ng/g for all chemicals). The highest level of PFOA (2.35 ng/g ww) was detected in an apple purchased in Decatur, IL, the location of a 3 M PFOA production plant, while the highest PFOA level (0.85 ng/g ww) corresponded to milk purchased in Pensacola, FL.

Egeghy and Lorber (2011) estimated a range of intakes from serum concentrations of PFOS reported in the US National Health and Nutrition Examination Survey (NHANES) using a first-order 1-compartment pharmacokinetic model. Total PFOA intakes (medians summed over all pathways) were estimated as 160 and 2200 ng/day for adults, and 50 and 640 ng/day for children under typical and contaminated scenarios, respectively. Food ingestion would be the primary route of exposure in the general population. However, for children the contribution from dust ingestion would be nearly as great as from food ingestion. Pharmacokinetic modeling suggested central tendency PFOS intakes for adults range between 1.6 and 24.2 ng/kg/day, and the forward-based intake estimates are within this range.

2.3. Asian countries

Gulkowska et al. (2006) analyzed 7 types of seafood collected in 2004 from local fish markets in two coastal Chinese cities, Zhushan and Guangzhou. Nine PFCs were determined using HPLC coupled with ESI-MS/MS. PFOS was the predominant fluorochrome, being found in all seafood samples, including fish, mollusks, crabs, shrimp, oysters, mussels, and clams. Concentrations of PFOS in seafood samples ranged from 0.3 to 13.9 ng/g ww, with the highest concentration found in mantis shrimp. The hazard ratios (HR) of non-cancer risk through seafood consumption, based on PFOS and PFOA concentrations, were calculated. HRs were less than the unity, which was attributed to the relatively low levels of these PFCs in the seafood. Recently, Zhang et al. (2010) determined the levels of 10 PFCs in samples of meat, meat products and eggs collected in China. The survey also included measuring PFC levels in samples of indoor dust. PFOA and PFOS were the most frequently detected PFCs in all these samples. Mean concentrations of PFOS and PFOA in foodstuffs were in the range of 0.05–1.59 ng/g ww, and 0.06–12.5 ng/g ww, respectively. The estimated daily intake (EDI) of PFOS and PFOA from meat, meat products, and eggs ranged from 6.00 to 9.64 ng, and from 254 to 576 ng, respectively, when the values below the LOQ were assigned as 0, and from 8.80 to 15.0 ng, and from 255 to 577 ng, respectively, when the values below the LOQ were set at 1/2 LOQ. The daily intakes of PFOA and PFOA from the consumption of meat, meat products, and eggs, and from dust ingestion, as calculated from the samples analyzed in that study, were compared with estimated daily intake of PFCs reported from the concentrations in drinking water, fish and seafood from China. The calculations indicated that dietary sources accounted for the overwhelming proportion of (>99% for PFOS and 98% for PFOA) total daily intake in adults. The foodstuffs analyzed in that study (meat, meat products and eggs) were not the major contributors to dietary exposure to PFOS, while meat was the primary contributor to dietary exposure to PFOA.
consumption showed that, for adults, the mean daily intake of PFOS and total PFCs was equal to, or lower, than 23 and 167 pg/kg, respectively.

Recently, Wu et al., in press measured 13 PFCs in 47 fatty fish and 45 shellfish samples collected from six coastal provinces in China. PFOS was the dominant PFC in fatty fish, which accounted for 38% of total PFCs, while PFOA was the predominant PFC in shellfish. The highest EDIs of PFOS and PFOA were found to be 694 and 914 pg/kg body weight/day, respectively. However, the highest estimated dietary intake (EDI) of total PFCs was 2513 pg/kg body weight/day. The EDI from seafood was found to be much lower than the TDI recommended by the EFSA (2008), indicating low health risk of PFC exposure via eating seafood among the coastal populations in China.

On the other hand, in the same lab of Shi et al. (2010), PFCs were detected in fish muscle collected from high mountain lakes in the Qinghai–Tibetan Plateau (China), the highest and biggest plateau on Earth. PFOS was found in 96% of the total 59 fish samples. The mean PFOS concentrations in fish muscle ranged 0.21–5.20 ng/g dw. No significant correlations were observed between PFCs concentrations and sampling altitude or ages (fish). The results demonstrated the existence of low levels, but detectable PFCs pollution in the Qinghai–Tibetan Plateau (Shi et al., 2010).

2.3.2. Japan

Kärrman et al. (2009) assessed the daily intake of 9 PFCs through the diet and beverage. The relationship between the dietary contamination and human serum levels was also evaluated. The study was performed using human biological and food duplicate samples collected in 2004 and archived in the Kyoto Human Specimen Bank (Koizumi et al., 2005). Kärrman et al. (2005) used daily duplicate samples from 20 Japanese women, including all foods and beverages being collected that specific day, together with matched serum samples. Two cities were included in the study, one small town in Miyagi Prefecture and Osaka city. The median daily intake calculated using the measured diet concentrations was 1.47 ng PFOS/kg and 1.28 ng PFOA/kg for Osaka, and 1.08 ng PFOS/kg and 0.72 ng PFOA/kg for Miyagi.

A summary of information concerning various recent studies above discussed is presented in Table 1. It includes the characteristics of the studies, the analyzed PFCs, as well as the most important remarks/results.

3. Influence of processing, cooking and packaging on the levels of PFCs in food

Relatively small quantities of PFCs are used in the manufacturing of food-contact substances, which represents potential sources of oral exposure to these chemicals. The most recognizable products to consumers are the uses of PFCs in non-stick coatings (polytetrafluoroethylene, PTFE) for cookware, and also their use in paper coatings for oil and moisture resistance (Begley et al., 2005; Sinclair et al., 2007).

There are very few reports on the influence of processing/cooking and packaging on the levels of PFCs in food. It is well known that perfluorinated substances like N-ETFOSA (N-ethyl perfluorooctane sulfonamide), N-N-ETFOSA (N,N-diethyl perfluorooctane sulfonamide), N-MeFOSA (N-methyl perfluorooctane sulfonamide), and PFOSA have been used in grease and water repellent coatings in food packaging. Therefore, food could become contaminated by this route, contributing to human body burdens of PFOS by degradation of the mentioned precursors (Fromme et al., 2009). Begley et al. (2005) found that analysis of PTFE cookware showed residual amounts of PFOA in the low μg/kg range, while PFOA was present in microwave popcorn bag paper at amounts as high as 300 μg/kg. The results suggested that fluoropolymer food-contact materials did not appear to be a significant source of PFCs (e.g. PFOA) relative to paper that will migrate to food and be consumed. It was based on the residual analysis of PFOA in fluorinated ethylene-propene copolymer (FEP) tubing, PTFE film used for sealant applications, and PTFE-coated cookware and migration experiments on PTFE film. Furthermore, an extreme heating test (abusive) of the cookware did not appear to increase the residual amount of PFOA in the cookware. From those data, the largest potential source of migratable fluorocarbons from food-contact materials appeared to be paper with fluorocarboxylic coatings/additives (Begley et al., 2005).

Since salts of PFOA have been used as a processing aid in the manufacture of many fluoropolymers, Sinclair et al. (2007) determined if these compounds would be still present as residuals after the process used to coat non-stick cookware or packaging, and could be released during typical cooking conditions. The authors identified and measured perfluoralkyl carboxylates (PFCAs), particularly PFOA, and fluorotelomer alcohols (FTOHs) released from non-stick cookware into the gas phase under normal cooking temperatures (179 to 233 °C surface temperature). PFOA was released into the gas phase at 7–337 ng (11–503 pg/cm²) per pan from four brands of non-stick frying pans. The fluorotelomers 6:2 FTOH and 8:2 FTOH were found in the gas phase of four brands of frying pans. A significant decrease in gas-phase PFOA following repeated use of one brand of pan was observed, whereas the other brand did not show a significant reduction in PFOA release following multiple uses. PFOA was found at 5–34 ng in the vapors produced from a prepacked microwave popcorn bag, while it was not found in the vapors produced from plain white corn kernels popped in a polypropylene container. On the packaging surface of one brand of microwave popcorn several PFCAs, including FTOHs, were found at concentrations in the order of 0.5–6.0 ng/cm². That study suggested that residual PFOA was not completely removed during the fabrication process of the non-stick coating for cookware. They would remain as residuals on the surface and might be off-gassed when heated at normal cooking. On the other hand, in order to evaluate if ingestion of chemicals applied to food contact paper packaging could be an indirect exposure to PFCs, D’eon and Mabury (2007, 2011) quantified in rats the load of perfluorinated acids upon exposure to polyfluoralkyl phosphate surfactants (PAPS), nonpolymeric fluorinated surfactants approved for application to food contact paper products. The authors demonstrated that oral exposure of rats to 8:2 mono or diPAPS resulted in increased PFOA blood levels, being both 8:2 PAPS congeners themselves absorbed from the gut into the bloodstream. The ingestion of PAPS with in vivo production of perfluorinated acids was also linked in those investigations (D’eon and Mabury, 2007, 2011).

Del Gobbo et al. (2008) investigated the influence of cooking (baking, boiling, and frying) on the levels of PFCs in 18 fish species purchased from Canadian markets. All cooking methods reduced the concentrations of perfluorinated acids, being baking the most effective method. PFOS was the compound most frequently detected, with concentrations ranging between 0.21 and 1.68 ng/g ww in raw and cooked samples, respectively. PFOSAs were detected only in scallops at concentrations ranging from 0.20 to 0.76 ng/g ww. Total concentrations of perfluorinated acids (perfluorocarboxylates and sulfonates) in samples were 0.21 to 9.20 ng/g ww, respectively, consistent with previous studies (Tittlemier et al., 2006, 2007). The results indicated that reducing consumption of fish muscle tissue was not warranted on the basis of PFC exposure concerns at the reported levels of contamination, even for high fish consuming populations. In a recent study performed in our laboratory and focused on assessing the influence of cooking processes on the concentrations of PFCs in various food items (Ericson-Jogsten et al., 2009), it was not quite clear if cooking with non-stick cookware could significantly contribute to reduce or to increase human exposure to PFCs. In a review on the influence of cooking processes on the concentrations of various metals and organic contaminants in foodstuffs (Domingo, 2011), it was concluded that although certain cooking processes could reduce or increase the levels of chemical contaminants in food, the influence of cooking on the levels of these contaminants would depend not only on the particular cooking process, but also even more on the
specific food item being cooked. Although in general terms, cooking procedures that release or remove fat from the product should tend to reduce the total concentrations of organic contaminants in the cooked food, this is likely not applicable to PFCs.

4. Human risk assessment of dietary exposure to PFCs

In recent years, some information on human risk assessment of dietary exposure to PFCs has been reported. An evaluation of the TDIs for PFOS and PFOA was performed by the UK Committee on Toxicity of Chemicals in Food, Consumer Products and the Environment (COT, Committee on Toxicity of Chemicals in Food and Consumer Products and The Environment (2006a,b). The COT recommended a TDI of 300 ng/kg for PFOS, while for PFOA, a TDI of 3000 ng/kg was suggested. On the other hand, the German Federal Institute for Risk Assessment and the Drinking Water Commission of the German Ministry of Health derived a provisional TDI of 100 ng/kg for PFOS (Fromme et al., 2009).

On the other hand, oral reference dose (RfD) values for most PFCs have not been established yet by any government or regulatory agency. However, provisional RfDs for PFOS and PFOA have been estimated on the basis of a rat chronic carcinogenicity study and a rat multigenerational study, respectively (Gulkowska et al., 2006). On this basis, the provisional RfD for PFOS was 0.06 mg/kg per day in a subchronic study in male rats. The CONTAM Panel established a TDI for PFOA of 1.5 μg/kg per day by applying an overall UF of 200 to the NOAEL of 0.31 mg/kg/day. The benchmark dose for a 10% effect size (BMDL10) was 0.31 mg/kg/day. The CONTAM Panel established a TDI for PFOA of 1.5 μg/kg per day by applying an overall UF of 200 to the NOAEL of 0.03 mg/kg/day. An UF of 100 was used for inter- and intra-species differences and an additional UF of 2 to compensate for uncertainties in connection to the relatively short duration of the key study and the internal dose kinetics. Moreover, the EFSA (2008) also reviewed a number of toxicological studies on PFOA. The lowest NOAEL identified was 0.06 mg/kg per day in a subchronic study in male rats. At the next higher dose (0.64 mg/kg), hepatocellular hypertrophy and increased liver weight were found. When the dose–response data on increased liver weight were modeled, the lower confidence limit of the benchmark dose for a 10% effect size (BMDL10) was 0.31 mg/kg/day. The CONTAM Panel established a TDI for PFOA of 1.5 μg/kg per day by applying an overall UF of 200 to the lowest BMDL10 of 0.3 mg/kg/day. An UF of 100 was used for inter- and intra-species differences and an additional UF of 2 to compensate for uncertainties relating to the internal dose kinetics. The recommended TDIs for PFOS and PFOA (EFSA, 2008, 2011) of 150 and 1500 ng/kg/day, respectively, are notably higher than the suggested provisional RfDs.

5. Conclusions

The scientific information here revised suggests that dietary intake may be the most important source of exposure to PFCs, particularly PFOS and PFOA, for the general non-occupationally exposed population. However, that same information seems to indicate that, at the current food levels of PFCs, human health risks would not be of concern in most countries in which dietary studies have been performed. It is interesting to remark the notable differences in the results found among the studies carried out in various countries. These differences may be due to the food items included in the respective surveys, the selection of the food group samples, the PFCs analyzed and their detection limits, as well as to the parameters of the exposure analysis. However, even taking into account all these variables, it would be hard to explain some important differences, which could be hypothetically due to the food package or the cooking procedure.

Anyhow, because of the rather limited information about human dietary exposure to PFCs, studies in a number of countries focused on determining exposure through the diet of the general population to these compounds are necessary. This may be especially important in...
those countries where environmental and health regulations are not as rigorous as in Western countries. The correlation of PFCs body burdens and dietary intake of PFCs should be also established. Other sources of exposure to PFCs such as drinking water and dust should be also taken into account for a complete assessment of human health risks derived from exposure to PFCs. This can be particularly important for some countries in which, due to their weather characteristics, people spend more time inside and, therefore, exposure to PFCs via household products is expected to be higher.

References


Berger U, Glynn A, Holmström KE, Berglund M, Ankarberg EH, Törnkvist A. Fish consumption, body burdens and health risks of perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS) in the Norwegian population. Environ Res 2010;110:710–70


Haug LS, Thomesen C, Brantsæter AL, Kvalø HE, Haugen M, Becker G. Diet and particularly seafood are major sources of perfluorinated compounds in humans. Environ Int 2010b;36:772–8.


