Review

New and Existing Oils and Fats Used in Products with Reduced *Trans*-Fatty Acid Content

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ABSTRACT

The US Food and Drug Administration's final ruling on *trans*-fatty acid labeling issued in 2003 has caused a rapid transformation in the fat and oil industries. Novel ingredients and improved technologies are emerging to replace partially hydrogenated fats in foods. We present an overview of the structure and formation of *trans* fatty acids in foods, and a comprehensive review of the newly formulated products and current procedures practiced by the edible oil industry to reduce or eliminate *trans* fatty acids in response to the Food and Drug Administration's regulations mandating *trans* fat labeling of foods.
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Trans-fatty acid (TFA) intake has been convincingly associated with risk of heart disease based on epidemiologic and clinical studies (1-27). There has been concern about the safety of TFA since partially hydrogenated oils were established as alternatives to lard and butter in processed foods (28). Whereas initial human feeding studies suggested TFA did not adversely affect plasma total cholesterol levels in individuals fed formula diets containing partially hydrogenated oils (29,30), in one of these studies serum lipoprotein profiles were not evaluated (29). In another study it was found there was no change in serum lipoprotein profiles due to TFA in the experimental diets (30). However, results of later investigations conflicted with these early findings. Mensink and Katan (14) investigated the effect of TFA compared to saturated fatty acids (SFA) and *cis*-monounsaturated fatty acids (oleic acid) on serum low-density lipoprotein (LDL) and high-density lipoprotein (HDL) cholesterol levels in individuals fed natural mixed diets containing 10% of energy intake as any of those fats. Their results indicated that TFA had as many unfavorable effects on serum lipoprotein profiles as SFA, because TFA increased LDL cholesterol levels but also decreased HDL cholesterol levels.

Concerned about health issues regarding TFA, the US Food and Drug Administration (FDA) requested the Food and Nutrition Board of the Institute of Medicine to prepare a report on TFA to assist in their consideration of a citizen petition for *trans*-fat labeling of foods (15). Possible adverse effects of TFA cited in this report included changes in blood lipid concentrations, with numerous studies indicating an increase in total cholesterol and LDL cholesterol levels. There was also concern about the potential effect of high TFA intake on individuals with elevated concentrations of lipoprotein a (15). Numerous population-based prospective studies as well as controlled feeding trials were cited in this publication.

Compelling data linking dietary TFA to increased risk of coronary heart disease (CHD) originated from large, population-based prospective studies, comprising 667 to 80,082 men and women in different age groups, monitored for 6 to 20 years (1,5,6,8,9) as well as controlled feeding trials. Among these studies are the US Health Professional's Follow-Up Study (1), the Finnish Alpha-Tocopherol, Beta-Carotene Cancer Prevention Study (8), the US Nurse's Health Study 14-year and 20-year follow-up (6,9), and the Dutch Zutphen Elderly Study (5). These studies were consistent in finding a positive strong association between TFA intake and risk of CHD. Interestingly, a weaker correlation between SFA intake and risk of CHD was reported (1,6,8,9). For instance, the Nurse's Health Study (6) estimated that replacement of 5% of energy from SFA by *cis*-unsaturated fats would reduce CHD risk by 42%, whereas substitution of 2% of energy from TFA by *cis*-unsaturated fat would result in a 53% reduction in CHD risk. These data suggested that small decreases of TFA in the diet would most likely produce a large reduction in CHD risk (6,12). The increased CHD risk related to TFA consumption predicted by these studies can be partly explained by the adverse effects of TFA on blood lipid profiles. Controlled feeding trials have shown that TFA intake compared to *cis*-unsaturated fat increases LDL cholesterol and decreases HDL cholesterol levels, which consequently increases the total cholesterol/HDL cholesterol ratio (2,14,16-23), a predictor of CHD risk. Also, TFA raise levels of lipoprotein a, which has been associated with increased risk for cardiovascular and cerebrovascular disease (15,24). In addition, TFA raise plasma triglyceride concentrations, another marker of CHD risk (12,13). Plasma markers of

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systemic inflammation and endothelial dysfunction such as C-reactive protein, tumor necrosis factor receptors, E-selectin, interlukin-6, and vascular cell adhesion molecules, are also unfavorably affected by TFA consumption (10,11,13,25). Other studies have shown that TFA competes with essential *cis*-fatty acids by inhibiting their incorporation into membrane phospholipids, and interfere with n-3 and n-6 fatty acid metabolism, eicosanoid biosynthesis, and prostaglandin balance that in turn may trigger thrombogenesis (12,26,27). High TFA intake has also been linked to insulin resistance (12).

Based on analytical data for individual fatty acids generated by Enig and colleagues (31,32) and by Slover and colleagues (31,33), and US Department of Agriculture (USDA) production and sales figures of commodity foods, the average TFA intake of the US population by 1983 was estimated to be 8 g/day per capita, with 85% coming from foods containing partially hydrogenated oils and the rest from meat and dairy products. In 1999 Allison and colleagues (34), using food intake data from the 1989-1991 USDA Continuing Survey of Food Intakes by Individuals (35) and the TFA content of foods obtained from the 1995 USDA database of TFA content of selected foods (36), calculated the average TFA intake in the United States to be approximately 5.3 g/day per capita, with dietary partially hydrogenated oils remaining the major contributor (80%). More recently, based on the 1994-1996 USDA Continuing Survey of Food Intakes by Individuals (37), the 1995 USDA database of TFA content of selected foods (36), and other data, the FDA has estimated that the average TFA daily intake by US adults is 5.8 g per capita (38). The FDA also assessed TFA consumption by food groups, and reported that products containing partially hydrogenated oils constituted the major source of TFA intake (79.4%). Among foods containing partially hydrogenated oils, main contributors of TFA intake included margarine (16.56%), cakes and related products (23.82%), cookies and crackers (9.78%), fried potatoes (8.32%), chips and snacks (4.81%), and household shortening (4.28%) (38). TFA intake associated with animal products represented just 20.6% (38).

In 1999 the FDA issued a proposal to require that TFA in a serving of food be included in the amount of SFA declared on food labels (39). After public comment and deliberation, in 2003 the FDA issued the final TFA ruling requiring that TFA and SFA be itemized separately (38). Explicitly, the FDA final rule on TFA labeling mandates the declaration of TFA content in the Nutrition Facts label of food products, effective January 1, 2006 (38), with TFA reported in a separate line below SFA. According to the ruling, TFA are defined as "all unsaturated fatty acids that contain one or more isolated double bonds in *trans* configuration," which excludes fatty acids with conjugated double bonds. If the TFA content of a product is equal to or greater than 0.5 g per serving, it must be declared in the Nutrition Facts panel of said product. On the other hand, if the TFA content is below 0.5 g per serving, TFA must be declared as 0 g.

To comply with labeling regulations, the food and edible oil industries face the challenge of accurately analyzing and reporting TFA. In addition, although the required disclosure of TFA content does not include maximum allowable limits, the unhealthful image associated with TFA has prompted food manufacturers to evaluate their products and seek more healthful alternatives. As the TFA ruling becomes operative, dramatic changes are taking place at the core of long-established edible oil technologies. The outcome will most likely lead to changes in the fatty acid composition of many widely consumed processed food products, such as snack foods and margarines, which have been available for years. The expected reduction in TFA in US foods will result in overall reduction in daily TFA intake, and may contribute to improved health status for the public. In Denmark, for example, consumption of TFA has decreased from 8.5 g/day per capita in 1976 to 2.6 g/day per capita in 1996 (3,31). This decrease in TFA intake may be associated in part with reduced use of table and frying margarines and reduced content of TFA in Danish margarine products (31). Remarkably, during this 20-year period a simultaneous 50% decrease in deaths from CHD has been observed in the Danish population (3).

The purpose of this review is to give a general background on the properties and formation of TFA in foods and to present the evolving technologies and the novel ingredients that the food and edible oil industries are developing to provide products with low to zero TFA content.

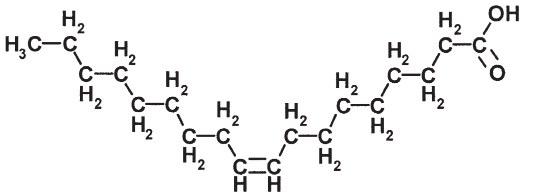
OCCURRENCE OF TFA

With rare exceptions, almost all edible fats and oils of plant origin contain unsaturated fatty acids in the *cis* conformation (40). TFA are found naturally, in low levels, in meat and dairy products as the result of microbial hydrogenation of *cis*-unsaturated fatty acids in the stomach of ruminant animals. However, the major source of TFA is products containing industrially produced partially hydrogenated vegetable oils (40). In addition, small amounts of TFA isomers are found in refined edible oils due to the high temperatures used during the deodorization procedure (41). The Figure illustrates the *cis* and *trans* configuration of double bonds in fatty acids.

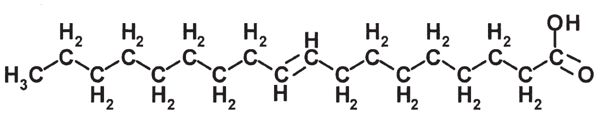
On average, the TFA content in ground beef (36,42), beef tallow* (40,42), butter† (40,42), and whole milk (36) is 1 g/100 g, 5 to 6 g/100 g, 2 to 7 g/100 g, and 0.07 to 0.1 g/100 g, respectively. Partially hydrogenated oils are a key component of margarines, shortenings, frying oils, baked products, confectionery products, deep-fried products, and many processed snack foods (31,36). For example, TFA concentrations reported in shortenings, margarine/spreads, breads/cake products, cookies and crackers, salty snacks, and cake frostings and sweets are 10 to 33

**Concentrations were estimated based on total fat value (grams per 100 g food) of beef tallow obtained from the US Department of Agriculture Nutrient Database, SR18 (No. 04001) (42) and the* trans-*fatty acid content of beef tallow in grams per 100 g total fat (5% to 8%) obtained from reference 40.*

†Concentrations were estimated based on total fat value (grams per 100 g food) of salted butter obtained from the USDA Nutrient Database, SR18 (No. 01001) (42) and the trans-*fatty acid content of butter in grams per 100 g total fat (5% to 8%) obtained from reference 40.*



Cis-9-Octadecenoic Acid (*Cis*-9-18:1 or Oleic Acid)



Trans-9-Octadecenoic Acid (*Trans*-9-18:1 or Elaidic Acid)

Figure. Chemical structures of *cis*- and *trans*-9-octadecenoic acid (18:1).

g/100 g, 3 to 26 g/100 g, 0.1 to 10 g/100 g, 1 to 8 g/100 g, 0 to 4 g/100 g, and 0.1 to 7 g/100 g, respectively (36,43)[‡].

Vegetable oils have a high content of polyunsaturated fatty acids (eg, linoleic and linolenic acids) and are prone to oxidation. Industrial hydrogenation is performed to increase the stability, resistance to oxidation, and shelf life of the oil. In addition, hydrogenation raises the melting point of unsaturated vegetable oils, which are liquid at room temperature, converting them into solid/semisolid fats (40,41,44,45) suitable for products such as shortenings and margarines for which a solid fat structure is essential.

PRODUCTION AND PROPERTIES OF PARTIALLY HYDROGENATED VEGETABLE OILS

Based on work done by the French chemist Paul Sabatier on the metal-catalyzed hydrogenation of unsaturated organic compounds, German chemist Wilhelm Normann developed the method for hydrogenation of edible oils in 1903 (44). Chemically, the hydrogenation of oils is the reduction of the double bonds in unsaturated fatty acids to single saturated bonds, by the reaction of hydrogen gas in the presence of a metal catalyst. The metal catalyst used at the time was nickel, and it has practically remained the same in the current hydrogenation procedures (41). Complete reduction of all double bonds in the oil would yield 100% SFA, whereas reduction of only a fraction of the double bonds results in partially hydrogenated fats. During the process of hydrogenation, due to the reaction mechanisms, the *cis* double bond can open up and reform into a *trans* double bond, as well as shift positions along the fatty acid carbon chain. By adjustment of the hydrogenation reaction parameters, such as catalyst concentration, hydrogen pressure, temperature, and agitation, the production of *trans* double bonds can be modulated. For example, maximum formation of TFA isomers is achieved at low hydrogen pressures (100 to 200 kilopascal [kPa]), high temperatures (200°C to 215°C), and a catalyst concentration of 0.005% nickel/oil. Whereas lower formation of TFA isomers (but higher conversion of the double bonds to saturated bonds) is achieved at higher hydrogen pressures (300 kPa), lower temperatures (165°C to 180°C), and slightly higher catalyst concentrations (0.008% nickel/oil) (41).

The TFA content of partially hydrogenated oil can range from 10 to 60 g/100 g, with 25 to 45 g/100 g being the most frequent concentration (41). By comparison, the concentration of TFA in ruminant fats (eg, beef tallow and butter) is 5 to 8 g/100 g (40,41), and up to 3 g/100 g in refined edible oils (41).

Structurally, *cis* double bonds in unsaturated fatty acids produce a bend in the chain that prevents unsaturated fatty acids from packing as tightly as SFA (see the Figure). As a consequence, a *cis* unsaturated fatty acid has a lower melting point than a SFA with the same molecular weight. Conversely, the *trans* double bonds do not create a bend on the fatty acid chain. Therefore, *trans* unsaturated fatty acid chains are virtually straight, resembling SFA, and display higher melting points than the corresponding *cis* isomers.

INDUSTRIAL USE OF PARTIALLY HYDROGENATED VEGETABLE OILS

The patent for the technology to produce partially hydrogenated oil was acquired by the British company Joseph Crossfield and Sons, establishing the manufacture of partially hydrogenated oil in Europe around 1906 (44). Partially hydrogenated oils were introduced in the US food supply in 1911 when Procter and Gamble (Cincinnati, OH), after obtaining rights to the patent, launched Crisco shortening, made of partially hydrogenated cottonseed oil. However, partially hydrogenated oils were not extensively used in the United States until 1950, when the food industry became interested in manufacturing margarines out of partially hydrogenated oil (45). Margarines based on partially hydrogenated oil were less expensive to produce, and had higher melting points, longer shelf life, and improved organoleptic properties compared to butter or lard. By the 1970s margarine sales doubled those of butter, mainly because research at the time indicated that SFA and cholesterol were linked to heart disease, and butter and lard are major dietary sources of SFA and cholesterol. As a result, partially hydrogenated oil replaced butter and lard in numerous products, including baked goods, shortenings, confectionery, and deep-fried foods (45).

ALTERNATIVES TO PARTIALLY HYDROGENATED VEGETABLE OILS

With the TFA labeling requirement in place, the food and edible oil industries have been motivated to explore al-

‡Trans-*fatty acid values from reference 43 were converted from* trans *fatty acid grams per serving to grams per 100 g food.*

ternatives to TFA in their products. Technically, reformulation of the fats to exclude TFA and simultaneously preserve the structural and palatable characteristics of the food product (eg, mouth-feel, plasticity, and flavor), and minor undesirable effects in health, is not an easy task. In addition, some manufacturers have sought to offer TFA alternatives that have a targeted fatty acid profile aside from simply zero TFA. A number of technologies have been developed and are currently in use by the food and edible oil industries in products with minimal to zero TFA content (46-52), including:

- Modification of the chemical hydrogenation process to produce partially hydrogenated fats with low TFA content.
- Production of oil seeds with modified fatty acid composition through plant breeding and genetic engineering techniques.
- Use of tropical oils (eg, palm oils, palm kernel oil, and coconut oil) and fractionated tropical oils.
- Interesterification of mixed fats.

Some of these technologies have been available to the food industry for some time; however, for a number of reasons, including cost and technical challenges, the industry did not fully embrace them when they were created. In fact, TFA reductions in ingredient type foods such as oils, shortenings, and margarines started in the mid 1990s; however, with the TFA labeling requirement, there has been more incentive for multi-ingredient manufacturers to incorporate the lower TFA fats into their products. For example, the average fat content of US margarines decreased from 80 g/100 g in 1980 to 40 to 70 g/100 g by 2000 (53,54) in response to consumer petitions for lower-fat and lower-energy products. List and colleagues (54) report that the average TFA content of US margarines/spreads was 19.5 g/100g in 1992, decreased to 16.1 g/100 g in 1995, and to 8.8 g/100 g in 1999. Several low- and no-fat margarine-like-spreads were available before 1998, such as Promise, Imperial soft tub, and I Can't Believe It's Not Butter (Unilever Bestfoods North America, Englewood Cliffs, NJ), and Fleischmann's margarine/spread line (ConAgra Foods, Inc, Omaha, NE) (53). In 1998 Unilever Bestfoods North America reformulated their Promise line of regular and low-fat spreads to contain zero TFA, and so did ConAgra Foods, Inc, with their Fleischmann's line of regular and low-fat spreads (53). Therefore, there was a clear effort by the margarine industry to reduce TFA in their products. At the time, there were several published studies comparing the effects of butter and margarines containing TFA on blood lipid profiles (55,56). Judd and colleagues (56), in a controlled feeding study, compared the effects of butter, a market-representative tub-type margarine containing TFA, and a zero *trans*-tub-type margarine high in polyunsaturated fatty acids on the blood lipid and lipoprotein concentrations of 46 subjects. Although consumption of both margarine diets resulted in a lowering of total and LDL cholesterol levels compared with the butter diet, the favorable blood lipid effect was more pronounced with the *trans*-free margarine.

Examples of commercial products based on the technologies enumerated above are summarized in Table 1. Some of these products were designed to have a favorable fatty acid profile beyond simple elimination of TFA and/or other desirable qualities such as reduced calorie content.

Modification of the Hydrogenation Process

Bunge Oils, Inc (St Louis, MO), has developed a proprietary method to chemically hydrogenate edible oils with the production of less than 10% *trans* isomers during the procedure (57). This new hydrogenation procedure involves the use of a conditioned nickel catalyst that selectively prevents the formation of *trans* stereoisomers. Based on this technology, Bunge is offering to the commercial food industry two low *trans* shortenings and two low *trans* margarines in their Elite product line (58). These products are derived from soybean and cottonseed oils and contain less than 6% TFA (see Table 1).

King and colleagues (59), at the USDA National Center for Agricultural Utilization Research, in Peoria, IL, report a procedure for the hydrogenation of soybean oil in supercritical carbon dioxide, hydrogen, and nickel catalyst with minor formation of *trans* products.

Wright and colleagues (60), at the University of Toronto (Toronto, Ontario, Canada), have also reported a method for the hydrogenation of canola oil using mixed metal catalysts (nickel and palladium) and lower temperatures that promotes the formation of *cis* isomers, and very low production of TFA (11%).

Lalvani and colleagues (61,62) working in the Mechanical Engineering and Energy Processes Department at Southern Illinois University (Carbondale, IL) have designed a promising and innovative process for the hydrogenation of edible oils. The process consists of the electrochemical hydrogenation of oils at low temperature in the presence of formate as electro-catalyst, with nickel and palladium as catalysts. This method is efficient in the production of significant amounts of hydrogenated fatty acids, and the use of low operating temperatures ($<$70°C) restricts the formation of TFA isomers to less than 10% of the oil content.

Manipulation of Fatty Acid Composition of Edible Oil Seeds Using Conventional Plant Breeding and Genetic Engineering Techniques

Many oil seeds with modified fatty acid composition have been created by both traditional seed breeding procedures and modern genetic methods for the purpose of altering nutritional and/or technical properties of the oil. Plant breeding techniques have been successful in selection of seed mutants expressing higher oil yields and a modified fatty acid composition (63). An example is the virtual elimination of erucic acid, a fatty acid with negative health implications, from rapeseed cultivars destined for edible oil production. These low erucic cultivars are used to produce canola oil, which has become a widely consumed cooking oil (63). Other successful breeding programs have been conducted with oil-producing sunflowers. In Russia from 1910 to the 1960s, sunflower seed varieties were selected that were capable of yielding 40% to 55% oil, as opposed to 30% to 35% oil in the wild type varieties (64). Several of these high oil sunflower varieties were introduced in the United States and Canada in

Table 1. Some examples of oil/fat industry technologies and products for reducing *trans*-fatty acids (TFA) in foods

Product	Description	Recommended applications	Fatty Acid Profile						Reference
			TFA (%)	SFA[a] (%)	PUFA[b] (%)	Oleic (%)	Linoleic (%)	Linolenic (%)	
Modification of chemical hydrogenation process									
Elite Vream RighT[c]	Partially hydrogenated shortening from soybean/cottonseed oils	Multiple uses	<6	25-29	NA[d]	NA	NA	NA	58
Elite Vreamay RighT[c]	Partially hydrogenated shortening from soybean/cottonseed oils	Cakes and icings	<6	25-29	NA	NA	NA	NA	58
Elite Victor RighT[c]	Low *trans* margarine from soybean/ cottonseed oils	All purpose margarine	<6	25-29	NA	NA	NA	NA	58
Modification of fatty acid profile of oilseeds by plant breeding or genetic engineering									
Clear Valley/Odyssey mid/high-oleic canola oils[e]	Mid/high-oleic canola oil	High stability oils for industrial frying, baking, and blending with other fats	<1.5	6	NA	65-75	12-22	<3.0	76
Clear Valley/Odyssey high-oleic sunflower oils[e]	High-oleic sunflower oil	High stability oils for industrial frying, baking, and blending with other fats	<1.5	8	NA	79	11	<0.5	76
NuSun[f]	Mid-oleic sunflower oil	High stability oil for industrial frying, baking, and blending with other fats. Contains 66% RDA[g] for vitamin E	Trace	9	NA	65	25	<1.0	77
Natreon canola oil[h]	Mid-oleic canola oil	High stability oils for industrial frying, baking, and blending with other fats	~1	7	18	74	NA	NA	83
Natreon high oleic sunflower oil[h]	High-oleic sunflower oil	High stability oils for industrial frying, baking, and blending with other fats	~1	10	7	>80	NA	NA	83
Trisun[i]	High-oleic sunflower oil	High stability oil for industrial frying, baking, and spray coating of cereals and dried fruits	Trace	8	NA	81	9	0.1	84
Nutrium Low Lin soybean oil[j]	Low linolenic soybean oil	High stability oil	0	NA	NA	NA	NA	<3	85
Vistive soybeans[k]	Low linolenic soybeans	NA	0	NA	NA	NA	NA	<3	86
Tropical oils									
Sans Trans 55[l]	Palm oil bead flake shortening	Dry cake mixes, icing, and heat stabilizer	0	73	NA	NA	NA	NA	88
Sans Trans 50[l]	Palm oil flake shortening	Structuring fat for icing and bakery dry mixes	0	65	NA	NA	NA	NA	88
Sans Trans 45[l]	Palm oil plastic shortening	Cookies, crackers	0	55	NA	NA	NA	NA	88
Sans Trans 39[l]	Palm oil soft plastic shortening	Cakes, vegetable dairy products	0	50	NA	NA	NA	NA	88
Sans Trans Fry[l]	Palm oil soft plastic shortening	Frying	0	55	NA	NA	NA	NA	88
Sans Trans Liquid Fry[l]	Palm oil liquid shortening	Frying	0	45	NA	NA	NA	NA	88
Flake shortenings[m]	Palm and palm kernel oil shortenings	Baked goods (biscuits, cookies, pizza dough)	0	NA	NA	NA	NA	NA	89
Zero-Trans Nutresca APS-96[n]	Palm and palm kernel oil shortening	All-purpose shortening	0	74	3	17	NA	NA	90
Palm Oil 81-20-RBD[n]	Refined palm oil	Baking, frying, pasta shortenings, margarines	0.4	47	9	38	NA	NA	90
Nutreolin 64[n]	Prefractionated palm oil with vitamins A and E	Baking, frying, shortenings, coloring agent for margarines	0	43	14	43	NA	NA	90
Nutreolin 70[n]	Prefractionated palm oil with vitamins A and E	Cooking, baking, salad dressings	0	36	14	50	NA	NA	90

(continued)

Table 1. Some examples of oil/fat industry technologies and products for reducing *trans*-fatty acids (TFA) in foods (continued)

			Fatty Acid Profile							
Product	Description	Recommended applications	TFA (%)	SFA[a] (%)	PUFA[b] (%)	Oleic (%)	Linoleic (%)	Linolenic (%)	Reference
NovaLipid line[o]	Palm oil, palm kernel oil, coconut oil, palm oleine, palm stearine-based oils, and shortenings	Ice cream, chocolate coating and filling, margarines, frying, bakery	0	NA	NA	NA	NA	NA	91
Interesterification									
Novalipid line[o]	Shortenings made from interesterified soybean oil with fully hydrogenated soybean and cottonseed oils	Wide range of baking applications (pastries, cakes, cookies, breads)	<1	NA	NA	NA	NA	NA	91
Benefat Salatrim[p]	Low-energy triglyceride blend, made by intersterification of acetic/propionic/butyric triglycerides (short-chain), with long-chain triglycerides (stearic acid) derived from fully hydrogenated vegetable oil	Reduced-calorie baked products, confectionery, chocolate coating, biscuit filling, nutrition bars	0	33-66	NA	NA	NA	NA	96
Enova[oq]	Edible oil with 80% diacylglycerides made by interesterification of soybean/canola oil-derived-unsaturated fatty acids with glycerol	Baking, grilling, frying, salads	0	4	50	36	NA	NA	99
Neobee MCT[r]	Medium-chain triglycerides oils/shortenings made by esterification of a blend of C8[s] and C10[t] acids fractionated from coconut and palm kernel oils with glycerol	Nutritional products, carrier for flavors, vitamins, essential oils and color; baking, confectionery, margarines, spreads; coatings of dried fruits; beverages	0	100	0	0	0	0	101
Neobee MLT-B[r]	Shortening made from interesterified medium-chain triglycerides, triestearin, and fully hydrogenated soybean oil	Baking, margarines, coatings, salad oils	0	100 C8: 30% C10: 20% C16[u]: 25% C18[v]: 25%	0	0	0	0	101
Vivola[w]	Edible oil made from medium-chain triglycerides, n-3, n-6, and phytosterols	Cooking, baking, and salad dressing	0	65	NA	NA	NA	NA	103
Other fats									
TransEnd 350[e]	Soft solid shortening made from high-oleic canola oil and fully hydrogenated cottonseed oil	Cookies, crackers, breads, pizza dough, cake mixes, scones	<2	10-14	NA	NA	NA	NA	76

(continued)

Table 1. Some examples of oil/fat industry technologies and products for reducing *trans*-fatty acids (TFA) in foods (continued)

Product	Description	Recommended applications	Fatty Acid Profile: TFA (%)	SFA[a] (%)	PUFA[b] (%)	Oleic (%)	Linoleic (%)	Linolenic (%)	Reference
TransEnd 370[e]	Shortening made from high-oleic canola oil and fully hydrogenated cottonseed oil	Cookies, biscuits, dough mix, doughnuts	<2	13-17	NA	NA	NA	NA	76
TransEnd 390[e]	Solid shortening made from high-oleic canola oil and fully hydrogenated cottonseed oil	Pastries, biscuits, pie crusts	<2	18-22	NA	NA	NA	NA	76
Essence[n]	Nonhydrogenated shortening blends	Blending with other oils Cookies, pie crust, cakes, crackers, pizza crust	<1	20-33	NA	NA	NA	NA	90

[a]SFA=saturated fatty acids.
[b]PUFA=polyunsaturated fatty acids.
[c]Bunge Oils Inc (St Louis, MO).
[d]NA=not available.
[e]Cargill Inc (Minneapolis, MN).
[f]National Sunflower Association (Bismarck, ND).
[g]RDA=Recommended Dietary Allowance.
[h]Dow AgroSciences (Indianapolis, IN).
[i]Humko Oil Products (Cordova, TN).
[j]Dupont (Wilmington, DE) and Bunge Oils Inc (St Louis, MO).
[k]Monsanto Co (St Louis, MO).
[l]Loders Crocklaan (Channahon, IL).
[m]Golden Foods (Louisville, KY).
[n]Aarhus United (Port Newark, NJ).
[o]ADM (Decatur, IL).
[p]Danisco (Denmark).
[q]Kao Corp (Tokyo, Japan).
[r]Stepan Co (Northfield, IL).
[s]C8=caprylic acid.
[t]C10=capric acid.
[u]C16=palmitic acid.
[v]C18=stearic acid.
[w]Forbes-Med Tech Inc (Vancouver, Canada).

the mid-1960s. Also, high-oleic (*cis* 18:1) sunflower seed lines were produced in Russia in 1976 by selective breeding and mutagenesis (64), and were introduced and further developed in the United States in 1983 (64,65). High-oleic sunflower oil has better oxidative stability in deep-frying applications and extended shelf life compared to traditional sunflower oil. The latter has a higher content of linoleic (*cis* 18:2) than oleic acid and requires hydrogenation to enhance its resistance to oxidation. The high-oleic sunflower oil was commercialized in the United States in the late 1980s. However, holders of the patent on the high-oleic sunflower hybrid planting seed (≥80% oleic acid) were not willing to license the breeding materials to other companies, thus limiting the supply of high oleic sunflower oil and increased its cost relative to other commercial oils (66). The patent holder was, however, willing to license its mid-oleic breeding stock, which allowed the National Sunflower Association (Bismarck, ND) to develop the mid-oleic oil NuSun, released in 1998 (67,68).

Genetic molecular biology tools offer a more direct way to modify fatty acid profiles (68-70). The resulting oil seed mutants are able to produce oils with a targeted fatty acid composition (see Table 2). For example, by chemical mutagenesis and genetic hybridization, soybean oil with a lower content of the more oxygen-labile linolenic acid (*cis*-18:3), and higher amounts of oleic acid (*cis*-18:1) was produced (71-74). This low linolenic/high oleic soybean oil has increased stability to oxidation, demonstrated by its longer shelf life and better performance in deep-frying applications. Other examples include canola oil seed mutants with low linolenic/high oleic acid content (75); soybean mutants with increased SFA, such as stearic (18:0) and/or palmitic acid (16:0), to augment solid fat content and hence avoid the need for hydrogenation (74); and soybean mutants with decreased SFA levels to enhance the nutritional/health value (74).

Many of these modified oils are now available on the market. Cargill Inc (Minneapolis, MN), under the brand names Clear Valley and Odyssey, offers mid- to high-oleic canola oils (65% to 85% oleic) with low content of linolenic acid (<3%) (ie, Clear Valley 65, 75, and 85, and Odyssey

Table 2. Fatty acid composition of various edible oil seeds and genetic variants

Variety	Fatty Acid Composition (g/100 g)					Origin	Reference
	Palmitic (16:0)	Stearic (18:0)	Oleic (18:1)	Linoleic (18:2)	Linolenic (18:3)		
Sunflower							
Traditional	7	4-6	20-30	60-70	<1		66
High oleic	5	4-5	80-90	5-9	<1	PB[a]	66
Mid oleic	4-5	4-5	55-75	15-35	<1	PB	66
Soybean							
Traditional	11	4	23	54	8		74
Low linolenic	10-15	5-6	32-41	41-45	2	PB/MTG[b]/GE[c]	71-74
High palmitic	25	4	16	44	10	PB/MTG	71
High stearic	9	26	18	39	8	PB/MTG	71
High oleic	8	3	84	3	1	GE	68
Low palmitic	4	3	25	58	8	PB/MTG	68
Canola							
Traditional	4	2	62	22	10		75
High oleic/Low linolenic	4	2	89	2	3	GE	68

[a]PB=plant breeding.
[b]MTG=mutagenesis.
[c]GE=genetic engineering.

90 Plus 200) and high-oleic sunflower oils (80% oleic) with <0.5% linolenic acid (Clear Valley High Oleic Sunflower and Odyssey 100) (76). These oils have a high stability because of the low content of linolenic acid and are designed for deep-frying applications or for blending with other more saturated fats (see Table 1).

The National Sunflower Association marketed NuSun, a mid-level (65%) oleic sunflower oil (77). The NuSun sunflower germplasm lines were developed at the USDA Agricultural Research Service in Fargo, ND, by traditional plant breeding methods (78). Various other sunflower seed mutants have been engineered with mid-oleic acid levels (65% to 75% oleic acid) as well as hybrids that produce low levels of palmitic and stearic acids (66-70,79,80). Sunflower oil is naturally rich in tocopherols (vitamin E), which protect against oxidation/rancidity, and this trait has been perpetuated in the mutant germplasm lines. NuSun is recommended for deep-frying purposes, as it is resistant to oxidation over extended use, and it is currently being used in the new zero-*trans* Frito-Lay (Plano, TX) snacks (81) and zero *trans*-fat Crisco shortening (82).

Other edible oil companies have invested in the production of genetically modified oilseeds; some examples of them are displayed in Table 1 (83-86).

Tropical Oils

Palm, palm kernel oil, and coconut oils, having a high content of SFA (50%) and higher melting points, have been considered as candidates to replace partially hydrogenated solid fats, especially in bakery and confectionery goods. Fractionation of these oils by physical methods allows the isolation of fractions with different melting points suitable for numerous applications (87). For example, typical palm oil fractionation products are palm olein (soft fat), used as an ingredient in cooking and salad oils; and palm stearin (hard fat), used as an ingredient of frying fats, shortenings, and margarines. Loders Crocklaan (Channahon, IL) has introduced in the market Sans-Trans, zero *trans*-fats prepared from palm oil. SansTrans features a range of palm oil fractions with different degrees of plasticity, varied content of saturated fatty acids (73% to 45%) and melting points (54°C to 16°C) that are suitable for bakery, confectionery, and deep-frying applications (88). Other products with similar characteristics as SansTrans are now available to the food industry. Some examples of these products are described in Table 1 (89-91).

Interesterification

Interesterification of mixed species of triglycerides is another option for the oil industry to produce customized fats with a range of melting points to suit different foodservice applications. Interesterification is the hydrolysis of the ester bond between the fatty acid and glycerol and subsequent reformation of the ester bond among the mixed free fatty acids and glycerol. The resulting mixture of triacylglycerols contains fatty acid distributions representative of the starting fats. Interesterification can be achieved chemically or enzymatically. Chemical interesterification is a random process, but to a certain extent, the composition of fatty acids in the resulting interesterified triglyceride can be controlled by the relative amounts of each type of fat. During chemical interesterification there is substantial oil loss (approximately 30%) due to the formation of soap and fatty acid methyl esters (92). Enzymatic interesterification by the use of microbial lipases is more selective since lipases interact with specific triglyceride ester bonds (eg, 1,3-lipases). Enzymatic interesterification is preferred over chemical interesterification when a precise triglyceride composition is required (92,93). The major drawbacks of enzymatic interesterification are long reaction times (hours to days), higher sensitivity to reaction conditions (eg, pH and temperature), and high cost (92,93).

Interesterification is usually done by blending high-saturated hard fats (eg, palm oil, palm stearin, and fully hydrogenated vegetable oils) with liquid edible oils to produce fats with intermediate characteristics. Chemical and enzymatic interesterification has been specially used in the formulation of margarines and shortenings (94,95) to provide products with no TFA but that still maintain physical properties, taste, and stability. Some of the zero *trans* margarines may have a higher content of saturated fatty acids (32% SFA, 0% *trans* fat) compared to conventional margarines that contain 8.5% to 23.4% SFA and 15% to 28% *trans* fat (43,95).

For example, ADM's (Decatur, IL) NovaLipid low-*trans*-fat line includes shortenings based on enzymatic interesterification of soybean and fully hydrogenated soybean and cottonseed oils containing 4% to 9% TFA (91).

Danisco (Copenhagen, Denmark), offers Benefat SALATRIM, which stands for short and long-chain triglyceride molecules (96). Benefat SALATRIM is produced by the interesterification of fully hydrogenated vegetable oils (containing C16 to C22 long-chain fatty acids) such as canola and soybean oil, with triacylglycerols of acetic, propionic, and/or butyric acids (short chain) (97). The resulting mixture of triacylglycerols contains short- and long-chain fatty acids randomly distributed on the glycerol backbone, with stearic acid as the predominant long-chain fatty acid (58 to 67 g per 100 g triacylglycerol) (98). Benefat SALATRIM is a reduced-energy fat due to the lower energy value of short-chain fatty acids and the incomplete absorption of stearic acid in the gastrointestinal tract, and provides approximately 5 kcal/g (98). Although Benefat SALATRIM was originally designed in the mid-1990s as a reduced-energy fat ingredient, its functional properties and fully saturated fatty acid pattern make it an attractive option for some food manufacturers to replace partially hydrogenated oil and reduce overall TFA in their products.

Kao Corporation (Tokyo, Japan) in partnership with ADM is marketing Enova in the United States. Enova is an edible oil composed principally of diacylglycerides (99). Enova is manufactured by 1,3-lipase-mediated-interesterification of unsaturated fatty acids derived from natural soybean and canola oils with glycerol. The content of diacylglycerides in Enova oil is close to 80% (see Table 1). Enova oil is part of a new generation of functional oils specifically designed to concurrently deliver nutritional and health benefits. Because diacylglycerides are not stored as fat in the body, it has been reported that consumption of oils such as Enova may have a positive effect in weight reduction and on blood lipid profiles (100).

Stepan Company (Northfield, IL) features a line of medium-chain triglycerides, with the brand name, Neobee. Neobee is based on caprylic and caproic acid triglycerides (101). Medium-chain triglycerides have a carbon chain length ranging from six to 10. Medium-chain triglycerides are not stored as fat, but are metabolized immediately by the body, and are reported to deliver similar nutritional and health benefits as products like Enova (102). One of the newer products that Stepan Company is offering is Neobee MLT-B, which is made from fully hydrogenated soybean oil, tristearin, and medium-chain triglycerides (personal communication, Richard Tenore, Stepan Company, September 22, 2004) (see Table 1).

Med-Tech Inc (Vancouver, BC, Canada) has recently marketed Vivola oil, another edible oil that can be classified as a functional/nutraceutical oil (103). Vivola oil is composed of medium-chain triglycerides (65%), and fortified with n-3 and n-6 fatty acids and phytosterols. Vivola oil has been claimed to reduce body weight and to help lower LDL cholesterol (103).

Other Technologies/Products

Cargill Inc offers a line of all-purpose shortenings, TransEnd, which are made from a blend of high-oleic canola oil and fully hydrogenated soybean oil (76), with less than 2.0% TFA (see Table 1). The procedure employed to manufacture the TransEnd products is proprietary. Aarhus United (Port Newark, NJ) offers a nonhydrogenated shortening blend by the trademark name of Essence (90). The nature of the fats and procedure used in this shortening is proprietary; however, the product is described as TFA-free, containing 20% to 33% SFA, and compatible for blending with other edible oils.

TFA ALTERNATIVES IN RETAIL FOOD PRODUCTS

In 2002, a major snack food manufacturer, Frito-Lay (Plano, TX), announced that it was eliminating TFA in many of its salty snack products (104,105). Frito-Lay snacks (eg, corn chips and cheese puffs) are fried in low-linolenic mixtures of corn, soybean, and sunflower oil (NuSun brand) (81) instead of partially hydrogenated oil. Frito-Lay was among the first companies to declare the TFA content of their products in the Nutrition Facts panel (105). Also, Smuckers (Orrville, OH) recently introduced a 0 g *trans*-fat Crisco shortening. This shortening contains a blend of fully hydrogenated cottonseed oil, sunflower oil (NuSun brand), and soybean oil (82). The spreads Promise and Promise Light contain zero TFA and are formulated by interesterification of liquid vegetable oils with palm and palm kernel stearins (106). Some other examples of products that have been reformulated to reduce TFA are displayed in Table 3 (107,108).

POTENTIAL IMPLICATIONS OF TFA REPLACEMENT ON FATTY ACID INTAKE

As TFA are replaced by alternate fats, the potential exists for a significant change in the overall pattern of fatty acid consumption in the United States. The health implications of these changes deserve careful attention. For example, many of the TFA alternatives (Table 1) contain SFA, particularly tropical fats (eg, coconut, palm, and palm kernel oils), which for some time were avoided in US products due to their high SFA content (109). However, several controlled feeding studies have shown that palm oil, that contains 50% SFA (45% palmitic [16:0], 5% stearic [18:0]), 40% monounsaturated, and 10% polyunsaturated fatty acids has no detrimental effects on blood lipid profiles (109,110). In fact, in some studies, a slight positive effect on HDL cholesterol and lipoprotein a was noted (109,110). Experiments with animal models have indicated that palm oil shows antithrombotic effects similar to those exerted by polyunsaturated fatty acids (109).

Table 3. Examples of retail products with reduced *trans*-fatty acid (TFA) content			
Product	**Manufacturer**	**Fat ingredients to reduce TFA**	**Reference**
Frito Lay snack chips	Frito-Lay (Plano, TX)	High stability vegetable oils (eg NuSun)	81,104,105
Zero gram *trans*-fat Crisco shortening	Smuckers (Orville, OH)	Blend of fully hydrogenated cottonseed oil, high stability sunflower oil (NuSun), and soybean oil	82
Promise Light and Promise margarines	Lipton (Englewood Cliffs, NJ)	Interesterification of liquid vegetable oils with palm and palm kernel stearines	106
Land O'Lakes spreadable butter and soft baking butter	Land O'Lakes (St Paul, MN)	Blend of canola oil and cream	107
Goldfish crackers	Pepperidge Farm (Norwalk, CT)	Nonhydrogenated canola and sunflower (NuSun) oils	82
Fleischmann's margarine with olive oil	Fleischmann's (Omaha, NE)	Blend of olive oil, soybean oil, and fully hydrogenated soybean oil	106
New, Improved Reduced-Fat Oreo, Golden Oreo Original, and Golden Uh Oh! cookies; Honey Maid Low-Fat Cinnamon Grahams, Newton Fat-Free Fig Chewy Cookies; Triscuit Whole Wheat Baked Crackers; SnackWell Fat-Free Devils Food Cookie Cakes; SnackWell Cracked Pepper crackers	Kraft (Glenview, IL)	NA[a]	107
Zero *trans*-fat UTZ snacks	UTZ (Hanover, PA)	NA	108

[a]NA=not available.

Unprocessed and processed palm oil contains rich amounts of tocopherols and tocotrienols (vitamin E), and crude palm oil is the richest natural plant source of carotene in terms of retinol equivalents (vitamin A) (110).

Individual SFA have been suggested to affect blood lipid profiles differently: lauric (12:0), myristic (14:0), and palmitic (16:0) acids increase LDL cholesterol levels, whereas stearic acid (18:0) has a neutral effect, attributed in part to its poor absorption (111,112). Lauric acid has been shown to decrease the total/HDL cholesterol ratio, due to a larger increase in HDL cholesterol (2,22). Mensink, Katan, and colleagues (2,22) have commented that even though consumption of SFA should not be promoted, lauric acid-rich palm kernel oil and coconut oil (approximately 50% lauric acid), in terms of effect on total/HDL cholesterol ratio, are still a better alternative for the food industry than partially hydrogenated oil in products that require solid fats for texture. Moreover, coconut and palm kernel oil are the basic sources of MCT (8:0 to 10:0) that are used in various low-energy and health products (see Table 1) (113).

Because TFA do not provide any known nutritional benefits and produce apparent unfavorable health effects, moving from TFA use to SFA use may produce a relative improvement in the dietary quality of processed foods that traditionally contained TFA. Nonetheless, the potential consequences of increased SFA in place of TFA in many processed products is a trend that deserves careful attention.

Alternative fats containing enhanced-oleic acid content to increase stability to oxidation, either through plant breeding or genetic modification, may possibly have negative health effects by reducing intake of the essential fatty acids linoleic acid (n-6) and linolenic acid (n-3) and reducing the overall consumption of *cis*-polyunsaturated fatty acids (69). Linoleic and linolenic acid appear to be strongly protective against CHD, and to reduce LDL cholesterol level and the total/HDL cholesterol ratio (4,114). Currently, genetically modified vegetable oils are mainly used in industrial food frying applications, to replace partially hydrogenated oil (70).

CONCLUSIONS

Trends indicate that the edible oil industry will continue evolving to offer TFA alternatives to the food industry and in turn to the public. With the passing of the January 1, 2006 deadline for including TFA content on food labels, more products will appear on supermarket aisles bearing the label zero TFA or TFA-free. Also, because epidemiologic and clinical research indicate the importance of overall fatty acid intake, including the relative levels of n-3 and n-6 fatty acids and not simply reduction of *trans* and saturated fats, it is certain that functional fat alternatives with targeted fatty acid profiles will continue to evolve. The effect of this potential trend on overall fatty acid intake and consequent health implications deserves attention.

In addition, it is important to recognize that the changing fatty acid composition of processed foods will have a significant influence on the assessment of fatty acid intake by the US population. Updated and accurate TFA composition data for existing food products continue to be especially important to the evaluation of health status relative to dietary fat intake. Satchithanandam and colleagues (43) summarized the TFA composition of US foods before the mandatory TFA labeling rule. Given the increased use of TFA alternatives, there is a clear need for ongoing sampling and analysis of foods to generate accurate, comprehensive, and publicly available food composition databases that can be used to track dietary intake of TFA and other fatty acids, and to study associations between the expected reductions in TFA intake and health risk factors. Selected foods are being analyzed for TFA content as part of the ongoing National Food and Nutrient Analysis Program (115), and the data are entered into the USDA National Nutrient Database for Standard Reference (42). However, the relatively frequent and continuing introduction of TFA alternatives to existing product formulations means that average database values may not accurately reflect the TFA content of individual samples of a particular food product, and in fact older and newer versions of a particular product/brand may coexist in the marketplace for some period of time. Therefore, researchers studying TFA intake and/or designing diets with targeted fatty acid composition should be particularly aware that snack foods, bakery items, confectionery items, and other products that have traditionally been made with partially hydrogenated oil may retain the same brand names yet have a significantly modified fatty acid content, and close attention to ingredient listings, nutrient composition data, and optional label claims on the exact foods used in research studies or in dietary recommendations is imperative.

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Mention of trade names, commercial products, or companies in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement of these products, over others not mentioned, by the authors, the USDA, or Virginia Polytechnic Institute and State University.

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