

Polyunsaturated fatty acids in the food chain in the United States^{1,2}

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ABSTRACT In the United States, intake of n-3 fatty acids is ≈ 1.6 g/d ($\approx 0.7\%$ of energy), of which 1.4 g is α -linolenic acid (ALA; 18:3) and 0.1–0.2 g is eicosapentaenoic acid (EPA; 20:5) and docosahexaenoic acid (DHA; 22:6). The primary sources of ALA are vegetable oils, principally soybean and canola. The predominant sources of EPA and DHA are fish and fish oils. Intake data indicate that the ratio of n-6 to n-3 fatty acids is $\approx 9.8:1$. Food disappearance data between 1985 and 1994 indicate that the ratio of n-6 to n-3 fatty acids has decreased from 12.4:1 to 10.6:1. This reflects a change in the profile of vegetable oils consumed and, in particular, an approximate 5.5-fold increase in canola oil use. The ratio of n-6 to n-3 fatty acids is still much higher than that recommended (ie, 2.3:1). Lower ratios increase endogenous conversion of ALA to EPA and DHA. Attaining the proposed recommended combined EPA and DHA intake of 0.65 g/d will require an approximately 4-fold increase in fish consumption in the United States. Alternative strategies, such as food enrichment and the use of biotechnology to manipulate the EPA and DHA as well as ALA contents of the food supply, will become increasingly important in increasing n-3 fatty acid intake in the US population. *Am J Clin Nutr* 2000;71(suppl): 179S–88S.

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INTRODUCTION

Dietary recommendations continue to evolve as we gain a better understanding of the health effects of nutrients. In recent years, the optimal level of n-3 fatty acids in the diet has been the focal point of intense scientific scrutiny. This has resulted in recommendations to increase consumption of the highly unsaturated n-3 fatty acids, specifically eicosapentaenoic acid (EPA; 20:5n-3) and docosahexaenoic acid (DHA; 22:6n-3), from 0.1–0.2 to 0.65 g/d. To achieve this 4-fold increase in intake, it is important to know what the current intake is, what the food sources are in the diet, and how the diet can be modified to appreciably increase the intake of these highly unsaturated fatty acids (HUFAs; fatty acids with ≥ 20 carbon atoms and ≥ 4 double bonds). An increase of the HUFA consumption would likely compliment the current dietary recommendations to reduce saturated fatty acid intake and bring us closer to our long-sought goal of defining the ideal fatty acid profile of a diet that achieves the optimum health benefits.

This article will discuss the consumption practices and sources of n-3 fatty acids in the US diet. A major emphasis will be how, in practice, Americans can achieve recommended intakes of n-3 fatty acids. Approaches for increasing n-3 fatty acid intake include increasing the consumption of food sources of these fatty acids and using biotechnology to change the fatty acid composition of foods commonly eaten. Another consideration is that n-3 fatty acid supplements may be a useful alternative approach to achieving a pharmacologic intake. Irrespective of the approach taken to increase n-3 fatty acid intake, it is likely that during the next decade we will witness an increase in the consumption of n-3 fatty acids and thereby realize the health benefits they uniquely confer.

CONSUMPTION OF POLYUNSATURATED FATTY ACIDS IN THE US

Polyunsaturated fatty acids (PUFAs) contribute $\approx 7\%$ of total energy intake and 19–22% of energy intake from fat in the diets of adults, a level that is within recommended intakes for both men and women. Linoleic acid (18:2n-6) is the major PUFA, comprising 84–89% of the total PUFA energy, whereas α -linolenic acid (ALA; 18:3n-3) contributes 9–11% of the total PUFA energy (equivalent to 1.1–1.6 g/d) in the diets of the adult population (**Table 1**).

The n-6 fatty acids, 18:4n-6 and 20:4n-6 (arachidonic acid), provide $\leq 0.1\%$ of energy intake. In addition, EPA and DHA together provide ≤ 0.1 –0.2% of energy intake. When expressed in grams in addition to percentage of PUFA energy intake, EPA and DHA provide ≤ 0.2 g/d and $< 2\%$ of energy from PUFAs. Thus, it is evident that HUFAs do not contribute appreciably to fat intake (**Table 1**).

SOURCES OF n-3 FATTY ACIDS IN THE US DIET

Vegetable oils, fish, and plant sources

The predominant sources of n-3 fatty acids in the diet are vegetable oils and fish. Fish are the major source of EPA and DHA, whereas vegetable oils are the major source of ALA. Other

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TABLE 1
Polyunsaturated fatty acid intake of adults in the United States by sex and age¹

Sex and age (y)	Total		18:2n-6		18:3n-3		18:4n-3 + 20:4n-6		20:5n-3 + 22:6n-3	
	1987-1988	1989-1991	1987-1988	1989-1991	1987-1988	1989-1991	1987-1988	1989-1991	1987-1988	1989-1991
	<i>g/d</i>									
Males										
12-19	16 ± 0.3	18 ± 1.1	14 ± 0.3	16 ± 0.9	2 ± 0.03	2 ± 0.07	0.1 ± 0.01	0.1 ± 0.01	0.1 ± 0.01	0.1 ± 0.07
20-39	17 ± 0.2		15 ± 0.2		2 ± 0.02		0.1 ± 0.01		0.1 ± 0.01	
20-49		18 ± 0.4		16 ± 0.4		2 ± 0.03		0.1 ± 0.01		0.2 ± 0.01
>40	16 ± 0.2		14 ± 0.2		2 ± 0.02		0.1 ± 0.01		0.1 ± 0.01	
50-69		16 ± 0.5		15 ± 0.4		1 ± 0.03		0.1 ± 0.01		0.2 ± 0.03
Females										
12-19	12 ± 0.3	13 ± 0.4	11 ± 0.2	12 ± 0.4	1 ± 0.03	1 ± 0.03	0.1 ± 0.0	0.1 ± 0.01	0.1 ± 0.0	0.1 ± 0.02
20-39	12 ± 0.2		11 ± 0.1		1 ± 0.01		0.1 ± 0.0		0.1 ± 0.0	
20-49		13 ± 0.2		11 ± 0.2		1 ± 0.02		0.1 ± 0.01		0.1 ± 0.01
>40	11 ± 0.1	12 ± 0.3	10 ± 0.1		1 ± 0.01		0.1 ± 0.0		0.1 ± 0.0	
50-69				11 ± 0.3		1 ± 0.02		0.1 ± 0.01		0.2 ± 0.02
Males and females										
>70		12 ± 0.3		11 ± 0.3		1 ± 0.02		0.1 ± 0.01		0.2 ± 0.00

¹ $\bar{x} \pm$ SE of 3-d intakes. Data for 1987-1988 adapted from reference 1. Data for 1989-1991 adapted from reference 2.

sources include nuts and seeds, vegetables and some fruit, and egg yolk, poultry, and meat, all of which collectively contribute minor quantities of n-3 fatty acids to the diet.

Of the commonly consumed oils in the United States, soybean and canola oil are the primary sources of ALA. The contents of ALA in soybean and canola oil are \approx 7.8% and 9.2%, respectively. Flaxseed oil is a particularly rich source of n-3 fatty acids (ie, ALA) although it is not a commonly used food oil.

Some fatty fish, most notably halibut, mackerel, herring, and salmon, are rich sources of EPA and DHA. For example, salmon contains 1.0-1.4 g n-3 fatty acids/100 g edible portion (raw), whereas mackerel contains \approx 2.5 g n-3 fatty acids (Table 2). Interestingly, and importantly, the content of n-3 fatty acids can vary appreciably among different types of fish. Specifically, Atlantic, Coho, and Sockeye salmon have markedly higher amounts of EPA and DHA than does Chinook salmon. Other lean varieties of fish do provide n-3 fatty acids and are sources of EPA and DHA, but to a much lesser extent.

In the United States, DHA per capita disappearance from fish is 0.25 g/d, which is similar to the worldwide average of 0.23 g/d; that of EPA is 0.16 g/d, compared with a worldwide average of 0.15 g/d. In the United States, DHA and EPA provide, on average, \approx 61% and 39% of HUFA intake, respectively.

Plant sources, ie, nuts, seeds, vegetables, legumes, grains, and fruit provide dietary ALA (Table 3). Of these specific foods, nuts, seeds, and soybeans are relatively rich sources of ALA. Because fats and oils contribute \approx 87% of the ALA in the US diet (7), it is apparent that the contribution of other terrestrial sources is minor.

Purslane, a vegetable used in soups and salads along the Mediterranean basin and in the Middle East, is unique because it is the richest source of ALA of any green leafy vegetable examined (6, 8). Moreover, it is one of the few plants known to be a source of EPA. Although not typically consumed in the US diet, purslane is nonetheless found in all 50 states and certainly could be developed as an important source of dietary n-3 fatty acids.

Food group contributors of dietary n-3 fatty acids

Central to the discussion of identifying food sources of n-3 fatty acids in the US diet is also understanding which food

groups are important contributors of ALA, EPA, and DHA. Jonnalagadda et al (1) reported the contribution of major food categories to the intake of individual fatty acids using dietary data collected in the Nationwide Food Consumption Survey (1987-1988). This study showed that for both males and females the food group "meat, poultry, fish, and mixtures" contributed \approx 90% of the EPA and DHA in the diet, and that this largely reflected fish consumption. Eggs were also a source of EPA and DHA (Table 4). Several food categories were found to be important sources of ALA, but this was largely a reflection of the use of vegetable oils rich in ALA for the preparation of many foods in these categories. For example, "grain products," "vegetables," and "meat, poultry, fish, and mixtures" were the predominant contributors of ALA to the diet along with "fats, oils, and salad dressings." The data presented clearly show that to appreciably increase EPA and DHA in the diet, a parallel increase in fatty fish or fish oil consumption is required. Likewise, to increase ALA intake it will be necessary to increase consumption of vegetable oils high in ALA at the expense of other fats in the diet.

TABLE 2
n-3 Fatty acid content of selected seafood¹

Seafood	n-3 Fatty acids
	% by wt
Mackerel	1.8-5.3
Herring	1.2-3.1
Salmon	1.0-1.4
Tuna	0.5-1.6
Trout	0.5-1.6
Halibut	0.4-0.9
Shrimp	0.2-0.5
Cod	0.2-0.3
Plaice	\approx 0.2
Flounder	\approx 0.2
Haddock	0.1-0.2

¹ Values are ranges unless indicated otherwise. The fatty acid content of seafood varies considerably by season and location of catch. Adapted from references 3 and 4.

n-3 Fatty acid supplements

A variety of n-3 fatty acid supplements are available to consumers. Many of these supplements are derived from marine oils and contain 180 mg EPA and 120 mg DHA per capsule. Another source of n-3 fatty acids is cod-liver oil in some capsules that contain 173 mg EPA and 120 mg DHA. However, these supplements must be taken with caution because of the high amounts of vitamin A and vitamin D in them. A vegetarian source of DHA (100 mg/capsule) derived from algae is now available.

Industry estimates indicate that ≈ 300 Mg (≈ 300 tons) of fish oil are used yearly for fish-oil supplements in the United States (I Newton, personal communication, 1998). On a per capita basis this is equivalent to 1.0 g fish oil/y. The average yearly contribution of EPA and DHA from fish-oil supplements to the US diet is 0.6–0.9 mg/person. Thus, fish-oil supplements currently are not an important source of HUFAs in the US diet.

VARIATION IN THE n-3 FATTY ACID COMPOSITION OF FOODS

There is considerable variation in n-3 fatty acid content of fish, vegetable oils, and animal products. This could significantly affect n-3 fatty acid consumption, thereby contributing appreciably to both intraindividual (within-person) and interindividual (between-person) variability in intake. Although there are no quantitative data about the intraindividual variability of n-3 intake, Basiotis et al (9) reported a relatively high intraindividual variability for total fat and linoleic acid intake based on food records of 29 individuals for 365 consecutive days. Interindividual variability of n-3 intake was reported by Dolecek and Grandits (10) on the basis of food intake records of 6438 men in the control group of the Multiple Risk Factor Intervention Trial. Interestingly, the SDs for EPA and DHA intake were larger than their corresponding means.

Another explanation for the high variability in n-3 fatty acid intake is the variation in the quantity of n-3 fatty acids found in fish. This is due primarily to variations in 1) the diet, location, stage of maturity, sex, and size of the fish and the season and water temperature in which it was caught, and 2) the canning oils and preparation methods used (11, 12). Whether fish are farm-raised (ie, in aquaculture) or caught from the wild can affect their fatty acid composition because of the difference in nutrient composition of the diet.

Factors such as cultivar, variety, growing region, and climatic conditions have marked influences on the ALA content of soybean and canola oil. For example, there have been substantial efforts over the years to reduce the ALA content of soybean oil through classic plant-breeding techniques and, more recently, by genetic manipulation. This is attractive to the edible-oil industry for use in a nonhydrogenated liquid salad oil and in deep-frying applications because of the increased oxidative stability. Low-ALA soybean varieties with much lower ALA contents, in the range of 3–4%, than the common *williams* variety (ie, $\approx 7.8\%$) are now becoming commercially available (13).

The ALA contents of plants vary by season and region. In western Canada, from which the United States gets most of its canola oil, the ALA content of canola oil ranged from 9.0% to 11.8% in the period of 1982–1996 (\bar{x} : 10.8%; 14). Regionally, the reported ALA contents of canola oil from Alberta, Manitoba, and Saskatchewan were 10.3%, 9.9%, and 9.4%, respectively (15). The average ALA content of flaxseed oil from western

TABLE 3

Terrestrial plant sources of α -linolenic acid (18:3n-3)¹

Source (100-g edible portion, raw)	α -Linolenic acid g
Nuts and seeds	
Almonds	0.4
Beechnuts (dried)	1.7
Butternuts (dried)	8.7
Chia seeds (dried)	3.9
Flaxseed	22.8
Hickory nuts (dried)	1.0
Mixed nuts	0.2
Peanuts	0.003
Pecans	0.7
Soybean kernels (roasted or toasted)	1.5
Walnuts, black	3.3
Walnuts, English and Persian	6.8
Vegetables	
Beans, navy, sprouted (cooked)	0.3
Beans, pinto, sprouted (cooked)	0.3
Broccoli (raw)	0.1
Cauliflower (raw)	0.1
Kale (raw)	0.2
Leeks (freeze-dried)	0.7
Lettuce, butterhead	0.1
Lettuce, red leaf	0.1
Mustard	0.1
Purslane ²	0.4
Radish seeds, sprouted (raw)	0.7
Seaweed, Spirulina (dried)	0.8
Soybeans, green (raw)	3.2
Soybeans, mature seeds, sprouted (cooked)	2.1
Spinach (raw)	0.1
Legumes	
Beans, common (dry)	0.6
Chickpeas (dry)	0.1
Cowpeas (dry)	0.3
Lentils (dry)	0.1
Lima beans (dry)	0.2
Peas, garden (dry)	0.2
Soybeans (dry)	1.6
Grains	
Barley, bran	0.3
Corn, germ	0.3
Oats, germ	1.4
Rice, bran	0.2
Wheat, bran	0.2
Wheat, germ	0.7
Wheat, hard red Winter	0.1
Fruit	
Avocados, California (raw)	0.1
Raspberries (raw)	0.1
Strawberries (raw)	0.1

¹Data from references 5 and 6.

²Also contains trace quantities of eicosapentaenoic acid.

Canada in 1996 was 58.7%. There is some seasonal variation, however, in ALA content. For example, the average ALA content of flaxseed oil ranged from 52% in 1989 to 59% in 1993 (16). The ALA content in western Canadian flaxseed oil also appears to vary markedly from region to region in reports showing that ALA contents of flaxseed oil from Manitoba, Saskatchewan, and Alberta were 57.8%, 59.3%, and 69.8%, respectively (15). As with other highly unsaturated vegetable oils, the ALA content of

TABLE 4

Percentage contribution of individual fatty acids to the total fatty acid intake by US Department of Agriculture Nationwide Food Consumption Survey food categories in the diets of men and women ≥ 20 y of age¹

Food category	4:0–10:0		12:0		14:0		16:0		18:0		18:1		18:2n–6		18:3n–3		18:4n–3 + 20:4n–6		20:5n–3 + 22:6n–3	
	M	W	M	W	M	W	M	W	M	W	M	W	M	W	M	W	M	W	M	W
Milk and milk products	42	59	44	45	43	45	18	19	18	19	10	11	2	2	11	12	0.3	0.3	0.1	0.1
Meat, poultry, fish, and mixtures	9	7	10	8	27	22	41	37	40	36	39	36	23	21	29	26	48	39	88	90
Eggs	1	1	1	0.4	1	1	4	2	5	3	4	4	4	3	4	2	34	32	8	6
Dry beans, peas, legumes, nuts, and seeds	0.1	0.1	1	1	1	1	3	3	3	2	3	4	5	5	2	2	6	6	0	0
Grain products	18	19	33	34	16	18	18	19	19	21	21	22	26	26	20	21	11	12	3	4
Fruit	0.1	0.1	1	1	0.1	1	0.4	1	0.1	0.1	0.3	0.4	1	1	1	1	0	0	0	0
Vegetables	3	4	2	3	3	4	7	7	7	7	11	10	18	16	16	16	1	1	0.2	0.4
Fats, oils, and salad dressings	9	10	7	7	8	9	9	10	8	9	10	12	22	25	18	20	0	0	0	0
Sugars, sweets, and beverages	1	1	2	2	1	1	1	1	2	2	1	1	1	1	1	1	0.2	0	0	0

¹Adapted from reference 1.

flaxseed oil is directly correlated with the linoleic acid content and inversely correlated with the oleic acid content (16).

Animal production practices, particularly the nutrient composition of the diet, can change the fatty acid profile of meat, milk, and eggs. For example, in muscle and adipose tissues of wild and domestic pigs, linoleic acid comprised 32% and 10% of total fatty acids, respectively; arachidonic acid comprised 8.5% and 0.4%, respectively (17). Likewise, the ratio of n–6 to n–3 fatty acids in egg yolk was 1.3:1 from range-fed chickens and 1.9:1 from commercially raised chickens (18).

MANIPULATION OF n–3 FATTY ACIDS IN ANIMAL PRODUCTS

On the basis of what is known about the effect of diet on the amount of n–3 fatty acids in animal products, researchers are manipulating animal feed in an attempt to increase the n–3 content of eggs, milk, and meat. Animal feed enriched with algae, fishmeal, or fish oil correspondingly increases EPA and DHA concentrations in tissues (eg, muscle and egg yolk). Accordingly, feeding animals diets rich in flaxseed or flax oil, which are good sources of ALA, results in increased amounts of ALA in eggs, milk, pork, chicken, and beef. Major obstacles to this innovative technology include the tendency of these fatty acids to oxidize, producing “off” flavors in food products, as well as the added expense of enriching animal feed with n–3 sources. Increasing the α -tocopherol content of a hen’s diet when feeding it n–3 fatty acids helps control oxidation and off flavors in eggs and meat (19), but increases the cost of feeding the animals.

Of the animal products enriched with n–3 fatty acids, eggs are currently the only products available on the market. Eggs were probably targeted first because a large percentage of the n–3 content of the hen’s diet is transferred to the egg yolk. The Flax Council of Canada notes that one n–3 fatty acid–enriched egg has about the same amount of n–3 fatty acids as 85 g (3 oz) fish (20). However, commercial production of n–3 fatty acid–enriched meat will not proceed until the issues of oxidation, cost, and extent of biohy-

dration of n–3 fatty acids by ruminants (eg, cattle and sheep) are addressed. The extent to which n–3 fatty acids will be incorporated into meat will also depend on the amounts fed to animals raised for meat and the rate of lipid deposition in meat, which affects the amounts of both intermuscular (seam fat) and intramuscular (marbling) fat. Milk enriched with n–3 fatty acids is high in fat, an undesirable trait given consumer trends in buying lower-fat milk. Therefore, the best opportunity for n–3 fatty acid–enriched milk to enter the marketplace may be in the development and production of butter and cheeses high in n–3 fatty acids.

CHANGES IN THE RATIO OF n–6 TO n–3 FATTY ACIDS OVER TIME

Over the course of evolution there appears, on the basis of estimates from studies of Paleolithic nutrition and modern-day diet assessment, to have been a remarkable change in the fat content and fatty acid profile of the human diet (21, 22). The Paleolithic (400 000–45 000 y ago) diet was likely much lower in total fat ($\approx 21\%$ of energy) and saturated fat (7–8% of energy) than our present-day diet (21, 22). Moreover, the diet of our hunter-gatherer ancestors contained approximately the same quantities of n–6 and n–3 fatty acids (ie, the ratio is thought to have been 1:1). Sources of n–6 and n–3 fatty acids were wild plants, animals, and fish (23, 24). Plant seeds are good sources of n–6 fatty acids and the green leaves of wild plants are good sources of ALA. The wild animals and birds that ate these food sources were sources of these fatty acids in the human food chain. Whereas EPA accounted for 4% of fatty acids in the fat of wild animals (18), domestic animals raised for meat production had undetectable amounts of EPA in their tissues.

At the onset of the industrial revolution (≈ 140 y ago) there was a marked shift in the ratio of n–6 to n–3 fatty acids in the diet; n–6 fatty acid consumption increased at the expense of that of n–3 fatty acids (25). This change reflected the advent of the modern vegetable oil industry as well as the increased use of cereal grains for domestic livestock. Raper et al (7)

TABLE 5

Ratio of n-6 to n-3 fatty acids in the US food supply

Source and time period	n-6:n-3
Raper et al, 1992 (7)	
1935-1939	8.4
1947-1949	9.0
1957-1959	10.2
1967-1969	9.9
1977-1979	10.1
1985	10.3
Authors' assessment	
1985	12.4
1994	10.6

reported a ratio of n-6 to n-3 fatty acids of 8.4:1 between 1935 and 1939 (estimated by annual per capita food use). From 1935 to 1985, this ratio increased to 10.3 ($\approx 23\%$ increase) (Table 5). Accompanying these changes has been a shift in the amounts of fats, oils, fruit, vegetables, nuts, coffee, tea, cocoa, and spices consumed. In 1985, these foods accounted for 68% of the ALA content in the food supply. This reflects an increase from the values reported from the periods of 1967-1969 and 1935-1939 (56% and 54%, respectively). To gain a perspective on whether the ratio of n-6 to n-3 fatty acids changed since 1985, we evaluated annual per capita food disappearance data from the US Department of Agriculture (26). As discussed by Ernst (27), food disappearance data are notoriously difficult to use as estimates of intake, especially of fats and oils. Some factors that make this estimation difficult include frying oil that is discarded after use, the extent to which external fat is trimmed from meat cuts, and use of oils for purposes other than eating. Nonetheless, these data are useful in assessing the diet as complementary measures to other methods used to quantify fat intake. As shown in Table 5, the ratio of n-6 to n-3 fatty acids we calculated for 1985 was slightly higher (12.4:1) than that reported by Raper et al (10.3:1) (7). Note that the ratio declined from 12.4:1 to 10.6:1 between 1985 and 1994. The change in the ratio reflects a greater disappearance of n-6 fatty acids, by $\approx 5\%$, and an accompanying increase in the disappearance of n-3 fatty acids, by 20% (Table 6). This shift is due largely to changes in vegetable oil consumption patterns and, in particular, a marked increase in the use (ie, disappearance) of canola oil (of ≈ 5.5 fold), an oil that has an n-6-to-n-3 fatty acid ratio of 2.2:1, which is distinctly different from the other oils presented in Table 6.

Historically, soybean oil has been and remains the predominant vegetable oil in the American diet. On an absolute basis, soybean oil consumption, reflecting both oil and partially hydrogenated fat, with an approximate ratio of 1:1 (28), remained constant between 1985 and 1994 (19 kg per capita) (Table 5). The relative disappearance of soybean oil, however, declined from 81.7% of the total vegetable oil consumed in 1986 to 76.4% in 1996 (Table 7). This change reflects the shifting market shares gained or lost by the other vegetable oils. Vegetable oil consumption increased from 23.1 to 25 kg/person from 1985 to 1994 (Table 6). Four oils (ie, soybean, cottonseed, corn, and canola) accounted for 96% of the total vegetable oil use in the United States in 1996. On the basis of these data, n-6 fatty acid intake from these oils increased from 8.4 to 8.8 kg \cdot person $^{-1} \cdot$ y $^{-1}$, and n-3 fatty acid intake availability rose from 0.545 to 0.669 kg \cdot person $^{-1} \cdot$ y $^{-1}$ (Table 6). These

changes in vegetable oil consumption are important contributors to the overall change in the ratio of n-6 to n-3 fatty acid in the US diet. This ratio could be reduced further by substituting oils that are high in n-3 fatty acids for those that are high in n-6 fatty acids. Increased canola oil intake, in particular, will decrease the n-6 to n-3 fatty acid ratio of the diet. Of the oils commonly used, canola oil and soybean oil could be substituted for corn oil and cottonseed oil by individuals to decrease the ratio of n-6 to n-3 fatty acids in the diet.

Although these calculations are insightful, they are particularly important because they reveal that the ratio of n-6 to n-3 fatty acids has been relatively stable for the past 40 y and considerably higher than what some believe to be the optimal ratio (ie, 2.3:1). Accordingly, it is obvious that our present diet has not changed sufficiently to meet this recommended ratio. It also is apparent that increasing EPA and DHA from 0.1 to 0.65 g/d is not going to alter the ratio appreciably. The key question that remains is, To what extent can we realistically lower the n-6 to n-3 fatty acid ratio, and how can this be achieved? A ratio of 2.3:1 translates to 6.7 g n-6 fatty acids and 2.9 g n-3 fatty acids in a 8360 kJ (2000 kcal) diet. The difficulty in meeting the recommended ratio is that many foods typically consumed in the American diet simply have a ratio of n-6 to n-3 fatty acids far above 2.3:1. Even if fish consumption is increased to achieve the goal of 0.65 g/d of EPA and DHA, the ratio will not be markedly lowered unless n-6 fatty acid consumption is decreased markedly. On the basis of these estimates, to achieve n-3 fatty acid recommendations in terms of grams and the ratio of n-6 to n-3 fatty acids, the emphasis should be on increasing EPA and DHA and decreasing n-6 fatty acids in the diet.

TABLE 6Per capita disappearance of dietary n-6 and n-3 fatty acids in 1985 and 1994¹

Food	Disappearance		n-6		n-3	
	1985	1994	1985	1994	1985	1994
	<i>kg</i>		<i>g</i>		<i>g</i>	
Beef	33.2	29.0	51.6	45.2	7.4	5
Pork	21.9	22.7	150.9	156.2	4.9	5
Chicken	20.6	28.9	128.4	179.8	11.5	16
Fish	6.8	6.8	24.6	24.6	45.7	45.7
Eggs	14.9	13.9	170.0	158.2	8.9	8.3
Milk						
Whole	49.1	34.5	43.8	32.1	26.0	19.2
2% fat	33.6	34.0	18.8	18.9	11.1	11.2
1% fat	7.3	9.4	1.7	2.1	1.1	1.4
Skim	6.8	13.1	—	—	—	—
Cheese	10.7	12.2	63.5	77.1	40.8	45.4
Oils	23.2	25.1	—	—	—	—
Soybean ²	18.9	19.1	4500.0	4540.0	387.0	391.0
Corn	2.0	1.8	1160.0	1054.0	—	—
Canola	0.3	1.8	65.0	370.0	30.0	169.0
Cottonseed	1.0	1.4	515.0	726.0	2.2	3.1
Animal fat ³						
Lard	5.9	5.3	482.0	430.0	16.0	14.0

¹Data from reference 26. Ratio of n-6 to n-3 fatty acids in 1985, 12.4; in 1994, 10.6.

²Calculations were based on the presumption that one-half of soybean oil disappearance is as partially hydrogenated fat and that hydrogenated soybean oil contained 12.5% 18:2n-6 and 1.5% 18:3n-3.

³Butterfat is included in the whole milk category.

TABLE 7Disappearance of vegetable oils (in million kilograms) in the United States in 1986 and 1996¹

Oil	1986	1996
	% (Gg)	
Soybean	81.7 (4924)	76.4 (6159)
Cottonseed	4.3 (260)	5.7 (461)
Olive	0.9 (54)	1.3 (106)
Corn	8.6 (520)	7.2 (584)
Canola	1.4 (82)	7.2 (581)
Sunflower	1.4 (85)	0.8 (68)
Safflower	0.4 (26)	0.3 (21)
Peanut	1.2 (73)	1.0 (84)

¹As a percentage of vegetable oil consumed. Total consumption in parentheses. From reference 26.

There appear to have been significant changes in the ratio of n-6 to n-3 fatty acids during human evolution. Since the mid-1800s, the ratio has stabilized for the most part with small fluctuations being noted resulting from changes in vegetable oil consumption. Therefore, it is reasonable to speculate that it is possible to reduce the ratio further, but certainly it is unlikely that, on a population basis, we will ever consume a diet similar to that of our ancestors during the Paleolithic period.

MEETING DIETARY RECOMMENDATIONS FOR n-3 FATTY ACIDS

To date, no official dietary recommendations have been made for n-3 fatty acids in the United States. Recommendations for total PUFA intake, however, have been made: 1-2% of energy from linoleic acid is required to prevent a fatty acid deficiency (29) and total PUFA intake should remain at 7% of energy (30) and not exceed 10% of energy (31). Although no formal recommendation for n-3 fatty acid intake has been made in the United States, a group of nutrition scientists has recently provided guidelines for specific recommendations for ALA, EPA, and DHA (Table 8, Figure 1; 21). This group suggests that intake of ALA be 2.2 g/d and that of EPA and DHA combined be 0.65 g/d. In addition, this group recommends an upper limit of 6.7 g linoleic acid/d.

Although the United States has not established official dietary recommendations for n-3 fatty acid intake, Canada (32) and the United Kingdom (33) have. Canada recommends a total n-3 fatty acid intake of 1.2-1.6 g/d, which is similar to the recommendation made by nutrition scientists in the United States but does not distinguish between individual n-3 fatty acids. The United Kingdom does distinguish between n-3 fatty acids and recommends that 1% of energy be from ALA and 0.5% be from EPA and DHA combined. The Committee on Medical Aspects of Food Policy, which includes the United Kingdom, recommends that the combined intake of EPA and DHA be 0.2 g/d (34). Australia has recommended that there be moderate increases in sources of n-3 fatty acids from plant foods (ALA) and fish (EPA and DHA) (35). Lastly, the North Atlantic Treaty Organization Advance Workshop on n-3 and n-6 Fatty Acids recommended that the combined intake of EPA and DHA be 0.27% of energy or 0.8 g/d (33).

Interestingly, some recommendations have been made on the basis of the ratio of n-6 to n-3 fatty acids (Figure 2). For

example, the World Health Organization has recommended a ratio of n-6 to n-3 fatty acids of 5-10:1 (37). Sweden has recommended that this ratio be 5:1 (38), and Japan (39) has recently changed its recommendation from 4:1 to 2:1 (W Lands, personal communication, 1998).

The recommended ratio of n-6 to n-3 fatty acids is 2.3:1 and has been made to maximize the conversion of ALA to DHA (40). Because of competition between n-6 and n-3 fatty acids for desaturase and elongase enzymes, the quantity of linoleic acid in the diet can affect the extent to which ALA is converted to EPA and DHA in vivo. Kinetic studies conducted in vivo (41) have shown that $\approx 15\%$ of dietary ALA is converted to the long chain n-3 fatty acids [which include 5 fatty acids of which 3 predominate: 20:5, 22:5, and 22:6 at typical intakes of both linoleic acid (15 g/d; 5% of energy) and ALA (2 g/d; 0.6% of energy)]. Quantitatively, this conversion results in ≈ 300 mg of n-3 long-chain fatty acids being derived via conversion from ALA. When dietary linoleic acid is increased to 30 g/d, conversion of ALA to the long-chain n-3 fatty acids is reduced by $\approx 40\%$ (41). Thus, the conditions that favor maximal conversion of ALA to EPA and DHA are critically dependent on the amount of linoleic acid in the diet.

The mean ratio of n-6 to n-3 fatty acid intake in the United States is $\approx 9.8:1$ (Figure 2) which is much higher than that recommended (2.3:1). Sixty percent of the population consumes a ratio of 8-12:1 (Figure 2). Hunter (42) has estimated the ratio to be 10 to 11:1, whereas other estimates indicate that, at least for some individuals, it may be as high as 20-25:1 (20). Thus, to achieve the recommended ratio, it is evident that the US diet will need to be modified (discussed below).

With respect to the modifications in the US diet that will be required, one of the more obvious changes will be to increase EPA and DHA intake, from 0.1-0.2 to 0.65 g/d (Table 6). This represents an increase in EPA and DHA intake of >4-fold and a decrease in linoleic acid from 11-16 g/d to 6.7 g/d (upper limit in an 8.4-MJ/d diet).

Dietary recommendations for n-3 fatty acids have been made on the bases of both absolute mass/d (ie, gram quantities) and

TABLE 8

Approximate quantity of fish or vegetable oils high in n-3 fatty acids needed to meet current recommendations

	Current US recommendations ¹		Canadian recommendation
	ALA, 2.2 g/d	EPA + DHA, 0.65 g/d	n-3 Fatty acids, 1.2-1.6 g/d
	g/d		
Fish			
Halibut		46-62	100-131
Mackerel		20-28	45-60
Herring		26-34	57-74
Salmon		42-56	90-117
Tuna		60-80	130-170
Shrimp		170-228	371-485
Oils			
Canola	24.2		14-18
Menhaden		2.6-3.4	5-7
Soybean	32.2		19-25
Walnut	21.9		12-16

¹From reference 21.

relative to n-6 fatty acid intake (ie, the ratio of n-6 to n-3 fatty acids). Variables that affect the ratio are energy intake, total PUFA intake and the absolute quantities of n-6 and n-3 fatty acids in the diet. As is apparent, depending on how the recommendation is made for n-3 fatty acid intake (ie, mass per day, percentage of energy, or the ratio of n-6 to n-3 fatty acids per day) different quantities of the n-3 fatty acids would need to be consumed to meet the recommendations.

Expressed on the basis of energy intake (ie, British Nutrition Foundation recommendation), the intakes of EPA + DHA and ALA would need to be increased by 10 and almost 2 times, respectively, to meet the dietary recommendation. Expressed simply as a recommended ratio of 2.3:1, the intake of total n-3 fatty acids would need to be increased by 1.4 and 3.6 g/d if PUFA intake was 4% or 7% of energy intake, respectively, within a 9200-kJ (≈2200 kcal) diet. Thus, it is apparent that depending on the specific dietary recommendation for n-3 fatty acids, the absolute quantity required in the diet can vary appreciably. Because of this inconsistency, a uniform dietary recommendation for n-3 fatty acids is clearly needed. Expressing the recommendation on a mass basis or as a percentage of energy would enable specific dietary recommendations to be made for ALA and for EPA and DHA combined.

It is evident from this discussion that there are several different plausible scenarios in which quantitative and qualitative recommendations for n-3 fatty acid intake can be met. First, the quantity of n-3 fatty acids could meet current recommendations (in grams) yet the ratio of n-6 to n-3 fatty acids could be considerably higher than 2.3:1. This would occur at high energy intakes as well as at high intakes of n-6 fatty acids. For example, if 14630 kJ (3500 kcal) were consumed in a diet that provided 7% of energy

from PUFAs, of which n-3 fatty acids comprised the upper level recommended (ie, 2.87 g/d), the n-6 to n-3 fatty acid ratio would be 9.4:1. Even at lower energy intakes, [ie, 6685 kJ/d (1600 kcal/d)], if total PUFA intake was relatively high (ie, 10% of energy), and the n-3 fatty acid intake recommendation (2.85 g/d) was met, the n-6 to n-3 ratio would be 5.2:1 which is significantly greater than that recommended. Lastly, the ratio of n-6 to n-3 fatty acids could be met while qualitative intake of the n-3 fatty acids fell short of recommended intake. From this discussion, it is apparent that as energy and PUFA intake increase, even if n-3 fatty acid intake recommendations are met (on a mass basis), additional n-3 fatty acids will need to be added to the diet to achieve the recommended ratio of n-6 to n-3 fatty acids.

A critical issue that must be addressed is how to effectively implement the dietary recommendations for n-3 fatty acids. Specifically, the recommendations must be translated into food choices that allow for the target nutrient goals to be achieved. With respect to n-3 fatty acids, there are 2 major food sources in the diet. Some vegetable oils are rich sources of ALA, and certain fish are rich sources of EPA and DHA.

There are 2 ways that current dietary recommendations for n-3 fatty acids can be translated into food choices. The first approach considers the current recommendation to be guided simply by the quantity of ALA and EPA and DHA recommended irrespective of energy intake, fat intake, or the ratios of dietary saturated (SFAs), monounsaturated (MUFAs), and PUFAs. The second approach considers the energy and total fat content of the diet, as well as the distribution of SFA, MUFA, and PUFA and the ratio of n-6 to n-3 fatty acids. However, this second approach does not specifically distinguish a recommendation for ALA from one for EPA + DHA, as does the current recommendation.

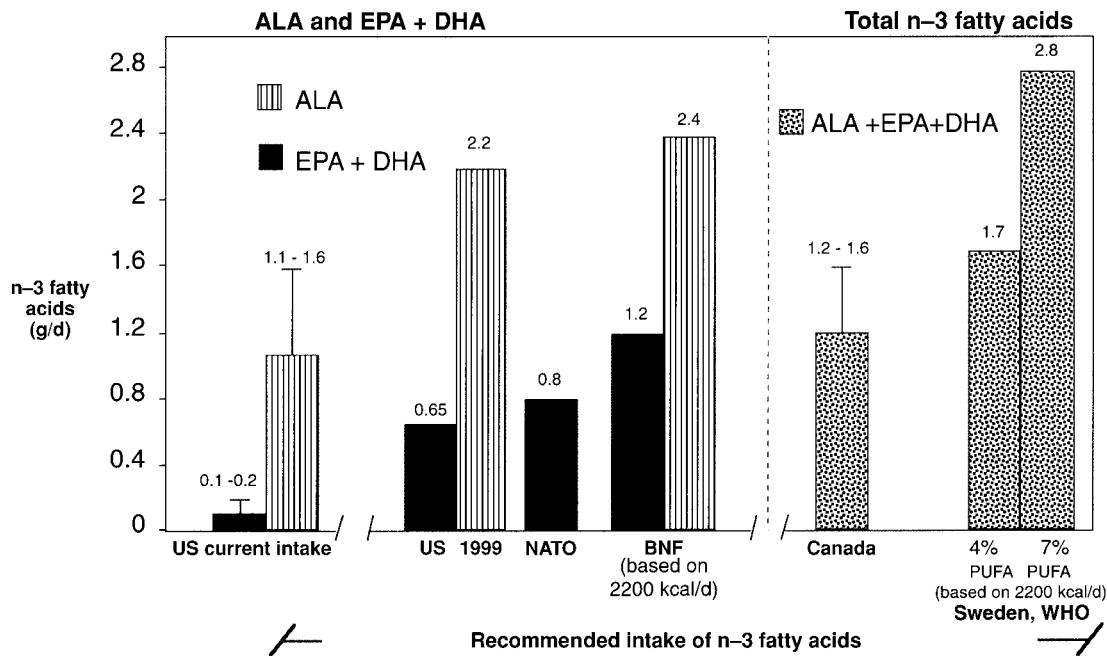


FIGURE 1. Current intake and recommended intakes of α -linolenic acid (ALA) and eicosapentaenoic acid (EPA) plus docosahexaenoic acid (DHA) expressed on the basis of mass/d (current; 21), percentage of energy (British Nutrition Foundation; BNF; 33), and as a ratio of n-6 to n-3 fatty acids of 5:1. The Canadian recommendations (32) are expressed on a mass basis. Gram quantities of EPA + DHA and ALA were calculated on the basis of a 9200-kJ (2200 kcal) diet [BNF, Swedish (38) and World Health Organization (WHO; 33) recommendations] and 4% and 7% of energy from PUFA (Swedish and WHO recommendations). PUFA, polyunsaturated fatty acid.

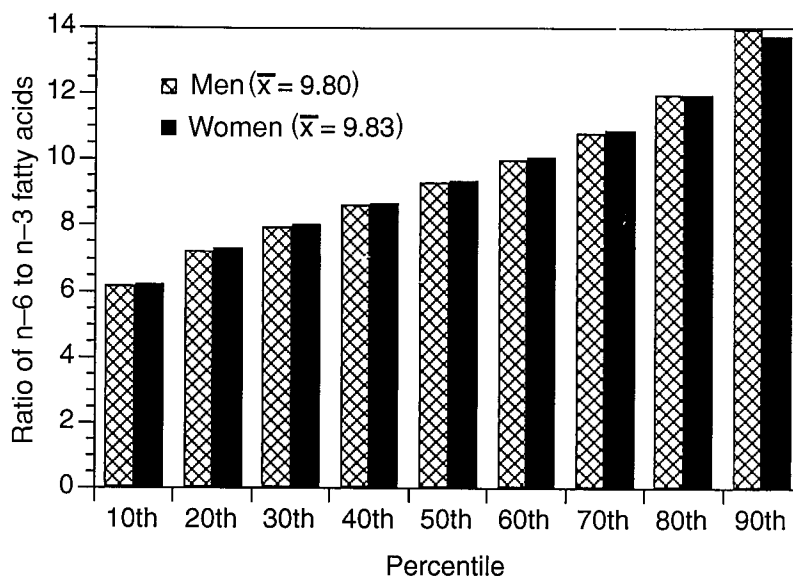


FIGURE 2. Ratio of n-6 to n-3 fatty acids in the diet of men and women in the United States. Data from reference 36.

It is important to recognize that these approaches result in somewhat different quantities of foods (eg, fish and n-3 fatty acid-rich vegetable oils) needed to meet the n-3 fatty acid target goals.

For the current recommendation, ≈ 20 – 62 g fatty fish (eg, halibut, mackerel, herring, and salmon) are required per day to meet the EPA and DHA recommendation of 0.65 g/d. Appreciably more lean fish would be required to meet this recommendation. In addition, ≈ 22 – 32 g/d of the vegetable oils listed in Table 7 are required to meet the recommendation for ALA. With respect to the Canadian recommendation, which does not distinguish ALA from EPA and DHA, and thus, reflects total n-3 fatty acid intake, it is apparent that if fish were used exclusively to achieve the n-3 fatty acid recommendation, appreciably more fatty fish would have to be included in the diet daily (ie, 45 – 131 g/d). Likewise, to meet the Canadian recommendation by using vegetable oil exclusively, more oil would need to be included in the diet daily (eg, 12 – 25 g/d). Thus, specific recommendations for EPA and DHA and for ALA have an appreciable influence on the quantity of fish required, as well as a greater but more subtle effect on the quantity of oil needed in the diet to achieve the recommendation for dietary n-3 fatty acids.

The n-3 fatty acid target can be achieved by including ≈ 4 fatty fish meals in the diet weekly along with ≈ 22 – 32 g/d of a vegetable oil relatively rich in ALA. Use of both fatty fish and oils high in n-3 fatty acids will facilitate the planning of diets that provide recommended amounts of both ALA as well as EPA and DHA. An obvious question that arises is whether the world fish supply is adequate to meet this projected need. Estimates from scientists at the National Fisheries Institute (Roy Martin, personal communication, 1997) indicate that this might be feasible if aquaculture expands rapidly. A 3-fold increase in fish consumption in the United States alone is not attainable because $\approx 60\%$ of fish eaten in the United States are imported and many stocks are depleted (but recovering). Nonetheless, because aquaculture is one of the fastest growing sectors of agriculture, it is possible that this objective can be met in the long run.

FOOD ENRICHMENT WITH n-3 FATTY ACIDS

Enriching available foods in EPA and DHA provides another option for increasing consumption of these fatty acids. Both oils and powders (produced by microencapsulation technology) enriched with either EPA or DHA are available for infant nutrition specifically. The powdered products can be used in bakery products, milk powders, and salad dressings (43). Technological advances in oil refining have enabled fish oil to be incorporated into vegetable oils for use in the preparation of a wide variety of food products, including canned fish (ie, salmon and tuna). However, foods enriched with high amounts of EPA and DHA sometimes impart a fishy aroma or flavor. Because these food products contain HUFAs that are susceptible to oxidation, considerable efforts have been made to make these products more oxidatively stable during processing, cooking, and storage. Controlling oxidation, and thus, the fishy aroma and flavor, remains a major hurdle in this food enrichment program.

Interestingly, 1 g fish oil provides ≈ 300 mg EPA + DHA, indicating that this food enrichment program could facilitate our meeting the current recommendations without the need to consume very large quantities of certain foods. Although this is a promising and emerging technology to increase EPA + DHA in the US diet, it is evident that an adequate fish oil supply must be available to meet the projected n-3 fatty acid intake recommendation worldwide.

USE OF BIOTECHNOLOGY TO MODIFY THE HUFACONTENT OF FOODS

The modern era of biotechnology has witnessed the development of many impressive molecular biology techniques. The advent of these technologies makes it possible to introduce candidate genes that regulate the production of proteins, carbohydrates, or lipids into many plant species of agronomic interest (44, 45). This approach could compliment classical genetic selection programs currently used to modify the nutrient composition of seeds and seed oils. Because of the vast chemical diversity of


plants, the genes required for the synthesis of many different types of lipids exist in nondomesticated species. Although higher plants do not synthesize EPA and DHA, the prospects of introducing the genes that would achieve this is clearly feasible (45). To accomplish this, genes would need to be introduced that elongate 18:4 (found in plants that accumulate γ -linolenic acid) and further desaturate the resulting 20- and 22-carbon fatty acids (45).

The ability to modify the storage lipid composition, and specifically the HUFA content, of commercially important crop plants by transferring the appropriate gene or genes to the desired host plant species is exciting because this biotechnology provides a powerful approach to produce transgenic plants that synthesize "designer" oils. It is not unreasonable to speculate that transgenic soybeans, rape (source of canola oil), or corn will be used to commercially produce oils that are high in EPA and DHA in the future (45). This biotechnology will have a significant effect on human nutrition. The availability of vegetable oils rich in HUFAs will likely play a significant role in helping the US population achieve the EPA + DHA intake goal of 0.65 g/d and, as a result, confer the health benefits ascribed to these unique fatty acids.

SUMMARY

The information presented herein shows clearly that with respect to n-3 fatty acids. EPA and DHA intakes are significantly below amounts that have been recommended by different countries and agencies, as well as by nutritionists in the United States. At the present time, increasing fish consumption by 4-fold is one strategy that will facilitate meeting the recommendations that have been made for intake of EPA and DHA. Manipulating animal feed and enriching food with EPA and DHA are other available options for increasing the intake of these fatty acids. However, it will be necessary to become more reliant on aquaculture to meet the goal of 0.65 g EPA + DHA/d owing to an inadequate supply of fish and fish oil. As further progress is made in producing designer oils via biotechnology, this will offer a complimentary means of increasing EPA and DHA consumption as well as dietary ALA.

Dietary recommendations for n-3 fatty acids have also been made in terms of percentage of energy, as well as on the basis of the ratio of dietary n-6 to n-3 fatty acids. Unlike the recommendation that is expressed on a mass basis, in which a fixed amount is recommended, the amount of n-3 fatty acids recommended using these approaches can vary appreciably among individuals depending on their intakes of energy, total fat, and n-6 fatty acids. Although favorable changes in the ratio of n-6 to n-3 fatty acids can be achieved more easily by decreasing total fat and n-6 fatty acid intakes, this does not necessarily mean that the recommended dose of EPA and DHA is met.

The foregoing summary points to the pressing need in the field to establish dietary recommendations for n-3 fatty acids that distinguish ALA from EPA and DHA. It would be preferable that the recommendation be made on a mass basis (g/d) and not just as a ratio of n-6 to n-3 fatty acids. 

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