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Lipid Composition and Contaminants in Farmed and Wild Salmon

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Levels of omega-3 (n-3) and omega-6 (n-6) fatty acids and lipid-adjusted concentrations of polychlorinated biphenyls (PCBs), dioxins, toxaphene, and dieldrin were determined in 459 farmed Atlantic salmon, 135 wild Pacific salmon, and 144 supermarket farmed Atlantic salmon fillets purchased in 16 cities in North America and Europe. These were the same fish previously used for measurement of organohalogen contaminants. Farmed salmon had greater levels of total lipid (average 16.6%) than wild salmon (average 6.4%). The n-3 to n-6 ratio was about 10 in wild salmon and 3−4 in farmed salmon. The supermarket samples were similar to the farmed salmon from the same region. Lipid-adjusted contaminant levels were significantly higher in farmed Atlantic salmon than those in wild Pacific salmon ($F = 7.27$, $P = 0.0089$ for toxaphene; $F = 15.39$, $P = 0.0002$ for dioxin; $F \geq 21.31$, $P < 0.0001$ for dieldrin and PCBs, with df = (1,64) for all). Levels of total lipid were in the range of 30−40% in the fish oil/fish meal that is fed to farmed salmon. Salmon, especially farmed salmon, are a good source of healthy n-3 fatty acids, but they also contain high concentrations of organochlorine compounds such as PCBs, dioxins, and chlorinated pesticides. The presence of these contaminants may reduce the net health benefits derived from the consumption of farmed salmon, despite the presence of the high level of n-3 fatty acids in these fish.

Introduction

Polyunsaturated fatty acids (PUFAs) are essential lipids that cannot be synthesized by mammalian organisms. Consequently these fatty acids must come from the diet. There are two categories of essential PUFAs; both consist of a number of different lipids varying in carbon chain length and the number of double bonds. Omega-3 (n-3) fatty acids have a double bond at the third carbon position, while omega-6 (n-6) fatty acids have a double bond at the sixth carbon position from the methyl end.

The n-6 fatty acids are present in a great variety of food sources. The precursor fatty acid for the n-6 class is linoleic acid, which is required for synthesis of arachidonic acid and prostaglandins (*1*). Vegetable oils and meats are rich in n-6 fatty acids, but these also are present at lower levels in fish and shellfish. While n-6 fatty acids are essential, excessive amounts may be harmful. The diets of most people in developed countries include excessive intake of n-6 fatty acids. While the diets of early humans probably had a n-3 to n-6 ratio of about 1, modern Western diets have a ratio of about 1/15 (*2*), primarily because of the widespread consumption of vegetable oils that are rich in linoleic acid (*3*).

Levels of n-3 fatty acids are particularly high in fish and shellfish. Algae and phytoplankton synthesize a variety of longer-chain n-3 fatty acids through conversion of linoleic acid to α-linolenic acid, and these longer-chain fatty acids become concentrated in seafood. However, n-3 fatty acids are also found in a number of other foods, including other meats, legumes such as soy and pinto beans, cereals, some nuts, and flaxseed, walnut, and canola oils (*4*). The n-3 fatty acid in plants is α-linolenic acid (18 carbons), while in seafood there are longer-chain n-3 fatty acids, especially eicosapentaenoic (EPA) (20 carbons) and docosahexaenoic (DHA) (22 carbons) acids. In general, the fattier the fish, the higher the levels of the n-3 fatty acids; however, up to 40% or more of total fat content, even in fish with relatively little fat, is in the form of n-3 fatty acids (*5*). Humans can synthesize the longer-chain fatty acids from α-linolenic acid (*6*, *7*), although this process is not as efficient as intake from fish consumption. Interestingly, young women have a greater capacity to synthesize longer-chain n-3 fatty acids from α-linolenic acid (*8*) than do young men (*9*). There are n-3 fatty acids, including significant levels of α-linolenic acid and lower levels of longer-chain n-3 PUFAs, in all ruminant and nonruminant animal meats (*4*) and particularly in grass-fed beef (*10*). Many cereals, vegetables, and dairy products contain α-linolenic acid but little or no longer-chain n-3 fatty acids (*4*).

The health benefits of eating fish such as salmon are well-known (*1*, *11*). However, salmon are relatively fatty carnivorous fish that bioaccumulate environmental contaminants, which themselves pose health risks. We have recently reported an analysis of the levels of 14 organochlorine contaminants and brominated diphenyl ethers in over 700 farmed, wild, and supermarket samples of salmon (*12*, *13*). We found that farmed salmon and supermarket fillets of farmed salmon contain on average about 10 times the levels of most of the organochlorine and organobromine compounds that are found in wild Pacific salmon on a wet weight basis. By following fish consumption guidelines developed by the U. S. Environmental Protection Agency (USEPA) for three of these substances (polychlorinated biphenyls (PCBs), toxaphene, and dieldrin) and assuming cancer risk additivity, we calculated that consumption of more than one meal a month, on average, would increase the risk of cancer beyond the level of 1 in 100 000. But the risk of cancer must be balanced against the benefits of the consumption of n-3 fatty acids. This report provides information on the content of various lipids in the farmed, wild, and supermarket salmon

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samples. This information on lipid content is the basis of a risk/benefit analysis that has been published independently (*14*).

Materials and Methods

A total of 459 whole farmed salmon from 51 farms in eight farming regions in six countries (Scotland, Norway, Faroe Islands, Eastern Canada, Maine, Western Canada, Washington state, and Chile) were purchased from suppliers. In addition, 135 wild Pacific salmon, including chum, coho, chinook, pink, and sockeye, were purchased from suppliers in Alaska and Western Canada. These fish were filleted, and composites were made of three farmed fish from the same farm or three wild fish of the same species from the same region. In addition, we purchased three farmed salmon fillets in each of three supermarkets in each of 16 cities in North America and Europe (Vancouver, Seattle, Los Angeles, San Francisco, Denver, Chicago, Toronto, New Orleans, Washington, DC, New York, Boston, London, Edinburgh, Paris, Frankfurt, and Oslo). A composite was made of the three fillets from each supermarket. A total of 246 composite samples were analyzed for 14 organochlorine contaminants, as previously reported (*12*). In addition, 13 samples of the food fed to farmed salmon were obtained from different parts of the world and were analyzed for the 14 organochlorine contaminants.

All samples were shipped to the analytical laboratory (AXYS Analytical, Sidney, British Columbia, Canada) fresh or frozen on ice or gel-packs. Fish were thawed and inspected by a fisheries biologist to verify species. Each fish was weighed, measured for length, and filleted to give two skin-on fillets. We analyzed skin-on fillets because most salmon is sold at retail outlets with the skin on. In each case, the fillets from three fish were ground and reground together to make a homogeneous composite.

Lipid analysis was performed by a method based on one recommended from the Association of Official Analytical Chemists (*15*). To conduct the fatty acid analysis, 2.5 g of wet fish tissue or fish feed were mixed with known amounts of internal standards (pentadecanoic acid and heptadecanoic acid) and digested in methanolic KOH for 12 h to ensure that the tissue was completely dissolved. Hydrochloric acid (1 M) was added to bring the solution to pH 5.0, and the fatty acids were then extracted into hexane. The hexane extract was dried, dissolved in methanol, and reacted with diazomethane to convert the fatty acids to their methyl esters. Analysis of the fatty acid methyl esters was accomplished using a Hewlett-Packard 5890 gas chromatograph equipped with a flame ionization detector. Chromatographic separation was achieved using a Restek Famewax chromatography column (30 m × 0.53 mm i.d., 0.50 μm film thickness). Detector response was initially calibrated using a series of six solutions that covered the working concentration range. Each calibration solution contained methyl esters of six individual n-6 fatty acids (linoleic, γ-linolenic, eicosadienoic, homo-γ-linolenic acid, arachidonic, and docosatetraenoic acids), five individual n-3 fatty acids (α-linolenic, eicosatrienoic, eicosapentaenoic, docosapentaenoic, and docosahexaenoic acids), and the two internal standards (pentadecanoic and heptadecanoic acids). (Concordance of common and IUPAC names: myristic, tetradecanoic; palmitic, hexadecanoic; stearic, octadecanoic; arachidic, eicosanoic; linoleic, *cis*-9,-12-octadecadienoic; γ-linolenic, *cis*-6,9,12-octadecatrienoic; eicosadienoic, *cis*-11,14-eicosadienoic; homo-γ-linolenic, *cis*-8,11,14-eicosatrienoic; arachidonic, *cis*-5,8,11,14-eicosatetraenoic; docosatetraenoic, *cis*-7,10,13,16-docosatetraenoic; α-linolenic, *cis*-9,12,15-octadecatrienoic; eicosatrienoic, *cis*-11,14,17-eicosatrienoic; eicosapentaenoic, *cis*-5,8,11,14,17-eicosapentaenoic; docosapentaenoic, *cis*-7,10,13,16,19-docosapentaenoic; docosahexaenoic, *cis*-4,7,10,13,16,19-docosahexaenoic acid.) Instrument calibration was verified every 12 h by analyzing one of the calibration solutions. This run was also used to verify the retention times of the individual fatty acids to ensure that they were properly identified in each sample. The fatty acid concentrations were obtained by internal standard quantification using the pentadecanoic acid and heptadecanoic acid internal standards.

All analyses were conducted in accordance with AXYS' accredited quality assurance/quality control (QA/QC) program. Each analysis batch of up to 20 samples also included four QA/QC samples: a procedural blank, a reference sample (NIST SRM 1546), a laboratory control sample (menhaden oil from Supelco), and an analysis duplicate. The sample results were reviewed and evaluated in relation to the QA/QC samples worked up at the same time. The sample internal standard recoveries and detection limits, procedural blank data, reference sample data, and laboratory control sample data were evaluated against method criteria to ensure data quality. All instrument QA specifications for USEPA methods were adhered to and applied to all analyses conducted for this study. All data met the QA/QC specifications. In general, duplicate measurements differed from each other by <20%. Blank concentrations were below the detection limits (0.03 mg/g for each fatty acid), and the results for the reference and laboratory control samples were within 20% of the expected values.

Fatty acid concentrations are reported as total n-6 fatty acids (the sum of the concentrations of linoleic, γ-linolenic, eicosadienoic, homo-γ-linolenic, arachidonic, and docosatetraneoic acids) and as total n-3 fatty acids (the sum of the concentrations of α-linolenic, eicosatrienoic, eicosapentaenoic, docosapentaenoic, and docosahexaenoic acids). Total lipid determinations were performed by gravimetric analysis in conjunction with the organochlorine contaminant analysis. An aliquot of the tissue extract prepared by Soxhlet extraction was evaporated to dryness, and the residue was weighed. The result was expressed as a percentage of the total tissue weight.

Attributes of farmed and wild salmon were compared by analysis of variance. In comparing wild vs farmed salmon, farmed salmon were considered as a single group. In addition, analysis of variance with multiple comparisons of means by Fisher's protected least significant difference (LSD) was used to test for differences among species of wild salmon and among regions in which salmon feed is produced. As indicated above, from each source of whole salmon or fillets, three replicate composite samples of three fish were analyzed. Analyses of variance reflected the hierarchical structure of different sources (farms for farmed salmon, suppliers for wild salmon, and cities for supermarket salmon fillets) with three replicate composites from each source.

While there are relationships among some of the attributes examined (e.g., weight and length, n-6 and n-3), these were not the focus of this paper; consequently we report the results for each attribute separately.

Results and Discussion

Table 1 shows the average percent total lipid, weight, and length in salmon from various sources and the feed used for farmed salmon. The percentage lipid in the farmed salmon (average 16.6%) is significantly greater than that in the wild salmon (average 6.4%) ($F = 148.13$ with df = (1,64), $P < 0.0001$), and the feed is approximately one-third lipid.

More details of the fatty acid composition are presented in Table 2. The n-3 fatty acids are present in large amounts in both the farmed and the wild salmon. The dominant n-3 fatty acids in both types of fish are *cis*-5,8,11,14,17-eicosapentaenoic acid (EPA) and *cis*-4,7,10,13,16,19-docosahexenoic acid (DHA). The supermarket fillets are similar in lipid

TABLE 1. Percent Lipid, Weight, and Length in Wild Pacific, Farmed Atlantic, and Supermarket Farmed Atlantic Salmon and in Salmon Feed[a]

	wild Pacific salmon	farmed Atlantic salmon	supermarket Atlantic salmon	salmon feed
percent lipid	6.44 (3.27)	16.59 (2.91)	14.47 (3.49)	33.20 (2.67)
weight (g)	3050 (1380)	4952 (403)	NA[b]	NA
length (cm)	68.3 (8.79)	73.8 (3.12)	NA	NA

[a] The numbers in parentheses are standard deviations. Differences between wild Pacific and farmed Atlantic salmon are significant at $P < 0.0001$ for percent lipid and weight and at $P = 0.0003$ for length. [b] Not applicable.

TABLE 2. Lipid Content (in mg/g Wet Weight) in Wild Pacific, Farmed Atlantic, and Supermarket Salmon and Feed[a]

	averages			
	wild salmon	farmed salmon	supermarket salmon	salmon feed
number	45	153	48	13
cis-9,12-octadecadienoic acid	0.67 (0.34)	6.47 (3.31)	6.04 (2.82)	17.19 (8.92)
cis-6,9,12-octadecatrienoic acid	0.03 (0.02)	0.14 (0.05)	0.13 (0.04)	0.40 (0.10)
cis-11,14-eicosadienoic acid	0.17 (0.07)	0.63 (0.26)	0.57 (0.22)	0.55 (0.17)
cis-8,11,14-eicosatrienoic acid	0.07 (0.03)	0.30 (0.10)	0.28 (0.09)	0.34 (0.10)
cis-5,8,11,14-eicosatetraenoic acid	0.30 (0.12)	0.91 (0.28)	0.86 (0.29)	1.95 (0.54)
cis-7,10,13,16-docosatetraenoic acid	0.05 (0.02)	0.34 (0.09)	0.31 (0.09)	0.41 (0.13)
total n-6 fatty acid	1.28 (0.55)	8.80 (3.83)	8.18 (3.27)	20.83 (8.97)
cis-9,12,15-octadecatrienoic acid	0.50 (0.24)	1.81 (0.78)	1.68 (0.79)	5.05 (2.12)
cis-11,14,17-eicosatrienoic acid	0.09 (0.04)	0.24 (0.09)	0.21 (0.08)	0.31 (0.10)
cis-5,8,11,14,17-eicosapentaenoic acid	4.14 (2.31)	10.79 (2.41)	9.69 (2.72)	26.38 (4.74)
cis-7,10,13,16,19-docosapentaenoic acid	1.20 (0.54)	5.19 (1.19)	4.79 (1.48)	4.25 (1.41)
cis-4,7,10,13,16,19-docosahexenoic acid	6.29 (2.00)	15.69 (3.01)	14.10 (3.06)	26.33 (7.41)
total n-3 fatty acids	12.22 (4.57)	33.73 (6.32)	30.47 (7.20)	62.36 (11.13)

[a] The numbers in parentheses are standard deviations. Differences between wild and farmed salmon are significant at $P < 0.0001$ for all six n-6 and all five n-3 fatty acids.

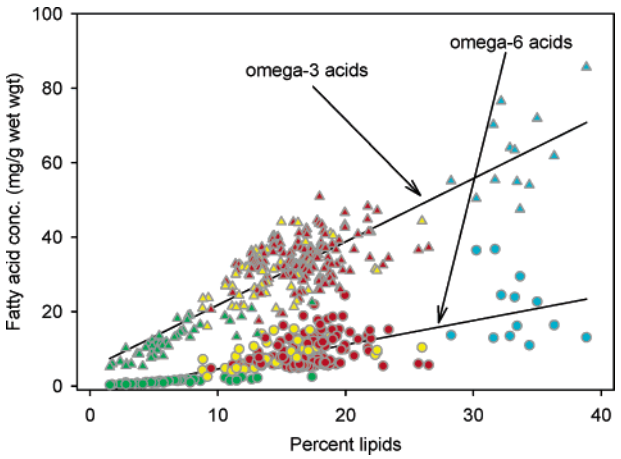

FIGURE 1. Concentration of omega-3 (n-3) and omega-6 (n-6) fatty acids as a function of percent total lipid in all fish samples. Green symbols are wild Pacific salmon, yellow are supermarket samples, red are farmed Atlantic salmon, and blue symbols are results from analysis of the fish feed. Triangles show levels of n-3 fatty acids, and circles show levels of n-6 fatty acids.

content to the farmed salmon samples, while the fish feed is more concentrated in all of the lipids. Figure 1 plots the concentration of n-3 and n-6 fatty acids as a function of percent total lipid for all samples analyzed. Both forms of PUFAs increase linearly with percent total lipid, and the ratio of n-3 to n-6 stays roughly constant over the range of lipid concentrations.

Table 3 shows the percent lipid, size of the fish, and amounts of total n-6 and n-3 lipids in farmed salmon from different countries and geographical regions. There is substantial variability in these characteristics in fish from the different regions ($F = 3.61$, $P = 0.0038$ for n-6; $F = 3.28$, $P = 0.0070$ for n-3; and $F \geq 6.04$, $P < 0.0001$ for percent lipid, weight, length, and percent of lipid as n-3, with df = (7,43) for all). For example, the lipid content of farmed salmon ranged from 14% (in Washington) to 20% (in Maine). Variability in the lipid composition was also observed. The percentage of n-3 fatty acids in the lipid ranged from 17% (in Scotland) to 26% (in Washington).

We also analyzed the salmon feed purchased in different regions for total lipid levels and total n-6 and n-3 lipids; these data are shown in Table 4. Total n-3 lipids and total n-6 lipids are the sums of the concentrations of the n-3 lipids and n-6 lipids listed in Table 2. In terms of lipid content and relative amounts of the PUFAs, there is little difference among these sites of origin of the feed. The data suggest that there may be differences among regions in levels of n-6, which ranged from 13.6 mg/g (in Scotland) to 30.1 mg/g (in British Columbia) ($F = 5.28$ with df = (3,9), $P = 0.0225$). More data would be needed to address this issue fully.

Table 5 shows similar data for each of the five species of wild salmon. Wild salmon species vary significantly in size, with the pink being the smallest and the chinook the largest ($F = 3.96$, $P = 0.0352$ for weight and $F = 8.62$, $P = 0.0028$ for length, with df = (4,10) for both). There was also some variation in percent lipid, with chum having the smallest (3.52% average) and chinook the largest (10.12% average), at a level slightly short of statistical significance ($F = 3.11$ with df = (4,10), $P = 0.0661$). Concentrations of n-3 fatty acids showed significant variability among the species ($F = 4.04$ with df = (4,10), $P = 0.0334$), but those of n-6 did not ($F = 2.55$ with df = (4,10), $P = 0.105$). The average percentage of n-3 fatty acids in the lipid varied from 16.1% to 25.4%, but differences among species were not statistically significant ($F = 1.90$ with df = (4,10), $P = 0.187$). The ratio of n-3 to n-6 levels in the wild salmon was about 10, whereas in the farmed salmon it was about 3−4. Among the wild salmon, chinook have the highest amount of lipid and the most n-3 fatty acids but, as shown in our previous papers (*12*, *13*), also have the highest concentrations of contaminants. None of the wild or farmed salmon showed n-3 levels as percent of total lipid as

TABLE 3. Percent Lipid, Weight, Length, and Fatty Acid Concentrations in Farmed Atlantic Salmon from Various Regions[a]

	Chile	Eastern Canada	Faroe Islands	Maine	Norway	Scotland	Washington	Western Canada
number	30	24	24	6	12	30	9	18
percent lipid	14.1 (2.1)	15.2 (2.3)	18.7 (3.1)	20.0 (1.8)	18.8 (2.1)	17.7 (1.8)	14.0 (1.9)	16.7 (1.8)
weight (g)	4874 (151)	4884 (167)	5279 (160)	4858 (99)	5545 (677)	4549 (387)	5187 (162)	4927 (187)
length (cm)	71.2 (1.5)	75.4 (2.7)	74.2 (2.2)	67.2 (4.2)	75.9 (1.9)	73.9 (1.7)	77.3 (2.4)	74.6 (3.2)
n-6 (mg/g)	8.2 (3.7)	9.1 (3.6)	7.4 (3.4)	11.9 (2.5)	10.8 (2.6)	6.7 (1.2)	6.3 (1.0)	13.8 (4.3)
n-3 (mg/g)	33.8 (3.4)	29.5 (6.8)	34.3 (4.2)	41.7 (6.7)	38.3 (4.5)	30.2 (4.5)	36.5 (3.7)	37.5 (8.9)
lipid as n-3 (%)	24.3 (3.0)	19.5 (4.0)	18.6 (2.5)	20.8 (2.1)	20.7 (3.4)	17.1 (2.0)	26.2 (1.8)	22.7 (6.5)
lipid per 250 g serving (g)	35.5	38.0	46.8	50.0	47.0	44.2	35.0	41.8
n-3 fatty acids per 250 g serving (g)	8.5	7.4	8.6	10.4	9.6	7.6	9.1	9.4

[a] Differences among the regions are significant for percent lipid, weight, length, and lipid as n-3 (%) at $P < 0.0001$, n-6 at $P = 0.0038$, and n-3 at $P = 0.0070$.

TABLE 4. Lipid Concentrations in Salmon Feed by Region[a]

	Scotland	Eastern Canada	British Columbia	Chile
number	4	2	4	3
percent lipid	32.22 (2.72)	34.99 (1.89)	32.27 (1.99)	34.55 (3.81)
total n-6 (mg/g)	13.60 (2.12)	22.95 (9.26)	30.13 (7.57)	16.67 (6.26)
total n-3 (mg/g)	57.00 (4.69)	54.65 (10.11)	63.55 (12.61)	73.07 (11.37)
% of lipid as n-3	17.78 (2.00)	15.57 (2.05)	19.62 (3.24)	21.12 (1.77)

[a] The numbers in parentheses are standard deviations. There are no significant differences among the four regions in percent lipid ($F = 0.86$, $P = 0.497$), total n-3 ($F = 1.94$, $P = 0.1943$), and % lipid as n-3 ($F = 2.44$, $P = 0.131$). There are significant differences in total n-6 among the regions ($F = 5.28$, $P = 0.0225$); using Fisher's protected LSD to compare pairs of regions with $\alpha = 0.05$, there were significant differences only between Scotland and British Columbia and between Chile and British Columbia.

TABLE 5. Percent Lipids, Weight, Length, and Fatty Acid Concentrations in Various Species of Wild Pacific Salmon[a]

	coho	chum	pink	sockeye	chinook
percent lipid	5.65 (1.61)	3.52 (1.44)	5.59 (1.27)	7.33 (2.77)	10.13 (4.19)
weight (g)	3159 (300)	3169 (641)	1529 (229)	2577 (390)	4815 (1839)
length (cm)	69.7 (1.87)	71.8 (2.73)	55.7 (1.73)	65.9 (3.14)	78.7 (8.83)
n-6 (mg/g)	1.27 (0.30)	0.65 (0.23)	1.29 (0.38)	1.65 (0.55)	1.53 (0.63)
n-3 (mg/g)	13.98 (3.69)	6.50 (1.34)	11.58 (3.00)	13.89 (3.90)	15.16 (4.67)
percent lipid as n-3 acids	25.4 (4.7)	20.8 (7.8)	20.8 (2.7)	19.9 (3.4)	16.1 (3.8)
lipid per 250 g serving (g)	14.1	8.8	14.0	18.3	25.3
n-3 fatty acids per 250 g serving (g)	3.5	1.6	2.9	3.5	3.8

[a] The numbers in parentheses are standard deviations. Differences among the species are significant for weight ($P = 0.0352$), length ($P = 0.0028$), and n-3 fatty acids ($P = 0.0334$). Through the use of Fisher's protected LSD to compare all pairs of species with $\alpha = 0.05$ for these, in weight there is a significant difference only between pink and chinook, in length there are significant differences only between pink and chum and between pink and chinook, and in n-3 fatty acids no pairwise differences are significant. Differences among the species are not significant for percent lipid ($P = 0.0661$), n-6 fatty acids ($P = 0.105$), and percent lipid as n-3 ($P = 0.187$).

high as has been reported for some nonfatty fish and shellfish (*5*).

Figures 2 and 3 show lipid-adjusted concentrations of PCBs, dioxin toxic equivalents (TEQs), toxaphene, and dieldrin in the salmon from different sources and in the salmon feed samples. These results should be compared to the wet weight results reported in Figures 2 and 3 in the publication of Hites et al. (*12*). The important conclusion is that the elevated contaminant levels reported by Hites et al. (*12*) on the basis of wet weight do not disappear after lipid adjustment. Note that even though the farmed salmon have significantly higher lipid concentrations than those of the wild salmon, there is still significant elevation of contaminant levels in the farmed salmon after lipid adjustment ($F = 7.27$, $P = 0.0089$ for toxaphene; $F = 15.39$, $P = 0.0002$ for dioxin; $F \geq 21.31$, $P < 0.0001$ for dieldrin and PCBs, with df = (1,64) for all).

The percent total lipid is markedly higher in farmed salmon than that in wild salmon ($F = 148.13$ with df = (1,64), $P < 0.0001$). As indicated by the data in Tables 3 and 5, there is variability in the lipid concentration of both the farmed salmon from one region to another and the wild salmon from one species to another. The lipid levels and levels of n-3 fatty acids in supermarket salmon are similar to those in wholesale farmed salmon, consistent with the expectation that supermarket salmon labeled as Atlantic salmon come from farms. The ratio of n-3 to n-6 fatty acids is substantially different in the farmed as compared to the wild salmon, being of the order of 10 to 1 in the wild and 4 to 1 in the farmed and supermarket samples. The concentration of n-3 fatty acids is higher in farmed salmon than that in wild salmon ($F = 177.64$ with df = (1,64), $P < 0.0001$), which is consistent with their higher lipid content. However, even after lipid adjustment, the levels of organochlorine contaminants are significantly elevated in farmed as compared to wild salmon.

Calculation of the lipid and n-3 fatty acid contents in a standard portion of farmed salmon (Table 3) indicates that while there is wide variability in contaminant levels observed for farmed salmon from different regions (*12*, *13*), there is relatively less variability in the lipid or n-3 fatty acid contents of the same fish. The less contaminated farmed salmon from Chile and Washington state have approximately the same

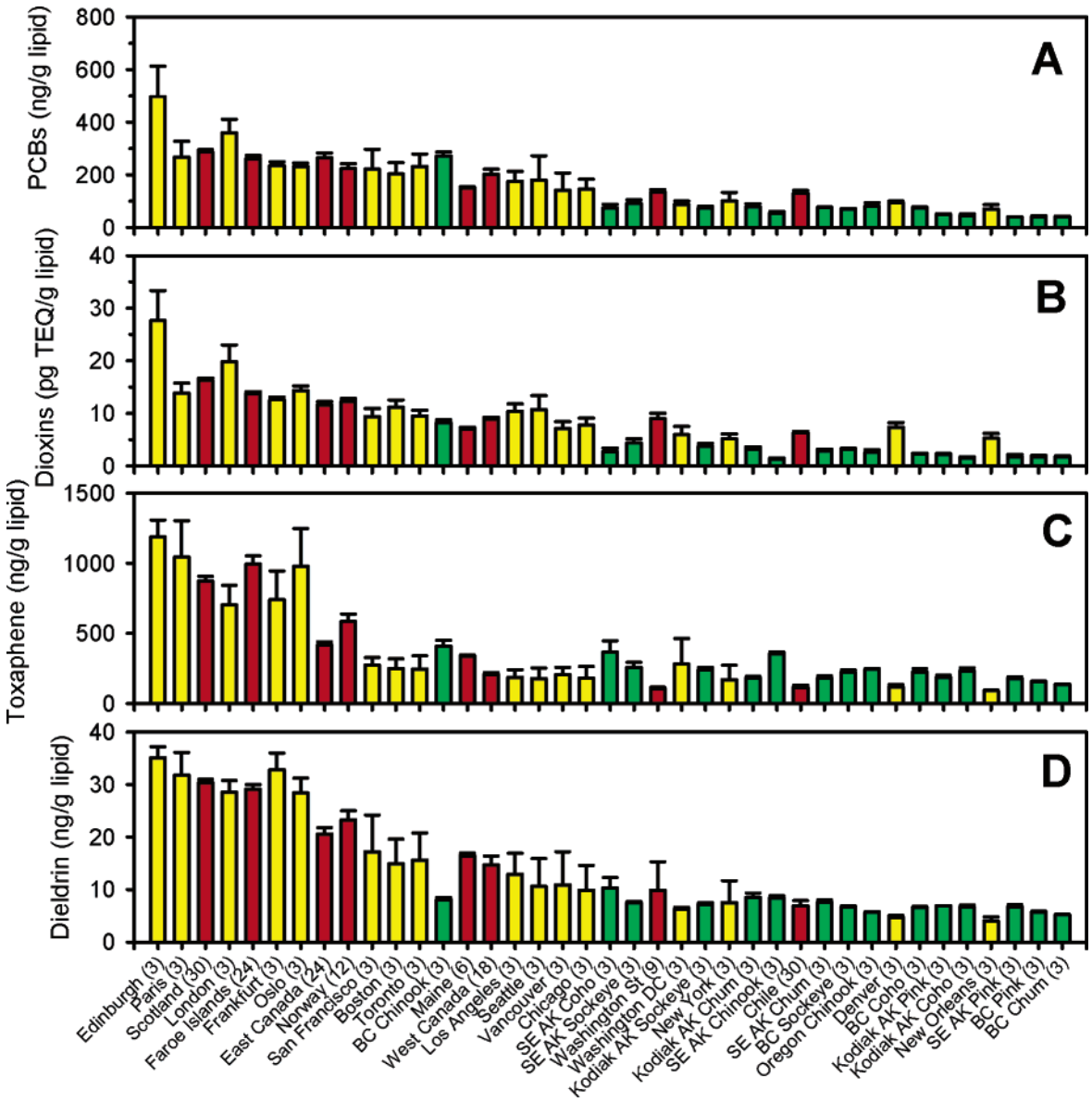

FIGURE 2. Concentrations of (A) PCBs in ng/g lipid weight, (B) dioxins in pg WHO-TEQ/g lipid weight, (C) toxaphene in ng/g lipid weight, and (D) dieldrin in ng/g lipid weight in farmed Atlantic, supermarket, and wild Pacific salmon. The concentrations are all given as functions of the locations where the salmon were grown or purchased. Red represents farmed salmon, green represents wild salmon, and yellow represents salmon purchased at supermarkets. The error bars represent standard errors. The number of samples is given in parentheses after the location identifier. The locations are sequenced by average contaminant rank.

concentration of n-3 fatty acids as do the more contaminated Northern European farmed salmon. The data in Table 5 indicate that a standard portion of wild salmon contains not only less n-3 fatty acids but less lipid overall than does a farmed salmon meal. There is, however, species to species variability in lipid and n-3 content as was observed for the contaminant concentrations in these fish (*12*, *13*). None of the wild fish species provides as much n-3 fatty acids per serving as do the farmed salmon.

There is a large literature on health effects of n-3 fatty acids in relation to a variety of different diseases. There is evidence that consumption of n-3 fatty acids is protective against sudden cardiac death due to cardiac arrhythmias (*16*, *17*). This beneficial effect is clear in populations that are at high risk, such as those who have already suffered from a heart attack, but is often not seen in populations at low risk (*1*, *18*, *19*). Several studies indicate that there is a level of fish consumption beyond which there is no additional benefit in prevention of sudden cardiac death (*20*, *21*, *22*), usually one fish meal of any variety (not just fatty fish) per week, while other studies have reported a dose-dependent decreased risk in relation to increased fish consumption (*23*) or with increased serum n-3 levels (*24*). Kris-Etherton et al. (*3*) have reviewed this literature and conclude that while not every study shows positive results, the overall evidence supports the conclusion that n-3 fatty acids, including α-linolenic acid from nonfish sources, are protective against coronary artery disease and stroke.

The n-3 fatty acids modulate the ionic currents to Na^+, Ca^{2+}, and K^+ in excitable tissues (*25*) and act to suppress automaticity of cardiac contraction (*26*). DHA, EPA, and α-linolenic acid all increase the fluidity of the sarcolemmal membrane, which is probably the biophysical basis for the effects on the ionic currents (*25*, *27*).

While the beneficial effects of n-3 PUFAs in preventing sudden cardiac death occur at relatively low concentrations, at higher concentrations n-3 PUFAs alter lipid metabolism and reduce levels of serum triglycerides and thus might reduce atherosclerosis (*28*). However, these actions occur only at intake levels that are not achievable from fish

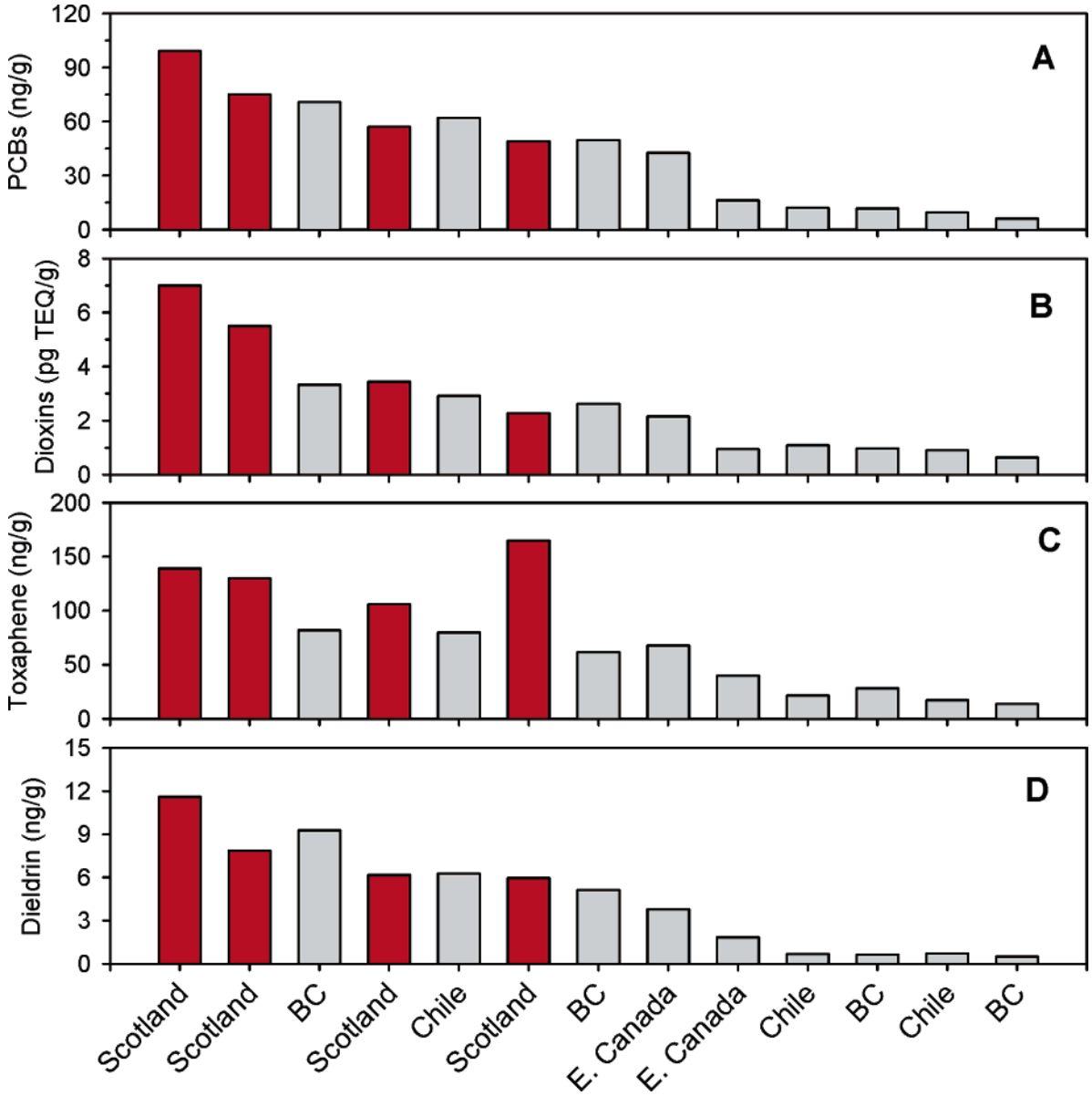

FIGURE 3. Concentrations of (A) PCBs in ng/g lipid weight, (B) dioxins (for detail, see Figure 2) in pg WHO-TEQ/g lipid weight, (C) toxaphene in ng/g lipid weight, and (D) dieldrin in ng/g lipid weight in commercial fish feed purchased at facilities in various countries at various times of the year. Each bar represents the analysis of one sample of fish feed, and the country from which it was obtained is indicated. The concentrations are given as functions of the locations where the fish feed was purchased. Fish feed purchased in Europe is indicated by red, and fish feed purchased in North or South America is indicated by gray. The locations are sequenced by average contaminant rank.

consumption without specific supplementation with fish oils. Thus the protective effects of fish consumption on cardiovascular mortality are probably due solely to the prevention of arrhythmias (*16*). A recent review has concluded that there is no convincing evidence for a protective effect of fish consumption on risk of cancers (*29*). This is particularly important given that most of the contaminants in farmed salmon are either known or probable carcinogens.

The n-3 fatty acids are present in high levels in neuronal membranes. Some have suggested that supplementation with n-3 fatty acids during pregnancy and in early postnatal life improves cognitive function of the infant (*30*, *31*). However Ghys et al. (*32*) examined the relationship between PUFA concentrations at birth and cognitive development at 4 years of age in 128 full-term neonates and found that cognitive development was dependent upon maternal intelligence, birth weight, maternal smoking habits, paternal education, and duration of breast feeding, but that there was no relationship to levels of n-3 fatty acids. There is convincing evidence for neurological abnormalities in animals fed an n-3-deficient diet (*33*), but this is unlikely to occur in full-term human infants. The contaminants present in farmed salmon, especially PCBs and dioxins, are known to cause decrements of IQ in children exposed prenatally (*34*). Schantz et al.(*35*) found that memory functions were depressed in older adults who ate large amounts of PCB-contaminated fish. Since these are persistent contaminants, with a half-life in the human body of 8−9.5 years (*36*), it is clear that the harmful effects may counteract any potential beneficial effects on cognitive function.

To examine the relationship between the higher concentrations of both contaminants and lipids in salmon, the contaminant data previously reported (*12*, *13*) for organochlorine concentrations in raw fish tissue were used to calculate lipid-adjusted concentrations. These recalculated results (Figures 2 and 3) show that contaminant concentra-

tions follow the same pattern that was reported previously, with a generally higher concentration in the farmed fish than that in the wild, although the pattern is somewhat muted after lipid normalization.

The American Heart Association has long recommended consumption of fatty fish as a method of reducing morbidity and mortality from cardiovascular disease (*11*, *37*). The present recommendation of the American Heart Association Dietary Guidelines is that at least two servings of fish be consumed per week (preferably fatty fish), in addition to consumption of vegetable oils and foods that are rich in α-linolenic acid. However, the recent report of Kris-Etherton et al. (*37*), speaking for the American Heart Association, states, "The fish recommendation must be balanced with concerns about environmental pollutants, in particular PCB and methyl mercury, described in state and federal advisories." This statement is consistent with our conclusions.

Our results show that farmed salmon are high in n-3 fatty acids. They are also high in persistent chlorinated contaminants that are known to cause cancer (*12*), neurobehavioral decrements in children (*34*), and reduced memory function in older adults (*35*). Thus, the consumer must balance the clear benefit in reducing risk of sudden cardiac death after a heart attack against the risk of cancer and neurobehavioral decrements, especially in children born to mothers who have significant body burdens of these contaminants. We have published elsewhere a risk−benefit analysis of contaminant levels and risk of both cancer and noncancer health effects vs benefits of n-3 fatty acids in reducing sudden cardiac death (*14*). This analysis has shown that the benefits of n-3 fatty acids exceed the risks for noncancer health effects, but that this is not the case for cancer risk from the more contaminated fish. Fish that are not contaminated with persistent organics or methyl mercury are a very healthy food, but the presence of these contaminants counterbalances the beneficial effects of fish consumption.

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Literature Cited

(1) Harper, C. R.; Jacobson, T. A.. The fats of life: The role of omega-3 fatty acids in the prevention of coronary heart disease. *Arch. Intern. Med.* **2001**, *161*, 2185−2192.

(2) Simopoulos, A. P. The importance of the ration of omega-6/omega-3 essential fatty acids. *Biomed. Pharmacother.* **2004**, *56*, 365−379.

(3) Kris-Etherton, P. M.; Harris, W. S.; Appel, L. J. Fish consumption, fish oil, omega-3 fatty acids, and cardiovascular disease. *Circulation* **2002**, *106*, 2747−2757.

(4) Meyer, B. J.; Mann, N. J.; Lewis, J. L.; Milligan, G. C.; Sinclair, A. J.; Howe, P. R. C. Dietary intakes and food sources of omega-6 and omega-3 polyunsaturated fatty acids. *Lipids* **2003**, *38*, 291−298.

(5) Illingworth, D. R.; Duell, P. B.; Connor, W. E. Disorders of lipid metabolism. In *Endocrinology and Metabolism*; Felig P., Baxter J. D., Frohman, L. A., Eds.; McGraw-Hill: New York, 1995; pp 1315−1403.

(6) Carnielli, V. P.; Wattimena, D. J. L.; Lutjenkijk, I. H. T.; Boerlage, A.; Degenhart, H. J.; Sauer, P. J. J. The very low birth weight premature infant is capable of synthesizing arachidonic and docosahexaenoic acids from linoleic and linolenic acids. *Pediatr. Res.* **1996**, *40*, 169−174.

(7) Salem Jr., N.; Wegher, B.; Mena, P.; Uauy, R. Arachidonic and docosahexaenoic acids are biosynthesized from their 18-carbon precursors in human infants. *Proc. Natl. Acad. Sci. U.S.A.* **1996**, *93*, 49−54.

(8) Burdge, G. C.; Wootton, S. A. Conversion of α-linolenic acid to eicosapentaenoic, docosapentaenoic and docosahexaenoic acids in young women. *Br. J. Nutr.* **2002**, *88*, 411−420.

(9) Burdge, G. C.; Jones, A. E.; Wootton, S. A. Eicosapentaenoic and docosapentaenoic acids are the principal products of α-linolenic acid metabolism in young men. *Br. J. Nutr.* **2002**, *88*, 355−363.

(10) French, P.; Stanton, C.; Lawless, F.; O'Riordan, E. G.; Monahan, F. J.; Caffrey, P. J.; Moloney, A. P. Fatty acid composition, including conjugated linoleic acid, of intramuscular fat from steers offered grazed grass, grass silage, or concentrate-based diets. *J. Anim. Sci.* **2000**, *78*, 2849−2855.

(11) Stone, N. J. Fish consumption, fish oil, lipids and coronary heart disease. *Circulation* **1996**, *24*, 2337−2340.

(12) Hites, R. A.; Foran, J. A.; Carpenter, D. O.; Hamilton, M. C.; Knuth, B. A.; Schwager, S. J. Global assessment of organic contaminants in farmed salmon. *Science* **2004**, *303*, 226−229.

(13) Hites, R. A.; Foran, J. A.; Schwager, S. J.; Knuth, B. A.; Hamilton, M. C.; Carpenter, D. O. Global assessment of polybrominated diphenyl ethers in farmed and wild salmon. *Environ. Sci. Technol.* **2004**, *38*, 4945−4949.

(14) Foran, J. A.; Good, D. H.; Carpenter, D. O.; Hamilton, M. C.; Knuth, B. A.; Schwager, S. J. Quantitative analysis of the benefits and risks of consuming farmed and wild salmon. *J. Nutr.*, *135*, 2639−2643.

(15) *Official Methods of Analysis of the Association of Official Analytical Chemists*, 15th ed.; Helrich, K., Ed.; Association of Official Analytical Chemists: Arlington, VA, 1990.

(16) De Caterina, R.; Madonna, R.; Zucchi, R.; La Rovere, M. T. Antiarrhythmic effects of omega-3 fatty acids: From epidemiology to bedside. *Am. Heart. J.* **2003**, *146*, 420−430.

(17) Siscovick, D. X.; Taghunathan, T. E.; King, I.; Weinmann, S.; Wicklund, K. G.; Albright, J. et al. Dietary intake and cell membrane levels of long-chain n-3 polyunsaturated fatty acids and the risk of primary cardiac arrest. *JAMA, J. Am. Med. Assoc.* **1995**, *274*, 1363−1367.

(18) Markmann, P.; Gronbaek, M. Fish consumption and coronary heart disease mortality. A systematic review of prospective cohort studies. *Eur. J. Clin. Nutr.* **1999**, *53*, 585−590.

(19) Mozaffarian, D.; Lemaitre, R. N.; Kuller, L. H.; Burke, G. L.; Tracy, R. P.; Siscovick, D. S. Cardiac benefits of fish consumption may depend on the type of fish meal consumed. The Cardiovascular Health Study. *Circulation* **2003**, *107*, 1372−1377.

(20) Albert, C. M.; Hennekens, C. H.; O'Donnell, C. J.; Ajani, U. A.; Carey, V. J.; Willett, W. C. et al. Fish consumption and risk of sudden cardiac death. *JAMA, J. Am. Med. Assoc.* **1998**, *279*, 23−28.

(21) Djousse, L.; Pankow, J. S.; Eckfeldt, J. H.; Folsom, A. R.; Hopkins, P. N.; Province, M. A. et al. Relation between dietary linolenic acid and coronary artery disease in the National Heart, Lung and Blood Institute Family Heart Study. *Am. J. Clin. Nutr.* **2001**, *74*, 612−619.

(22) He, K.; Rimm, E. B.; Merchant, A. N.; Rosner, B. A.; Stampfer, M. J.; Willett, W. C. et al. Fish consumption and risk of stroke in men. *JAMA, J. Am. Med. Assoc.* **2002**, *288*, 3130−3136.

(23) Hue, F. B.; Bronner, L.; Willett, W. C.; Stampfer, M. J.; Rexrode, K. M.; Albert, C. M. et al. Fish and omega-3 fatty acid intake and risk of coronary heart disease in women. *JAMA, J. Am. Med. Assoc.* **2002**, *287*, 1815−1821.

(24) Albert, C. M.; Campos, H.; Stampfer, M. J.; Ridker, P. M.; Manson, J. E.; Willett, W. C. et al.. Blood levels of long-chain n-3 fatty acids and the risk of sudden death. *N. Engl. J. Med.* **2002**, *346*, 1113−1118.

(25) Leaf, A.; Xiao, Y. F. The modulation of ionic currents in excitable tissues by polyunsaturated fatty acids. *J. Membr. Biol.* **2001**, *184*, 263−271.

(26) Kang, J. X.; Leaf, A. Effects of long-chain polyunsaturated fatty acids on the contraction of neonatal rat cardiac myocytes. *Proc. Natl. Acad. Sci. U.S.A.* **1994**, *91*, 9886−9890.

(27) Leifert, W. R.; McMurchie, E. J.; Saint, D. A. Inhibition of cardiac sodium currents in adult rat myocytes by n-3 polyunsaturated fatty acids. *J. Physiol.* **1999**, *520*, 671−679.

(28) Demaison, L.; Moreau, D. Dietary n-3 polyunsaturated fatty acids and coronary heart disease-related mortality: A possible mechanism of action. *Cell. Mol. Life Sci.* **2002**, *59*, 463−477.

(29) Terry, P. D.; Rohan, T. E.; Wolk, A. Intakes of fish and marine fatty acids and the risk of cancers of the breast and prostate and of other hormone-related cancers: A review of the epidemiologic evidence. *Am. J. Clin. Nutr.* **2003**, *77*, 532−543.

(30) Helland, I. B.; Smith, L.; Saarem, K.; Saugstad, O. D.; Drevon, C. A. Maternal supplementation with very-long-chain n-3 fatty acids during pregnancy and lactation augments children's IQ at 4 years of age. *Pediatrics* **2003**, *111*, e39−e44.

(31) Williatts, P.; Forsyth, J. S. The role of long-chain polyunsaturated fatty acids in infant cognitive development. *Prostaglandins, Leukotrienes Essent. Fatty Acids* **2003**, *63*, 95−100.
(32) Ghys, A.; Bakker, E.; Hornstra, G.; van den Hout, M. Red blood cell and plasma phospholipids arachidonic and docosahexaenoic acid levels at birth and cognitive development at 4 years of age. *Early Hum. Dev.* **2002**, *69*, 83−90.
(33) Salem, N., Jr.; Moriguchi, T.; Greiner, R. S.; McBride, K.; Ahmad, A.; Catalan, J. N.; Slotnick B. alterations in brain function after loss of docosahexaenoate due to dietary restriction of n-3 fatty acids. *J. Mol. Neurosci.* **2001**, *16*, 299−307; discussion 317−321.
(34) Jacobson, J. L.; Jacobson, S. W. Intellectual impairment in children exposed to polychlorinated biphenyls in utero. *N. Engl. J. Med.* **1996**, *335*, 783−789.
(35) Schantz, S. L.; Gasior, D. M.; Polverejan, E.; McCaffrey, R. J.; Sweeney, A. M.; Humphrey, H. E. et al. Impairments of memory and learning in older adults exposed to polychlorinated biphenyls via consumption of Great Lakes fish. *Environ. Health Perspect.* **2001**, *109*, 605−611.
(36) Michalek, J. E.; Pirkle, J. L.; Caudill, S. P.; Tripathi, R. C.; Patterson Jr., D. G.; Needham, L. L. Pharmacokinetics of TCDD in veterans of operation ranch hand: 10-year follow-up. *J. Toxicol. Environ. Health* **1996**, *47*, 209−220.
(37) Kris-Etherton, P.; Daniels, S. R.; Eckel, R. G.; Engler, M.; Howard, B. V.; Krauss, R. M. et al. Summary of the scientific conference on dietary fatty acids and cardiovascular health. Conference summary from the Nutrition Committee of the American Heart Association. *Circulation* **2001**, *103*, 1034−1039.

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