JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

ARTICLE

pubs.acs.org/JAFC

Levels of Perfluorinated Compounds in Food and Dietary Intake of PFOS and PFOA in The Netherlands

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Supporting Information

ABSTRACT: This study presents concentrations of perfluorinated compounds in food and the dietary intake of perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) in The Netherlands. The concentrations of perfluorinated compounds in food were analyzed in pooled samples of foodstuffs randomly purchased in several Dutch retail store chains with nation-wide coverage. The concentrations analyzed for PFOS and PFOA were used to assess the exposure to these compounds in The Netherlands. As concentrations in drinking water in The Netherlands were missing for these compounds, conservative default concentrations of 7 pg/g for PFOS and 9 pg/g for PFOA, as reported by European Food Safety Authority, were used in the exposure assessment. In food, 6 out of 14 analyzed perfluorinated compounds could be quantified in the majority of the food categories (perfluoroheptanoic acid (PFHpA), PFOA, perfluorononanoic acid (PFNA), perfluorodecanoic acid (PFDA), perfluoro-1-hexanesulfonate (PFHxS), and PFOS). The highest concentration of the sum of these six compounds was found in crustaceans (825 pg/g product, PFOS: 582 pg/g product) and in lean fish (481 pg/g product, PFOS: 308 pg/g product). Lower concentrations were found in beef, fatty fish, flour, butter, eggs, and cheese (concentrations between 20 and 100 pg/g product; PFOS, 29−82 pg/g product) and milk, pork, bakery products, chicken, vegetable, and industrial oils (concentration lower than 10 pg/g product; PFOS not detected). The median long-term intake for PFOS was 0.3 ng/kg bw/day and for PFOA 0.2 ng/kg bw/day. The corresponding high level intakes (99th percentile) were 0.6 and 0.5 ng/kg bw/day, respectively. These intakes were well below the tolerable daily intake values of both compounds (PFOS, 150 ng/kg bw/day; PFOA, 1500 ng/kg bw/day). The intake calculations quantified the contribution of drinking water to the PFOS and PFOA intake in The Netherlands. Important contributors of PFOA intake were vegetables/fruit and flour. Milk, beef, and lean fish were important contributors of PFOS intake.

KEYWORDS: Perfluorinated compounds, food, dietary intake, exposure, The Netherlands

INTRODUCTION

Perfluorinated carboxylates and sulfonates as perfluorooctane sulfonate (PFOS) and perfluorooctanoate (PFOA) have been widely used in consumer and industrial products, including protective coatings for fabrics and carpets, paper coatings, insecticides, paints, cosmetics, and fire-fighting foams. The widespread use of PFOS and PFOA is due to their physicochemical characteristics such as resistance to degradation, thermal stability, and various surfactant properties.[1−4] PFOS and PFOA do not typically accumulate in lipids in contrast to the classical more lipophilic persistent organic pollutants like dioxins, furans, or polychlorinated biphenyls,[4,5] but rather in body compartments with high protein content.[6−8] Regarding the human health risk of PFOS and PFOA, the persistent nature of these compounds in the human body[9,10] and the long-term exposure to these compounds via food, drinking water, air, and house dust lead to their accumulation in the body.

For the assessment of the human exposure to PFOS and PFOA, different pathways have to be considered. Exposure via inhalation may result from outdoor and indoor air and from house dust. Oral exposure is mainly determined by the contamination of food and drinking water. Furthermore, the ingestion of dust and soil due to hand-to-mouth activities may also contribute to oral exposure in children. However, overall dietary exposure is suggested to be the dominant intake pathway in adults, responsible for 96% (PFOS) and 99% (PFOA) of the total intake of the general population using mean intake data.[3]

To date, little information is available concerning the human exposure to PFOS and PFOA through dietary intake in The Netherlands. This is the first study presenting the human exposure to PFOS and PFOA in The Netherlands from food and drinking water. Food products from relevant food categories purchased in 2009 in The Netherlands were analyzed for 14 perfluorinated carboxylates and sulfonates, including PFOS and PFOA. Conservative default concentrations in drinking water were obtained from European wide data as presented by EFSA.[4] In combination with consumption data of the third Dutch National Food Consumption Survey (DNFCS-3), the concentration

Received: December 24, 2010
Accepted: May 17, 2011
Revised: May 13, 2011
Published: May 17, 2011

data were used to estimate the long-term intake of PFOS and PFOA. In order to avoid unnecessary high and imprecise intake calculations, an nalytical method with a detection limit as low as pg/g product was used,[16] guaranteeing a minimum number of nondetects in the food samples.

MATERIALS AND METHODS

Food Samples. In November 2009, food products of 15 food categories were randomly purchased in several Dutch retail stores with nation-wide coverage. Each food category consists of several individual food items (see Supporting Information). The considered food categories and individual food items (between brackets) were the following: (1) flour (whole wheat flour/flour), (2) fatty fish (herring/eel/mackerel/salmon), (3) lean fish (cod/plaice/pollack/tuna), (4) pork (sausage/slice of bacon/pork chop/bacon/minced meat rolled in bacon), (5) eggs (chicken egg), (6) crustaceans (mussels/shrimp/crab), (7) bakery products (cake/almond paste cake/biscuits/brown spiced biscuit/pie), (8) vegetables/fruit (apple/orange/grape/banana/potato/onion, carrot, beet, chicory, or leek/tomato, cucumber, paprika, or mushroom/cauliflower, or broccoli/white cabbage, red cabbage, or Brussels sprout/spinach, endive, or lettuce/French beans), (9) cheese (Gouda cheese 48+ (>48% fat)/Edammer cheese 40+ (>40% fat)/cheese 48+ (>48% fat) less salt/cheese 30+ (>30% fat)/brie cheese), (10) beef (ground beef/beefburger/stewing steak/braising steak/minced steak), (11) chicken/poultry (chicken leg/quarter chicken/chicken filet/chicken burger/collared chicken), (12) butter (salt-free butter/salted butter/low-fat butter), (13) milk (half cream milk), (14) vegetable oil (margarine/low-fat margarine/frying fat (vegetable)/frying oil (vegetable)/sunflower oil) and (15) industrial oil (margarine/frying fat (industrial oil)/frying oil (industrial oil)). The food samples were transported to the laboratory of the Food and Consumer Product Safety Authority (VWA Zutphen, The Netherlands) where sample pretreatment (grinding and homogenization) and pooling were performed. The pooled food samples represented a certain food category. For example, the sample of the food category cheese consisted of a weight corrected pool of all sorts of cheese as recorded in DNFCS-3.[11] For example, the pooled cheese sample consisted of $213/250.5 \times 100 =$ 85% of gouda cheese, 48+ (see Supporting Information). Because it was anticipated that concentrations of perfluorinated compounds in the pooled food samples would be in the lower pg/g range, precautionary measures were taken to avoid contamination in every stage of the analysis (for details, see ref 16). Concerning the sampling and the postpurchase sample handling processes, several containers and packaging materials were tested for potential contamination with perfluorinated compounds. On the basis of these results, plastic containers lined with aluminum foil were selected for packaging the subsamples of the homogenized samples, as these materials contained the lowest (mostly below limit of detection (LOD)) levels of perfluorinated compounds.

Drinking Water. Drinking water contains perfluorinated compounds PFCs.[12−14] For this reason, drinking water was incorporated in the intake calculations. As concentrations of PFOS and PFOA in Dutch drinking water were not available, indicative default values for the concentrations of PFOS and PFOA present in drinking water based on European data[4] were used in the calculations, i.e., 7 pg/g for PFOS and 9 pg/g for PFOA. These concentrations are to be considered as conservative default values.

Analytical Method. The analysis of perfluorinated compounds in the different food categories was performed by the Institute for Environmental Studies (IVM, VU University, Amsterdam, The Netherlands). The following 14 compounds were analyzed: perfluorobutanoic acid (PFBA), perfluoropentanoic acid (PFPeA), perfluorohexanoic acid (PFHxA), perfluoroheptanoic acid (PFHpA), PFOA, and perfluorononanoic acid (PFNA); perfluorodecanoic acid (PFDA), perfluoroundecanoic acid (PFUDA), perfluorododecanoic acid (PFDoDA), perfluorotridecanoic acid (PFTrDA), perfluorotetradecanoic acid (PFTeDA), PFOS and potassium perfluoro-1-butanesulfonate (PFBS), and potassium perfluoro-1-hexanesulfonate (PFHxS). Both PFBS and PFHxS were quantified on the basis of their anions. IVM developed new extraction and cleanup techniques, based on extraction with a mixture of tetrahydrofuran and water (based on ref 17). The method detects perfluorinated compounds in the food samples as low as pg/g product. Detection was done by liquid chromatography coupled with electrospray ionization triple quadrupole mass spectrometry. The analysis was performed in the 15 pooled food category samples. Milk was analyzed according to a method by Tao et al.[15] Care was taken to avoid inaccuracies due to the presence of the bile acid interference present in products from animal origin (e.g., eggs and fish) and to avoid blank contributions during extraction, cleanup and instrumental analysis. For more details on the analytical method see van Leeuwen et al.[16] and Ballesteros-Gómez et al.[17]

Limit of Detection. The limits of detection (LOD) and quantification (LOQ) were determined as three respectively ten times the signal-to-noise ratio. On the basis of visual inspection of the chromatograms, all samples below the LOD were clearly nondetectable and therefore were assigned a zero value in the intake calculations. Likewise, samples exceeding the LOQ were assigned the measured concentration.

The content of samples exceeding the LOD, but below the LOQ, was considered uncertain. In the intake calculations, this uncertainty was incorporated by assigning these samples a concentration according to one of the following three scenarios: (1) concentration equal to LOD (low intake scenario), (2) the measured concentration (middle intake scenario), and (3) equal to LOQ (high intake scenario).

Intake Calculations. Food consumption data were obtained from DNFCS-3,[18] conducted in 1997/1998 in The Netherlands. This database contains information on the food products consumed by 6250 individuals (including the amounts), aged 1−97 years, on two consecutive days. In total, 1207 different consumed food products are listed in DNFCS-3. For each of these food products, a comprehensive description is available from the Dutch Food Composition Table.[19] Where possible, the consumed foods were linked directly to PFOS/PFOA concentrations. For example, industrial oils (e.g., cooking fat), vegetable oils (e.g., cooking fat fluid), cheese (e.g., Edammer cheese 40+ (>40% fat)), and bakery products (e.g., cakes) were linked to the PFOS/PFOA concentrations as determined in the corresponding food category. For the other (more complex) food products, the conversion model for primary agricultural products[20] was used to split food products into their constituting primary agricultural products (including their mass fractions). The PFOS/PFOA concentrations of all the separate ingredients, corrected for their fraction, were added to get the total PFOS/PFOA concentration in the consumed food. PFOS and PFOA concentrations in drinking water were directly linked to European wide data as presented by EFSA.[4] The individual daily intake was calculated by coupling the food consumption data with the corresponding PFOS/PFOA concentrations per food category for each individual in DNFCS-3 and summing the resulting exposure levels per day. This resulted in a frequency distribution of daily intakes for both compounds (short-term individual daily intake). These frequency distributions yield information on the variability of daily intakes in the population. Though such distributions show the variation in short-term PFOS/PFOA intake, they are unsuitable for an assessment of the long-term intake, which is required to assess the possible health risks of this intake. The reason for this is that a distribution of the long-term intakes would be considerably narrower than the distribution of daily intakes because within-subject variations disappear. An estimation of long-term intake can be made by statistical analysis applying the statistical exposure model (STEM).[21] STEM combines regression analysis on age by fitting a regression curve to the daily intake data and nested variance analysis to separate within-subject variance from between-subject variance. The

Table 1. Concentrations of Perfluorinated Carboxylates and Sulfonates (pg/g Product) in Food Categories Sampled in 2009 (Concentration Values >LOD Are Printed in Bold Font)

food category	PFBA	PFPeA	PFHxA	PFHpA	PFOA	PFNA	PFDA	PFUDA	PFDoDA	PFTrDA	PFTeDA	PFBS	PFHxS	PFOS
fatty fish	<43	<44	<5	**3**	**8**[b]	**5**	**4**	**36**	**10**	**41**	**3**	<1	**9**	**61**
lean fish	<30	<28	<3	**2**	**23**[b]	77	**48**	**177**	**56**	**229**	**24**	<1	**23**	**308**[b]
crustaceans	**31**	<34	<4	**5**	**46**[b]	**58**	**90**	**157**	**45**	**268**	**45**	<1	**44**	**582**[b]
butter	<31	<43	**20**	**5**	**16**[a]	**2**	**6**	<3	**2**	<19	<1	<3	**16**	**33**[a]
cheese	<99	<89	<9	**7**	<19	**7**	**8**	<16	<11	<92	<5	<12	<25	<85
milk	**43**	<23	<6	<3	**1**[a,b]	<1	**1**	<0.5	<0.5	<0.5	<2	<4	<2	**10**[b]
eggs	<4000	<512	<54	<2	<32	**6**	**11**	<19	<13	<107	<5	<3	<6	**29**[a]
pork	<112	<104	<11	**6**	**15**[a]	**2**	**2**	<4	<3	<23	<1	<3	<5	**14**[a]
beef	<48	<44	<5	<0.2	<5	**4**	**6**	**2**	<2	<14	<0.7	<2	<4	**82**
chicken/poultry	<91	<67	<7	**1**	<5	**1**	<1	<3	<2	<17	<0.8	<2	**3**	<5
bakery products	<345	<89	<9	<0.2	**5**[a]	**1**	**1**	<1	<0.7	<6	<0.3	<1	**6**	**4**[a]
vegetables/fruit	**130**	<34	<4	<0.2	**5**[a]	**1**	**2**	<2	<2	<14	<0.7	<6	<12	<47
flour	<57	<28	**11**	**14**	**17**	**15**	**9**	**4**	**4**	<9	<0.4	<1	**18**	<9
vegetable oil	<32	<28	<3	**1**	<3	<0.1	<0.6	<2	<1	<11	<0.6	<0.9	<2	<3
industrial oil	<54	<52	<5	**3**	**6**[a]	<0.3	**2**	<3	<2	<16	<0.8	<3	**7**	<12

[a] Value between LOD and LOQ. [b] Mean value of two separate measurements of the same sample.

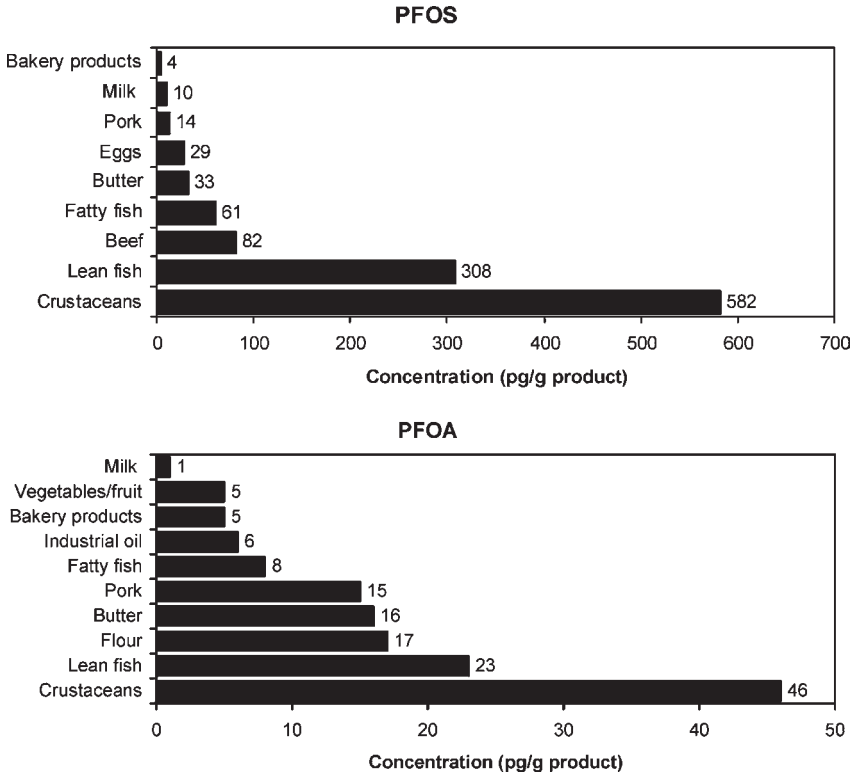

Figure 1. Concentrations of PFOS and PFOA in food categories. Only values >LOD are presented.

within-subject variance is filtered out, leaving an estimate of the long-term between-subject variance. To obtain the life-long average intake for the population, the intakes of all age classes were summed, and this sum was divided by the number of age classes. STEM has previously been applied in dietary intake studies of dioxins and polybromintated diphenylethers.[22,23]

STEM has been integrated into the Monte Carlo Risk Assessment software (MCRA) release 6.2.[24,25] The Beta-Binomial-Normal (BBN) model as implemented MCRA release 6.2 was applied for the calculation of the long-term PFOS/PFOA intake.

RESULTS

Concentrations of Perfluorinated Compounds in Food Categories. One or more perfluorinated compounds could be detected in all food categories examined. Out of 14 compounds, most were detected in crustaceans ($n = 11$), followed by lean and fatty fish ($n = 10$), and butter and flour ($n = 8$). Five or less compounds were detected in the other food categories. The concentrations of the 14 compounds are presented in Table 1.

Table 2. Contribution of Various Food Categories to the Individual Daily Intake (As Obtained from the DNFCS-3) of PFOS and PFOA[a]

	PFOA			PFOS		
food category	concentration (pg/g product)	intake (pg/kg bw/day)	percentage of individual daily intake	concentration (pg/g product)	intake (pg/kg bw/day)	percentage of individual daily intake
fatty fish	8	0.4	0.2	61	3.1	1.0
lean fish	23	2.2	0.9	308	29.5	9.2
crustaceans	46	0.7	0.3	582	8.5	2.6
butter	16	0.6	0.3	33	1.3	0.4
cheese	0	0	0	0	0	0
milk	0.5	3.9	1.6	10	78.8	24.5
eggs	0	0	0	29	7.7	2.4
pork	15	14.9	5.9	14	13.9	4.3
beef	0	0	0	82	68.1	21.2
chicken/poultry	0	0	0	0	0	0
bakery products	5	3.7	1.5	4	3.0	0.9
vegetables/fruit	5	47.4	18.9	0	0	0
flour	17	38.4	15.3	0	0	0
vegetable oil	0	0	0	0	0	0
industrial oil	6	0.7	0.3	0	0	0
drinking water	9*	137.9	55.0	7*	107.3	33.4

[a] Measured concentrations were used when values were between LOD and LOQ (middle scenario). Values < LOD were assigned 0, values above the LOQ their measured values. *, concentrations in drinking water were based on calculations provided by EFSA, 2008.

Only PFHpA, PFOA, PFNA, PFDA, PFHxS, and PFOS could be detected in the majority of the food categories. PFPeA and PFBS were not detected in any food category and PFBA only in three categories. PFUDA, PFDoDA, PFTrDA, and PFTeDA were observed in 6 food categories. The concentration of the individual congeners in the different food categories was below 100 pg/g product, except for PFUDA, PFTrDA, and PFOS in lean fish and crustaceans. The food categories cheese, pork, chicken/poultry, bakery products, flour, vegetable oil, and industrial oil contained the lowest concentrations (<20 pg/g product for each compound). In this study, concentrations of PFOS and PFOA are presented in Figure 1. Highest concentrations of PFOS and PFOA are found in crustaceans and lean fish. PFOS concentrations in these samples are about 13 times higher than the PFOA concentrations.

Short-Term Individual Daily Intake: Contribution of Food Categories. Table 2 presents the contributions of the different food categories and drinking water to the short-term individual intake of PFOS and PFOA. For PFOA vegetables/fruit (19%), flour (15%) and pork (6%) were important contributors, whereas for PFOS, milk (25%), beef (21%), lean fish (9%), and pork (4%) were important. The other food categories showed a contribution of less than 2% for both compounds.

Given the conservative default concentration for PFOS and PFOA in drinking water, this single source contributed to 33% and 55% of the total intake of the Dutch population. respectively.

Although fish and crustaceans showed the highest PFOS concentrations, their contribution to the intake was rather limited due to the low fish consumption rate of the Dutch population.

Long-Term Intake. Age dependent intakes of PFOS and PFOA are presented separately for males and females (see Table 3). Ages 2, 10, and 40 years are presented to elucidate possible intake differences between children and adults. Table 3 also presents the percentiles of the life-long average exposure. Percentile values of PFOS and PFOA are in the same range between males and females. However, females tended to have a structurally slightly higher intake of the two compounds, when expressed per kg body weight. For PFOS, the best estimate of the median (P50) life-long intake ranged from 279 (95% CI: 273−298) to 329 pg/kg bw/day (95% CI: 309−347) in the three different scenarios. For PFOA, the estimate of the median life-long intake varied between 212 (95% CI: 192−22) and 346 pg/kg bw/day (95% CI: 326−360). Estimated levels of high life-long intake (P99) ranged from 578 to 645 pg/kg bw/day for PFOS and 462 to 675 pg/kg bw/day for PFOA. As expected, increasing dietary intakes were observed when using the LOD (low scenario), values between LOD and LOQ (middle scenario), and LOQ (high scenario), respectively.

Daily intakes expressed as kg body weight were higher in children compared to that in adults (40 years of age), with highest intakes in very young children (2 years of age compared to 10 years) for both PFOS and PFOA.

Comparison of Dietary Intake to the TDI. In 2008, EFSA's contaminants panel established a tolerable daily intake (TDI) of 150 ng/kg bw/day for PFOS and 1500 ng/kg bw/day for PFOA.

The calculated median (P50) life-long intake of PFOS was around 0.3 ng/kg bw/day, which was 500 times lower than the corresponding TDI. Even the P99 of life-long exposure in the high intake scenario (0.65 ng/kg bw/day, females) was 230-fold lower than the TDI. The highest dietary intake of PFOS was observed in 2-year-old children, but the P50 (0.7−0.8 ng/kg bw/day) and even the P99 (1.4−1.5 ng/kg bw/day) were around 200- and 100-fold lower than the TDI, respectively.

The calculated median (P50) life-long intake of PFOA varied between 0.2 and 0.35 ng/kg bw/day, depending on which scenario was used for the calculations. This calculated dietary intake was 4300−7500 lower than the TDI of 1500 ng/kg bw/day. Even the P99 in the high intake scenario (0.68 ng/kg bw/day, females) was 2200-fold lower than the TDI. The highest

Table 3. Percentiles of Age-Dependent Long-Term Dietary Intake (Including Drinking Water) of PFOS and PFOA (pg/kg bw/day)[a]

PFOS (low scenario)	P50 (2.5−97.5)		P90 (2.5−97.5)		P95 (2.5−97.5)		P99 (2.5−97.5)	
age (years)	male	female	male	female	male	female	male	female
2	687 (657−718)	737 (695−763)	1035 (974−1070)	1099 (1038−1153)	1162 (1087−1198)	1235 (1163−1291)	1428 (1333−1498)	1539 (1430−1617)
10	293 (283−305)	314 (304−324)	437 (423−454)	471 (452−484)	492 (473−510)	528 (505−545)	615 (577−636)	650 (619−678)
40	253 (249−261)	273 (266−278)	376 (368−393)	406 (394−420)	420 (411−441)	453 (438−472)	512 (500−554)	561 (537−591)
life-long average intake	279 (273−298)	298 (278−318)	416 (406−445)	445 (415−476)	446 (455−500)	499 (464−534)	578 (562−623)	618 (569−666)
PFOS (middle scenario)	P50 (2.5−97.5)		P90 (2.5−97.5)		P95 (2.5−97.5)		P99 (2.5−97.5)	
age (years)	male	female	male	female	male	female	male	female
2	707 (699−755)	747 (716−807)	1038 (1028−1106)	1104 (1059−1175)	1150 (1145−1232)	1233 (1175−1309)	1418 (1405−1513)	1528 (1416−1608)
10	311 (306−320)	328 (320−341)	460 (449−472)	480 (469−500)	512 (499−526)	539 (519−558)	634 (611−652)	660 (634−696)
40	267 (262−271)	281 (275−288)	391 (385−402)	413 (400−427)	437 (429−450)	461 (444−477)	532 (524−559)	567 (538−595)
life-long average intake	291 (285−309)	309 (290−329)	428 (418−456)	454 (424−485)	478 (465−510)	507 (471−543)	588 (569−630)	623 (573−671)
PFOS (high scenario)	P50 (2.5−97.5)		P90 (2.5−97.5)		P95 (2.5−97.5)		P99 (2.5−97.5)	
age (years)	male	female	male	female	male	female	male	female
2	748 (706−787)	785 (747−822)	1081 (1025−1131)	1140 (1079−1198)	1208 (1134−1257)	1256 (1202−1329)	1467 (1378−1540)	1518 (1464−1633)
10	341 (332−351)	359 (348−370)	495 (480−512)	520 (504−536)	553 (530−571)	573 (558−595)	679 (636−702)	706 (666−737)
40	286 (279−293)	300 (294−307)	413 (403−424)	435 (426−447)	459 (446−472)	489 (470−497)	568 (540−581)	596 (565−611)
life-long average intake	313 (294−329)	329 (309−347)	453 (424−478)	477 (447−503)	504 (469−532)	530 (495−559)	614 (567−652)	645 (597−685)
PFOA (low scenario)	P50 (2.5−97.5)		P90 (2.5−97.5)		P95 (2.5−97.5)		P99 (2.5−97.5)	
age (years)	male	female	male	female	male	female	male	female
2	385 (368−400)	407 (393−425)	593 (565−615)	631 (603−658)	675 (637−696)	714 (678−747)	851 (794−884)	891 (846−945)
10	181 (176−185)	192 (187−197)	275 (269−285)	296 (287−303)	311 (303−324)	332 (324−345)	395 (378−410)	414 (404−435)
40	222 (218−226)	236 (233−242)	342 (333−349)	367 (354−372)	385 (377−395)	416 (401−423)	493 (470−502)	520 (497−535)
life-long average intake	212 (192−221)	226 (205−236)	326 (295−341)	347 (314−363)	368 (332−386)	392 (354−411)	462 (414−488)	493 (442−520)
PFOA (middle scenario)	P50 (2.5−97.5)		P90 (2.5−97.5)		P95 (2.5−97.5)		P99 (2.5−97.5)	
age (years)	male	female	male	female	male	female	male	female
2	424 (408−445)	452 (436−474)	645 (613−671)	684 (655−715)	724 (688−753)	770 (735−801)	899 (851−948)	954 (916−994)
10	203 (197−209)	216 (209−221)	306 (296−315)	327 (316−335)	342 (333−357)	368 (354−376)	427 (412−446)	461 (438−471)
40	237 (232−241)	252 (247−257)	357 (349−364)	382 (372−389)	401 (391−411)	429 (418−438)	507 (484−517)	529 (513−548)
life-long average intake	229 (211−241)	244 (224−256)	346 (317−363)	367 (337−386)	389 (356−409)	413 (378−435)	484 (440−512)	513 (467−544)
PFOA (high scenario)	P50 (2.5−97.5)		P90 (2.5−97.5)		P95 (2.5−97.5)		P99 (2.5−97.5)	
age (years)	male	female	male	female	male	female	male	female
2	691 (671−716)	736 (714−765)	985 (967−1039)	1065 (1030−11−7)	1092 (1073−1155)	1186 (1141−1234)	1340 (1295−1409)	1448 (1388−1495)
10	328 (323−329)	355 (347−363)	477 (467−690)	513 (500−526)	529 (519−545)	567 (555−586)	647 (627−669)	683 (670−715)
40	314 (308−319)	338 (329−341)	456 (444−461)	487 (473−492)	506 (492−511)	539 (524−547)	612 (594−630)	649 (635−669)
life-long average intake	324 (306−336)	346 (326−360)	468 (441−487)	500 (471−520)	519 (489−541)	555 (522−578)	630 (591−662)	675 (632−707)

[a] Within parentheses: 95% confidence interval. Values were set according to the three scenarios as described in Material and Methods.

dx.doi.org/10.1021/jf104943p | J. Agric. Food Chem. 2011, 59, 7496–7505

dietary intake of PFOA was observed in 2-year-old children, but the P50 of the high scenario (0.7 ng/kg bw/day) and even the P99 (1.3−1.4 ng/kg bw/day) was around 2100- and 1100-fold lower than the TDI of 1500 ng/kg bw/day, respectively.

DISCUSSION

Exposure Assessment. This study presents dietary intake calculations of PFOS and PFOA in The Netherlands, including the intake of these compounds via daily drinking water. The median life-long intake for PFOS amounted to 0.3 ng/kg bw/day and, depending on the intake calculation scenario, 0.2 to 0.35 ng/kg bw/day for PFOA. These intakes were well below the TDIs of 150 ng/kg bw/day for PFOS and 1500 ng/kg bw/day for PFOA. From these results, it can be concluded that the exposure of the Dutch population to PFOS and PFOA from food and drinking water has limited toxicological relevance.

The concentrations found in the food items analyzed in this study were, in general terms, lower than those reported in other dietary studies of perfluorinated compounds in foods. In the present study, the measured concentrations ranged from 0.001 to 0.6 ng/g product. In a Canadian study, PFOS was detected in beef steak, ground beef, popcorn, and marine and freshwater fish.[26] The measured concentrations were >2 ng/g, except for popcorn (1 ng/g). PFOA was only detected in roast beef (2.6 ng/g) and popcorn (3.6 ng/g). The British Food Safety Agency (FSA) has presented concentration data of PFOS in fish, liver, and kidney, while PFOA was detected in whitebait, crab, and liver.[27] The concentrations ranged from 1 to 20 ng/g. Both studies showed higher concentrations in food products compared with the results reported in the present study. However, studies in Spain[13] and Norway[34] reported lower levels of PFOS in vegetables, fish, meat, eggs, and dairy products (0.02−0.7 ng/g). PFOA was only detected in milk (0.06 ng/g). Measured concentrations were in the same range compared with those the present study.

In the current study, the highest concentrations of PFOS and PFOA were observed in crustaceans and lean fish. The PFOS concentrations in fish samples in this study were lower than those reported for freshwater fish in German waters[28] and slightly lower than in Swedish freshwater fish.[29] The results presented here were also lower compared to those in an earlier Dutch survey of freshwater and marine fish from 2004.[30] Several possible explanations for the lower concentrations measured in this study are (i) the focus (partly) of the earlier study on hotspot findings, resulting in higher levels, (ii) the possible drop of levels in the environment since the 2004 study, (iii) the use of a less sensitive analytical method, and/or (iv) the use of pooled samples for each food category in the present study. Concentrations of perfluorinated compounds in individual food items that make up the food category could have been higher than those reported for the pooled food category samples since food items with levels <LOD in the same category can effectively dilute concentrations in individual food items. PFOS and PFOA have been demonstrated to accumulate in fish from fresh water.[31,32] Therefore, fish may be an important dietary source of PFOS and PFOA for high fish consumers, whereas for moderate fish consumers such as the Dutch population, fish only forms a minor source. Freshwater and marine fish, and seafood, have been analyzed for perfluorinated compounds. In fish, higher levels of PFOS have been found than PFOA. The difference between the PFOS and PFOA fish concentrations are caused by a lower potential of PFOA to accumulate in fish than PFOS. Differences in accumulation from the diet and from fresh water have been demonstrated for PFOS and PFOS in laboratory experiments in fish.[31,32] The relatively low PFOS concentrations in fish samples in the present study are in accordance with the low concentrations found in (farmed) fish consumed in The Netherlands[33] and Norway.[34] As in fish, the accumulation of PFOS (and PFOA) from the diet is much less efficient than from fresh water[31,32] farmed fish is expected to have much lower PFOS concentrations compared to fresh water fish.

Next to drinking water (see below), the main food contributors of the PFOA intake were vegetables/fruit (19%) and flour (15%). For PFOS, next to drinking water, the main contributors were milk (25%) and beef (21%). Despite relatively high concentrations of PFOS and PFOA in fish and crustaceans, the contribution to the total intake was low due to the relatively low consumption of fish and crustaceans in The Netherlands. The results suggest that perfluorinated compounds may penetrate or accumulate differently in the various food products. For example, PFOS was detected in eggs and beef, while PFOA was not detected in these food categories. However, PFOA was detected in vegetables/fruit and flour, while PFOS was not found in this food category.

Finally, the calculations reported here are based on food consumption data collected from April 1997 to March 1998, i.e., the DNFCS-3. Though food consumption data from a more recent food questionnaire among young adults in The Netherlands (2003) did reveal differences in food consumption patterns with respect to the DNFCS-3, these differences were found to only marginally affect the intake presented in this study (data not shown).

Analytical Method. The analytical method used detects perfluorinated compounds in the food samples as low as pg/g product. The method allows for a clear discrimination of the signal-to noise ratio and the definition of the LOD and the LOQ. The content of samples exceeding the LOD, but below the LOQ, was considered uncertain. This uncertainty was incorporated in the intake by assuming a sample content at the level of the LOD, at the level of the measured concentration or on the level of the LOQ. It might be argued that this approach leads to conservative, low, intake calculations of PFOS and PFOA. Usually, the content of samples below the LOD is not set at a zero value but merely at one-half of the LOD value (to mimic the measurement uncertainty in the LOD).

However, in order to avoid unnecessary high and imprecise intake calculations, this article just pleads for the application of analytical methods which minimize the number of nondetects in food samples which are used in intake calculations. Nevertheless, even with the current analytical method a number of nondetects were found. To illustrate the sensitivity of the intake calculations for setting these nondetects at a zero value, the intake calculations as shown in Table 3 were repeated with all nondetects set at their LOD (worst case approach). This resulted in only a 2.5-fold increase in the long term dietary intake of PFOS, whereas the PFOA intake was only marginally affected (see Supporting Information).

The life-long dietary intake of PFOS and PFOA in the present study (P99: 0.5−0.6 ng/kg bw/day for PFOS and PFOA) was very low compared to that in studies performed in the UK,[27] Belgium,[35−37] Canada,[26] and Europe,[4] somewhat lower than that in Spain,[13] and comparable to that in a study in Norway.[34] The FSA presented an average adult dietary intake of 10 ng/kg bw/day

for both PFOS and PFOA, and a high level dietary intake of 20 ng/kg bw/day for both compounds. These high intakes, however, result from the attribution of relative high LOD levels of PFOS/PFOA to food products in which PFOS/PFOA levels were below the LOD (LODs ranging from 1 to 20 ng/g product for PFOS and 1−10 ng/g product for PFOA).[38] Ericson et al.[13] calculated a dietary intake of PFOS of 1.06 ng/kg bw/day, while Tittlemier et al.[26] estimated a dietary intake of PFOS of about 4 ng/kg bw/day. EFSA[4] calculated an average dietary exposure for PFOS of even 60 ng/kg bw/day and for PFOA 2 ng/kg bw/day. A study performed in Belgium calculated an average dietary exposure for PFOS and PFOA of 20−25 and 5.6−6.2 ng/kg bw/day, respectively.[35−37] Recently, Haug et al.[34] presented a dietary intake for PFOA of 0.4 ng/kg bw/day and for PFOS of 0.3 ng/kg bw/day (calculated for a person of 70 kg). These data are in the same range as the present study (average dietary intake for PFOA is 0.2 ng/kg bw/day and for PFOS 0.3 ng/kg bw/day).

In conclusion, the dietary intake of PFOS and PFOA varies significantly between studies, with the present study confirming the low concentrations and corresponding low intake of these compounds in food previously found in Spain[13] and Norway.[34] These differences may indicate true differences, i.e., higher PFOS and PFOA levels in the food samples investigated in the other studies. However, the sensitivity of analytical chemical methods to detect PFOA and PFOA in food may play an important role as well. Not surprisingly, using a sensitive analytical method as in this study resulted in a relatively low dietary intake of PFOS and PFOA in The Netherlands. These results stress that prudence is called for in using the results of not sensitive enough chemical analyses in food for intake calculations of perfluorinated compounds: using such analyses will result in an overestimation of the dietary exposure.

Drinking Water. In the absence of monitoring data in The Netherlands, PFOS and PFOA concentrations in drinking water as compiled by EFSA have been used as a substitute for the concentrations of PFOS and PFOA in Dutch drinking water. In this context, the EFSA database assumes that fresh water can be used as a direct source for drinking water, a situation which is not uncommon in The Netherlands. However, the used concentrations are prone to considerable uncertainty. First, the used PFOS concentration of 7 ng/L for combined drinking water and fresh water is to be considered as the average of a rather wide distribution with a Q_{10} of 1.0 ng/L and a Q_{90} of 18 ng/l, with minimum and maximum reported concentrations in Europe ranging from 0.01 to 56 ng/L. Corresponding values for the used PFOA concentration of 9 ng/L are 0.6 ng/L (Q_{10}), 21 ng/L (Q_{90}), 0.05 ng/L (minimum), and 456 ng/L (maximum).[3] In this context, the used concentrations are considered defendable as preliminary, indicative for the Dutch situation. In case, monitoring data reveal that Dutch drinking water has a substantially lower PFOS and PFOA concentration than fresh water (EFSA reports a minimum/maximum of 0.4−8.10 ng/L for PFOS and 1.0−4.0 for PFOS in drinking water) than would lead to a substantial lowering of the contribution of drinking water to the exposure to PFOS and PFOA. For example, in the present study a concentration of 7 ng PFOS/L drinking water contributed to 33% of the combined PFOS exposure from drinking water and food. However, when Dutch drinking water would contain EFSA's median/average concentration of 1 or 3 ng/L, this contribution reduces to 6 and 17%, respectively.

Likewise, an even lower contributions of drinking water is expected when the exposure from food is higher than that calculated in the present study. Given a daily drinking water intake of 1.3 L containing 1 ng PFOS/L and a daily intake from food of 90 ng/day, Fromme et al. calculated a contribution of only 1.5% of drinking water to the total intake.[3]

In conclusion, PFOS and PFOA concentrations in drinking water show considerable regional and local variation.[3,4,13] On average, the contribution of drinking water to the total exposure of these compounds may be limited. However, in the case where freshwater is directly used for the preparation of drinking water or when local sources contain high PFOS and PFOA concentrations drinking water may become an important route of exposure to these compounds, if not the dominant source.[13]

Time Trend of Historic Exposure: Serum Levels. Though the intake calculations presented here reflect the dietary intake of the Dutch population to PFOS and PFOA, they are limited to one point in time, i.e., the year 2009. In this context, we cannot evaluate whether this intake shows an increasing or decreasing time trend. However, as PFOS and PFOA are removed slowly from the body[9,10] the time-trend in serum levels may mimic the historic long-term time trend in food.[23] Haug et al.[39] evaluated this time-trend in archived human serum in Norway. In the serum, PFHpA, PFOA, PFNA, PFDA, PFUDA, PFDoDA, PFTrDA, PFHxS, and PFOS could be detected. With the exception of PFUDA, PFDoDA, and PFTrDA, which could only be detected in fish, these compounds were also found in Dutch food. In serum, PFOS and PFOA showed an increasing time-trend in the period between 1976 and 2006 until the mid 1990s followed by a stabilization period until 2000, after which the serum concentration started to decrease. This decrease was considered consistent with the phase-out of these compounds (at the beginning of 2000, the major manufacturer 3M phased out the production of PFOA, though PFOA continued to be produced by others). PFNA levels did not show such a decrease after 2000, whereas PFDA levels even kept an increasing time-trend beyond 2000. In serum, PFOA and PFOS were found to be correlated. As such a correlation was not found with other perfluorinated compounds as PFBS, PFUDA and PFDoDA, this was interpreted as PFOS and PFOA sharing common sources for human exposure, i.e., dust, food, drinking water, and air. A decreasing time-trend of PFOA and PFOA in serum between 2000 and 2006 has also been observed in the USA,[40−42] with PFOA decreasing slower than PFOS. Though this decrease too is consistent with the phase-out of these compounds, the fact that PFOA's elimination half-life form the human body is shorter (geometric mean, 3.5 years; 95% CI, 3.0−4.1) than that of PFOS (geometric mean, 4.8 years; 95% CI, 4.0−5.8) suggests that part of the PFOA in serum originated from the (still) ongoing production of PFOA itself or from the production of fluorotelomer-based PFOA precursors (ref 40 and also see above).

Direct and Indirect Exposure to PFOS and PFOA. Potential routes of human exposure to PFOS and PFOA are inhalation of air, ingestion of house dust, drinking water, and food (direct exposure), and the intake of precursors (PreFOS) which have been detected in indoor and outdoor air and in food after migration from food packaging materials (indirect exposure). Once absorbed in the body, these precursors may be metabolized to PFOS or PFOA.

Fromme et al.[3] reviewed and compared the direct and the indirect exposure to PFOS/PFOA and PreFOS. Direct PFOS and PFOA intakes were estimated at 1.6 ng/kg bw (95th

percentile: 8.8 ng/kg bw) for PFOS and 2.9 ng/kg bw (95th percentile: 12.6 ng/kg bw) for PFOA. For the average human, the diet contributed to 96% (PFOS) and 99% (PFOA) of the direct exposure. House dust (50 mg/day; 37.8 ng/g) was responsible for 2% (PFOS) and 0.6% (PFOA) of the total intake, while air (indoor and outdoor together) is responsible for only 0.3% (PFOS) and 0.08% (PFOA). Drinking water (1.3 L/day, 1 ng/l) contributed to 1.5% (PFOS) and 0.8% (PFOA) of the daily intake. Taking a high intake scenario (house dust, 5065 ng/g; drinking water, 6 ng/L) led to an increase of the contribution of dust to the total daily intake from 2 to 48% (PFOS) and 0.6 to 8% (PFOA). Clearly, as with drinking water, the contribution of house dust to the total exposure of PFOS and PFOA may be limited in the average situation. However, in the case of high PFOS and PFOA dust concentrations, house dust may equal the diet as the route of exposure to these compounds.[3,43] Indirect exposure was estimated by means of the sum of 4:2, 6:2, 8:2, and 10:2 FTOH (SumFTOH) and the sum of *N*-EtFOSE, *N*-MeFOSE, *N*-EtFOSA, and *N*-Me*FOSA* (SumFOSE/FOSA). The overall mean (and high) daily intake was 0.14 ng/kg bw (95th percentile: 1.1 ng/kg bw) for the SumFTOH and 1.6 ng/kg bw (95th percentile: 11 ng/kg bw) for the SumFOSE/FOSA. The indirect exposure amounted to 5−9% and 107−124% of the direct PFOA and PFOS intake, respectively.

The interpretation of the indirect exposure in terms of contribution to the amount of PFOS/PFOA in the human body, however, needs information on the absorption of the precursors and their subsequent conversion to PFOS or PFOA. In vivo, the absorption of 8:2 FTOH ranged from 27−57% in the rat.[44] In vitro experiments with rat hepatocytes revealed 8:2 FTOH to be metabolized to PFOA at a low efficiency (only 1.4% conversion of 8:2 FTOH[45]). Furthermore, human hepatocytes appeared to have an even lower efficiency for this conversion.[45] Similarly, *N*-EtFOSE is absorbed for 80% and quickly metabolized to PFOSA in the rat.[46] As a major pathway, PFOSA is efficiently metabolized to PFOSA *N*-glucuronide, with the formation of PFOS being a minor pathway. Here, the human liver possesses a relative high *N*-glucuronosyltransferase activity.[47,48] These results suggest that FTOHs have only a small contribution to the PFOA exposure of adults and that the contribution of the converted FOSEs/FOSAs to the PFOS exposure of the general population can be estimated to lie around 10%.[3] The relative low contribution of PreFOS to the PFOS and PFOA intake for the general population was confirmed by Vestergren et al.[49] However, this author also hints at the possibility that PreFOS may contribute to up to 80% of the PFOS and PFOA intake in subgroups of the population. Furthermore, it should be kept in mind that PreFOS concentrations in food show considerable variation and may gain in importance as the source for PFOS and PFOA, in particular as the production of these latter compounds has been phased out. In this context, we suggest that the uncertainty in the food levels of PreFOS be resolved by the regular monitoring of these compounds in food.[42]

■ ASSOCIATED CONTENT

Supporting Information. An extensive table showing the pooled food categories and their constituting food products, and the amount of the food products and the total amount per category. This material is available free of charge via the Internet at http://pubs.acs.org.

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■ ACKNOWLEDGMENT

Erik Roerink and Hans van Rhijn of the VWA laboratory in Zutphen are gratefully acknowledged for their skillful sample preparation. Kees Swart of the VU University in Amsterdam is gratefully acknowledged for his skillful analysis of PFCs in the food samples. Jacqueline van Engelen and Polly Boon of the RIVM are acknowledged for their constructive comments on the manuscript.

■ ABBREVIATIONS USED

PFOS, perfluorooctane sulfonate; PFOA, perfluorooctanoate; DNFCS-3, third Dutch National Food Consumption Survey; LOD, limit of detection; PFBA, perfluorobutanoic acid; PFPeA, perfluoropentanoic acid; PFHxA, perfluorohexanoic acid; PFHpA, perfluoroheptanoic acid; PFNA, perfluorononanoic acid; PFDA, perfluorodecanoic acid; PFUDA, perfluoroundecanoic acid; PFDoDA, perfluorododecanoic acid; PFTrDA, perfluorotridecanoic acid; PFTeDA, perfluorotetradecanoic acid; PFBS, potassium perfluoro-1-butanesulfonate; PFHxS, potassium perfluoro-1-hexanesulfonate; 4:2 FTOH, 1*H*,1*H*,2*H*,2*H*-perfluoro-1-hexanol; 6:2 FTOH, 1*H*,1*H*,2*H*,2*H*-perfluoro-1-octanol; 8:2 FTOH, 1*H*,1*H*,2*H*,2*H*-perfluoro-1-decanol; 10:2 FTOH, 1*H*,1*H*,2*H*,2*H*-perfluoro-1-dodecanol; *N*-EtFOSE, *N*-ethyl perfluorooctane sulfonamidoethanol; *N*-MeFOSE, *N*-methyl perfluorooctane sulfonamidoethanol; *N*-EtFOSA, *N*-ethylperfluorooctane sulfonamide; *N*-Me*FOSA*, *N*-methylperfluorooctane sulfonamide; LOQ, limit of quantification; BBN model, Beta-Binomial-Normal model; MCRA, Monte Carlo Risk Assessment; TDI, tolerable daily intake; FSA, British Food Safety Agency.

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