Polyunsaturated fatty acids in the diet have long been considered essential to the growth and proper nutrition of humans and animals. In recent years, however, these fatty acids have been used to treat and prevent atherosclerosis, and, on an experimental basis, to inhibit thrombosis. It should be emphasized that these additional uses are not at all based upon the premise that atherosclerosis and thrombosis represent essential fatty acid deficiencies, but rather that the polyunsaturated fat may affect these pathological processes through other mechanisms.
mechanisms. The purpose of this review is to explore in depth the actions of the principal polyunsaturated fatty acids upon the plasma lipids and thrombosis and, in particular, to differentiate the effects of the two different families of essential fatty acids: those derived from vegetable oils (chiefly the ω-6 fatty acids) and those derived mainly from fish oils (the ω-3 fatty acids, see table 1). Past studies on the effects of feeding polyunsaturated fats have not appreciated the possible metabolic differences between these two structurally different families of polyunsaturated fatty acids.

The effects of dietary fat upon atherosclerosis may be mediated through two key processes: first, the influx of lipids and lipoproteins, such as low density lipoproteins (LDL), from the plasma into the arterial wall and, second, the formation of platelet thrombi in advanced atherosclerosis.1,2 Dietary fat affects lipid infiltration through its actions to elevate or depress the concentrations of the circulating lipoproteins, especially LDL and very low density lipoproteins (VLDL), which are the major transport moieties for cholesterol and triglyceride. Atheromatous lipid deposits especially occur when the plasma levels of cholesterol and LDL are high.3 Less well understood are the effects of dietary fat upon platelet function and thrombosis. These effects may be mediated, in part, through prostaglandins synthesized from essential fatty acids.4

Since 1952, the plasma cholesterol lowering effects of polyunsaturated fat in the human diet have been demonstrated by many investigators.5,6 In a typical experiment, a polyunsaturated fat has been substituted for a predominantly saturated fat; i.e., corn oil for cocoa butter. After several weeks of such a feeding, there occurs a remarkable lowering of plasma cholesterol levels which can be promptly reversed if saturated fat is reintroduced into the diet. Gram for gram, saturated fat is twice as effective in raising the plasma cholesterol level as polyunsaturated fat is in lowering it.7,8 Although increased fecal excretion of cholesterol and its derivatives usually accompanies the fall in plasma cholesterol levels, the precise mechanisms of action of polyunsaturated fats remain the object of intensive study.

Suggestions that dietary fat might affect thrombosis date back to studies conducted over 20 years ago in which saturated fat was considered to be "thrombogenic" and polyunsaturated fat "nonthrombogenic."9-11 Only recently, with the discovery of platelet and vessel wall prostaglandins, has a more precise mechanism of how dietary fatty acids might affect thrombosis been elucidated.4 Twenty-carbon fatty acids of both the ω-6 and ω-3 families serve as substrates for the synthesis of different prostaglandins having diverse activities. The thromboxanes induce platelet aggregation and vasoconstriction; the prostacyclins inhibit platelet aggregation and produce vasodilation.12 There is currently great interest in the possibility that dietary ω-3 polyunsaturated fatty acids may alter platelet function in an anti-thrombogenic direction.

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Table 1. Major Families of Polyunsaturated Fatty Acids

<table>
<thead>
<tr>
<th>Family designation</th>
<th>Parent fatty acid</th>
<th>Major metabolites</th>
<th>Characteristic structure</th>
<th>Principal sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>ω-9</td>
<td>C18:1 ω-9 oleic acid</td>
<td>C20:3 ω-9* eicosatrienoic acid</td>
<td>H₃C-C=C-C-C-C-C-C-C-½=C=R-RCOOH</td>
<td>Synthesis from acetate; animal and vegetable fats</td>
</tr>
<tr>
<td>ω-6</td>
<td>C18:2 ω-6 linoleic acid</td>
<td>C20:4 ω-6 arachidonic acid</td>
<td>H₃C-C=C-C-C-C-½=C=R'-RCOOH</td>
<td>Many vegetable oils</td>
</tr>
<tr>
<td>ω-3</td>
<td>C18:3 ω-3 linolenic acid</td>
<td>C20:5 ω-3 eicosapentaenoic acid</td>
<td>H₃C-C-½=C=R'-RCOOH</td>
<td>Some vegetable oils, leaves (18:3)</td>
</tr>
<tr>
<td></td>
<td>C22:6 ω-3 docosahexaenoic acid</td>
<td></td>
<td></td>
<td>Marine oils (20:5, 22:6)</td>
</tr>
</tbody>
</table>

A fourth family of polyunsaturated fatty acids (ω-7) can be synthesized from palmitoleate (C16:1 ω-7), but only trace amounts of ω-7 polyunsaturated fatty acids are present in the tissues. The omega (ω) number indicates the location of the first double bond counting from the methyl end of the fatty acid (ω is the last letter of the Greek alphabet). An alternative nomenclature frequently used is the "n" system where "n" replaces the ω (e.g., 18:2 ω-6 = 18:2 n-6).13

*Accumulates only in essential fatty acid deficiency.
Polyunsaturated Fatty Acid Families and Interrelationships

The three major families of unsaturated fatty acids are the oleic acid (ω-9) family, the linoleic acid (ω-6) family, and the linolenic acid (ω-3) family. These fatty acid families, which are not metabolically interconvertible, are described in Table 1.

Polyunsaturated fatty acids are ultimately derived from plants, seeds, leaves, and phytoplankton. Seeds and leaves are the principal sources of linoleic and linolenic acids, whereas phytoplankton synthesize eicosapentaenoic acid and docosahexaenoic acid, the major ω-3 fatty acids. Since phytoplankton are at the bottom of the marine food chain, all other forms of marine life eventually become enriched with these ω-3 fatty acids. Indeed, the ω-3 fatty acids may provide the required degree of unsaturation to allow fish membranes to remain fluid in very cold water. Tables 2 and 3 list some of the common dietary sources of polyunsaturated fatty acids and provide a detailed breakdown of three fats frequently used in the experimental studies alluded to in this review. Members of the ω-6 and ω-3 families are regarded as essential fatty acids (EFA) since they cannot be synthesized de novo in the body. The principal and best characterized EFA is linoleic acid, C18:2 ω-6. A dietary intake of 1% to 2% of total calories as linoleic acid is sufficient to prevent EFA deficiency, whereas higher levels (2% to 4% of calories) are needed to reverse the condition. Precisely how linoleic acid participates in human nutrition is becoming clearer. Linoleic acid is the obligatory precursor of arachidonic acid, which, in turn, serves as a principal substrate for prostaglandin synthesis. This relationship between linoleic acid, arachidonic acid, and prostaglandins has led to much speculation that EFA deficiency is, in fact, a “prostaglandin deficiency.” This contention, however, has not been supported.

<table>
<thead>
<tr>
<th>Source†</th>
<th>Linoleic</th>
<th>Arachidonic</th>
<th>Linolenic</th>
<th>Eicosapentaenoic</th>
<th>Docosahexaenoic</th>
<th>Saturated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Predominantly ω-6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safflower oil</td>
<td>73</td>
<td>—</td>
<td>0.5</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>Corn oil</td>
<td>57</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>13</td>
</tr>
<tr>
<td>Cottonseed oil</td>
<td>50</td>
<td>—</td>
<td>0.4</td>
<td>—</td>
<td>—</td>
<td>25</td>
</tr>
<tr>
<td>Sunflower seed oil</td>
<td>56</td>
<td>—</td>
<td>0.3</td>
<td>—</td>
<td>—</td>
<td>10</td>
</tr>
<tr>
<td>Peanut oil</td>
<td>29</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>19</td>
</tr>
<tr>
<td>Predominantly ω-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linseed oil</td>
<td>15</td>
<td>—</td>
<td>55.0</td>
<td>—</td>
<td>—</td>
<td>13</td>
</tr>
<tr>
<td>Salmon oil</td>
<td>1</td>
<td>—</td>
<td>1.0</td>
<td>8</td>
<td>5</td>
<td>26</td>
</tr>
<tr>
<td>Cod liver oil</td>
<td>2</td>
<td>—</td>
<td>1.0</td>
<td>12</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>Channel catfish oil</td>
<td>6</td>
<td>2.0</td>
<td>0.7</td>
<td>4</td>
<td>9</td>
<td>26</td>
</tr>
<tr>
<td>Mackerel</td>
<td>2</td>
<td>2.0</td>
<td>1.0</td>
<td>10</td>
<td>16</td>
<td>35</td>
</tr>
<tr>
<td>Whale oil</td>
<td>1</td>
<td>4.0</td>
<td>—</td>
<td>3</td>
<td>7</td>
<td>19</td>
</tr>
<tr>
<td>Both ω-6 and ω-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soybean oil</td>
<td>51</td>
<td>—</td>
<td>7.0</td>
<td>—</td>
<td>—</td>
<td>15</td>
</tr>
<tr>
<td>English walnut oil</td>
<td>55</td>
<td>—</td>
<td>11.0</td>
<td>—</td>
<td>—</td>
<td>11</td>
</tr>
<tr>
<td>Low in both ω-6 and ω-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cow milk fat</td>
<td>2</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>62</td>
</tr>
<tr>
<td>Human milk fat</td>
<td>7</td>
<td>0.2</td>
<td>0.7</td>
<td>0.6</td>
<td>0.3</td>
<td>50</td>
</tr>
<tr>
<td>Lard</td>
<td>10</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>36</td>
</tr>
<tr>
<td>Chicken fat</td>
<td>17</td>
<td>—</td>
<td>1.0</td>
<td>—</td>
<td>—</td>
<td>33</td>
</tr>
<tr>
<td>Beef tallow</td>
<td>4</td>
<td>—</td>
<td>0.5</td>
<td>—</td>
<td>—</td>
<td>48</td>
</tr>
<tr>
<td>Egg yolk</td>
<td>11</td>
<td>6.0</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
<td>53</td>
</tr>
<tr>
<td>Beef liver</td>
<td>10</td>
<td>6.0</td>
<td>0.5</td>
<td>—</td>
<td>—</td>
<td>39</td>
</tr>
<tr>
<td>Coconut oil</td>
<td>2</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>88</td>
</tr>
<tr>
<td>Olive oil</td>
<td>8</td>
<td>—</td>
<td>0.7</td>
<td>—</td>
<td>—</td>
<td>14</td>
</tr>
<tr>
<td>Cocoa butter</td>
<td>3</td>
<td>—</td>
<td>0.2</td>
<td>—</td>
<td>—</td>
<td>60</td>
</tr>
<tr>
<td>Palm oil</td>
<td>9</td>
<td>—</td>
<td>0.3</td>
<td>—</td>
<td>—</td>
<td>48</td>
</tr>
</tbody>
</table>

*Monounsaturated fatty acids constitute the remaining fatty acids. They are thought to have neutral effects upon plasma lipid levels.
†See refs. 78, 114–118.
Table 3. Detailed Fatty Acid Composition of Dietary Fats Commonly Used in Experimental Studies

<table>
<thead>
<tr>
<th>Fatty acid</th>
<th>Name</th>
<th>Butter fat</th>
<th>Corn oil</th>
<th>Salmon oil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(saturated)</td>
<td>(ω-6)</td>
<td>(ω-3)</td>
</tr>
<tr>
<td>4:0-12:0</td>
<td>—</td>
<td>11</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>14:0</td>
<td>Myristic</td>
<td>10</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>16:0</td>
<td>Palmitic</td>
<td>26</td>
<td>11</td>
<td>15</td>
</tr>
<tr>
<td>16:1 ω-7</td>
<td>Palmitoleic</td>
<td>2</td>
<td>trace</td>
<td>6</td>
</tr>
<tr>
<td>18:0</td>
<td>Stearic</td>
<td>12</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>18:1 ω-9</td>
<td>Oleic</td>
<td>25</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>18:2 ω-6</td>
<td>Linoleic</td>
<td>26</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>18:3 ω-3</td>
<td>Linolenic</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>20:1 ω-9</td>
<td>Eicosenoic</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>20:4 ω-6</td>
<td>Arachidonic</td>
<td>—</td>
<td>—</td>
<td>trace</td>
</tr>
<tr>
<td>20:5 ω-3</td>
<td>Eicosapentaenoic</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>22:1 ω-11</td>
<td>Cetoleic</td>
<td>—</td>
<td>—</td>
<td>9</td>
</tr>
<tr>
<td>22:5 ω-3</td>
<td>Docosapentaenoic</td>
<td>—</td>
<td>—</td>
<td>3</td>
</tr>
<tr>
<td>22:6 ω-3</td>
<td>Docosahexaenoic</td>
<td>—</td>
<td>—</td>
<td>8</td>
</tr>
<tr>
<td>Polysaturated/saturated</td>
<td>0.05</td>
<td>5.5</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Iodine value</td>
<td>31</td>
<td>123</td>
<td>167</td>
<td></td>
</tr>
</tbody>
</table>

*Trace = < 1%.

by experimental evidence, which has shown that prostaglandins per se do not uniformly alleviate the symptoms of EFA deficiency. Thus, some of the biochemical mechanisms through which linoleic acid functions remain obscure.

The essentiality of the ω-3 family has been questioned because of the finding that some, but not all, of the symptoms of EFA deficiency can be reversed by linolenic acid (e.g., normalization of 20:3/20:4 ratios but not reproductive function). Recent studies, however, have raised the possibility that ω-3 fatty acids may be essential, not for prostaglandin synthesis, but as vital structural components of specialized membranes. For example, docosahexaenoic acid (C22:6 ω-3) appears to play a role in the proper functioning of nervous tissues, and impaired maze-running abilities have been found in ω-3 fatty-acid-deficient rats. Remarkably high levels of C22:6 ω-3 are found in brain and retinal cells as well as in spermatozoa. Although further studies will be required to document structural or metabolic defects resulting from dietary ω-3 fatty acid deprivation, the presence of high levels of these unique acids in certain tissues and the known inability of mammalian cells to synthesize these de novo imply a dietary requirement for ω-3 fatty acids.

Under normal circumstances when the dietary intakes of ω-6 and ω-3 fatty acids are adequate, little or no elongation of oleic acid to eicosatrienic acid (C20:3 ω-9) occurs. However, severe restrictions in the dietary intakes of ω-6 and ω-3 fatty acids, or inhibition of fatty acid mobilization from adipose tissue (as occurs during prolonged hyperalimentation with glucose-containing solutions), will lead to the formation of significant amounts of C20:3 ω-9. An elevated ratio of C20:3 ω-9 to C20:4 ω-6 in the plasma lipids or a depression of linoleic acid in plasma cholesterol esters and phospholipids are indicative of an EFA deficiency.

### Omega-6 Fatty Acids and Plasma Lipids

#### Plasma Cholesterol

The hypocholesterolemic effects of polyunsaturated fatty acids present in vegetable oils has been appreciated for almost 30 years. In 1952, Kinsell et al. suggested that it was not simply the amount of fat in the diet, but the type of fat (animal or vegetable) that affected the plasma cholesterol levels. Later, this point was clearly demonstrated by Ahrens et al., who showed that feeding two vegetable fats (cocoanut oil and corn oil) led to vastly different plasma cholesterol levels. The iodine number (total unsaturation) of the oil, rather than its source, was found to be strongly correlated with the degree of cholesterol lowering. About the same time, it was shown that the addition of polyunsaturated fats to a fat-free diet resulted in a reduction in plasma cholesterol levels, which was of the same magnitude as the rise observed when saturated fats were added. The possibility that hypercholesterolemia resulted from EFA deficiency was discounted when it was shown that a fish oil high in ω-3 polyunsaturates but low in linoleic acid effectively reduced plasma cholesterol levels.
On the basis of this and other similar studies, Hegsted et al. and Keys et al. developed predictive equations from which the magnitude of change in plasma cholesterol that occurs after substitutions in the cholesterol or fatty acid composition of the diet could be calculated. Both equations predict that, on a gram for gram basis, saturated fatty acids will raise cholesterol levels about twice as much as polyunsaturated fatty acids will lower them. These equations were derived from studies in which linoleic acid was the polyunsaturated fat acid fed; they may not apply to fish oil feeding studies.

Several previous studies have demonstrated that polyunsaturated fatty acids derived from vegetable oils (principally linoleic acid) will reduce plasma cholesterol levels in normal, healthy volunteers. Typically, vegetable oils comprised 40% of the total calories, and the cholesterol intake was about 400 mg/day. The average decline in plasma cholesterol levels in these studies was about 13%, but ranged from 0 to 28%.

The extent of cholesterol lowering was related to at least two factors: 1) the magnitude of the difference between the P/S ratios (polyunsaturated to saturated fatty acids as a percent of total calories) of the saturated and the polyunsaturated diets; and 2) the presence of cholesterol in the diet. For example, in eight of these studies, the P/S ratio of the polyunsaturated diet averaged about 7-fold higher than that of the saturated diet (1.5 vs 0.2), and these studies reported an average decrease in plasma cholesterol levels of only 8%. In six other studies, the P/S ratio of the polyunsaturated diet averaged 27-fold higher than that of the saturated diet (4.6 vs 0.17), and this difference was associated with an average cholesterol decrease of 20%.

In terms of the effects of cholesterol in the diet, only three of these studies employed cholesterol-free diets. In one, a P/S ratio difference of 25-fold produced only an 8% decrease in plasma cholesterol levels, and in another, no change in cholesterol levels was found with a 9-fold P/S ratio range. Connor, et al. repeated the latter experiment using a 94-fold difference in P/S ratios and produced a 20% decrease in cholesterol levels. Thus, it appears that plasma cholesterol levels are less responsive to changes in the dietary P/S ratio when cholesterol is absent from the diet. The relatively small decrease in plasma cholesterol levels (8%) induced by the more practical shift in P/S ratios (7-fold) may indicate that simply changing the P/S ratio of the dietary fat without regard to other factors (e.g., the total amount of fat in the diet) may not produce physiologically important changes in the plasma cholesterol levels.

In hyperlipidemic patients, the effects of polyunsaturated vegetable oils have been similar to, or in some cases, greater than those reported in normal subjects. The average percent decrease was somewhat higher than that found in normals (22%; range, 13% to 33%). However, even in these hypercholesterolemic patients, those fed diets with the smallest difference in P/S ratios (2.0 vs 0.2) experienced the smallest decreases in plasma cholesterol levels (13%).

All phenotypic forms of hyperlipidemia showed some hypolipidemic response to dietary polyunsaturated fats. In the 17 Type IIa patients reported, the average decline in plasma cholesterol levels was 19%; in 15 Type IIb patients, 21%; in 29 Type IV, 15%; and in seven Type V, 16%. Thus, no particular phenotype was unusually responsive or resistant to changes in the amount of polyunsaturated fat in the diet.

**Plasma Triglyceride**

Investigators who have studied the effects of polyunsaturated vegetable oils upon plasma triglyceride levels have occasionally reached divergent conclusions. In four studies, vegetable oils decreased triglyceride levels somewhat in normal subjects while in seven others there were no effects. Among those reporting that polyunsaturated vegetable oils were hypotriglyceridemic, one study involved dietary periods of only 10 days' duration. In the study that employed the longest dietary periods (7–9 weeks per period), no effects of vegetable oil upon triglyceride levels could be demonstrated, which suggests that the 10-day study may have been too short to allow for plasma lipids to stabilize. In other studies, plasma triglyceride levels were depressed by only 13% to 15% during vegetable oil feeding. Thus, the overall consensus suggests that the feeding of polyunsaturated vegetable oils has minimal effects upon the plasma triglyceride levels in normolipidemic subjects. Much confusion in this area has been due to the frequent although not universal findings in hyperlipidemic subjects that polyunsaturated vegetable oils lower plasma triglyceride levels. It appears that the hypotriglyceridemic response is influenced both by the initial triglyceride levels as well as the genotypic form of hyperlipidemia present. The physiological significance of these changes is not known.

**Plasma Lipoproteins and Apolipoproteins**

There is general agreement that increased dietary intakes of polyunsaturated vegetable oils lower the concentrations of LDL cholesterol and in addition, reductions in high density lipoprotein (HDL) cholesterol levels have been found in four studies, but not in four others. The results of both of our recent metabolic studies support the conclusion that no change in plasma HDL levels occurs during polyunsaturated fat feeding. In the studies in which HDL concentrations fell, similar or greater reductions in the concentrations of LDL also occurred, so that the LDL:HDL ratio remained fairly constant.
The effects of dietary \(\omega-6\) polyunsaturated fatty acids on the concentrations of plasma apoproteins are consistent with the lipoprotein changes. Decreases have occurred in the concentrations of apoprotein B \(38, 42, 45, 53, 54, 58\) and either no change \(56, \) or a decrease in the concentrations of apoprotein A-1 \(50, 56, 58, 59\). The effects of polyunsaturated fatty acids upon the concentrations of apoprotein E are not known.

In summary, there is universal agreement that a high intake of polyunsaturated vegetable oils will reduce plasma cholesterol and LDL levels. There is probably little effect of \(\omega-6\) polyunsaturated fatty acids upon plasma triglyceride and VLDL levels \(40, 44, 47, 56\), although the data in this area are not clear. \(37, 38, 41, 50, 56\). HDL cholesterol levels have been variably affected by diets rich in linoleic acid. Future studies to settle these questions must be carefully conducted to allow adequate time for plasma lipids to stabilize on different dietary regimes; they must control caloric intake to prevent the confounding influences of weight changes upon lipoprotein metabolism; and they should examine the effects upon plasma lipids of reasonable changes in the amount of polyunsaturated fat in the diet.

**Hypollipidemic Mechanisms of Linoleic Acid**

The mechanisms by which polyunsaturated \(\omega-6\) fatty acids exert their hypolipidemic effects have been examined extensively, but to date no unifying mechanism has been found to be operative in all situations. \(38-39\) Proposed mechanisms have included: 1) decreased cholesterol absorption; 2) increased excretion of neutral and acidic steroids; 3) decreased cholesterol synthesis; 4) transfer of cholesterol from plasma to tissues; 5) changes in the cholesterol-to-protein ratio in LDL; and 6) changes in the rates of synthesis or catabolism of individual lipoproteins. In addition, the changes in the fatty acid composition of membrane lipids (fluidity) may affect lipoprotein metabolism in the following ways: changes in the lipoprotein particle itself may make it a better substrate for catabolic enzymes, or for binding to cellular receptors; or changes in cellular membranes may affect the local milieu of receptors and membrane-bound enzymes so as to increase their reactivity toward their lipoprotein substrates. All of these possible mechanisms will be considered.

**Decrease in Cholesterol Absorption**

Significant differences in cholesterol absorption have not been found in normal \(48\) or in hyperlipidemic \(29\) subjects fed either saturated or polyunsaturated fats. Studies from our laboratory have also failed to reveal any differences in cholesterol absorption in normolipidemic subjects fed diets rich in saturated, monounsaturated, or polyunsaturated fatty acids of either the \(\omega-3\) or the \(\omega-6\) families. \(32, 44\)

**Increase in Fecal Steroid Excretion**

Several groups have explored the possibility that greater amounts of fecal steroids are excreted during polyunsaturated fat feeding. In normal subjects this was found to be the case in six studies \(31, 40, 41, 44, 46, 49\) but not in two others. \(39, 48\) Recent studies from our laboratory reconfirmed these findings and showed a 56% increase in total sterol excretion during 4 weeks of polyunsaturated fat feeding as compared to a comparable period on a saturated fat diet. \(44\) Increased fecal steroid excretion has also been reported in hypertriglyceridemic subjects \(32\) but not in those with hypercholesterolemia. \(29, 55\) In a more prolonged study (40 days) in normal subjects, fecal steroid excretion increased when polyunsaturated fat was substituted for saturated fat. \(46\) After adaptation during the later phases of the experimental diets, however, the fecal steroid excretions were similar. These findings imply that, after a change to a polyunsaturated fat diet, fecal steroid excretion rises as the plasma cholesterol level declines, but then returns to normal levels once a new steady state is reached. The enhanced fecal steroid excretion more than accounts for the loss of cholesterol from the plasma compartment as the plasma level falls. \(31\) The increased excretion of fecal steroids after \(\omega-6\) polyunsaturated fat diets may not be essential to their hypolipidemic effect, particularly in familial hypercholesterolemic subjects since they do not always have increased fecal steroid excretion. In fact, much of the current controversy concerning the effects of vegetable oil feeding upon fecal steroid excretion has been due to the failure to recognize that subjects with genetically distinct hyperlipidemias may respond differently. The reasons for these differences are unclear.

**Reduced Cholesterol Synthesis and the Transfer of Cholesterol to the Tissues**

The possibility that cholesterol synthesis is reduced by polyunsaturated fatty acids has been largely ruled out. \(29, 61, 62\) The lack of change in the steady-state excretion of steroids observed by Nestel et al. \(48\) further supports this view. Recent studies have shown similar rates of cholesterol synthesis in freshly isolated mononuclear cells from subjects fed saturated vs polyunsaturated fat diets. \(61\) Since mononuclear cells are an easily accessible "peripheral tissue" possessing LDL receptors, \(63\) these findings also imply that cholesterol does not shift into the peripheral tissues during polyunsaturated fat feeding. Such a shift would be expected to lower the rate of cholesterol synthesis in the cell by feedback inhibition. \(63\) Further evidence that polyunsaturated fatty acids do not enhance tissue uptake of cholesterol came from an analysis of liver tissue from subjects consuming diets rich in polyunsaturated and saturated fatty acids. No increase in hepatic cholesterol levels after feeding polyunsaturated fat was found. \(62\) Direct evidence that polyunsaturated...
fatty acids increase tissue cholesterol concentrations in humans is lacking; they may even, on a theoretical basis, decrease tissue concentrations.

**Decrease in the Cholesterol Content of Lipoproteins**

In 1969, Spritz and Mishkel proposed that as dietary polyunsaturated fatty acids became incorporated into plasma lipoproteins, the tortuous geometry of the linoleate molecule would reduce the amount of space available for cholesterol transport, thus lowering the proportions of cholesterol in each LDL particle. The hyperlipidemic patients in this study had decreased cholesterol-to-protein ratios in LDL. However, this decrease was not found in two other studies. Some but not all of the studies in normolipidemic subjects have reported similar decreases in the cholesterol content of LDL.

**Changes in the Rates of Synthesis and Catabolism of Lipoproteins**

Comparative studies of apolipoprotein metabolism in both normal and hyperlipidemic patients fed diets high in saturated fatty acids or rich in ω-6 polyunsaturates have been undertaken. Although most studies have examined parameters of LDL metabolism, reports of the influence of dietary polyunsaturated fatty acids on the synthesis and catabolism of VLDL and HDL have also been published. The kinetics of VLDL apoprotein B (apo B) have been compared in subjects fed diets rich in polyunsaturated vs saturated fatty acids. The synthesis of apo B after the polyunsaturate-rich diet was significantly reduced in all studies, but the fractional catabolic rate did not change appreciably. Substitution of polyunsaturated fatty acids for saturates decreased the synthesis of apo A-I, the major apoprotein in HDL, by 26%. No change in the fractional catabolic rate of apo A-I was noted.

The influence of polyunsaturated fatty acids on LDL apo B metabolism has been studied in both normal and hypercholesterolemic subjects. The fractional catabolic rate of LDL has consistently been increased after the substitution of polyunsaturates for saturated fats in the diet. In some but not all studies, these changes were paralleled by significant decreases in the absolute synthetic rates for LDL apo B. In all studies, however, the trends have been similar (decreased synthetic rate and increased fractional catabolic rate with polyunsaturated fat), but in some cases the difference has not reached statistical significance. A recent study in which saturated or ω-6 polyunsaturated fatty acids were isocalorically substituted for monounsaturated fatty acids has provided additional insights into the individual effects of saturated vs polyunsaturated fats on LDL metabolism. The fractional catabolic rate of LDL was significantly higher from the polyunsaturated diet than from either the monounsaturated or saturated regimens. This suggests that increased catabolism of LDL results primarily from the addition of polyunsaturated fat to the diet rather than from the removal of saturated fatty acids.

**Membrane Fatty Acid Composition and Lipoprotein Metabolism**

Polyunsaturated fat feeding alters the fatty acid composition of cellular membranes and plasma lipoproteins with a resultant increase in fluidity. A report that lipoprotein lipase is more reactive toward the more fluid lipoprotein particles implies that linoleate-enriched lipoproteins may be cleared more rapidly. In addition, the fatty acid composition of cellular membrane phospholipids can influence the activity of membrane-bound enzymes. An increase in the unsaturation of membrane phospholipids in cultured human fibroblasts led to a more rapid removal of LDL particles but no change in the number of LDL receptors. Thus, the activity of receptors or membrane-bound enzymes toward lipoproteins appears to be enhanced by higher levels of linoleic acid in the diet.

In summary, the literature attests to the fact that no single mechanism of action of ω-6 polyunsaturated fatty acids has yet been proven. Multiple pathways have been described in both normal and hyperlipidemic subjects, and these pathways are greatly affected by the type of lipid disorder present. Many of the observed effects of polyunsaturated fatty acids may be interrelated. For example, increases in fecal steroid excretion could be secondary to an increased rate of catabolism of LDL. This may be caused by changes in lipoprotein or membrane fluidity leading to changes in the activity of lipolytic enzymes or membrane receptors. Based on available evidence, we believe that the most promising mechanisms to explain the hypolipidemic effects of polyunsaturated fats relate to changes in the fluidity of lipoproteins and/or cellular plasma membranes. These physicochemical changes (which follow increased consumption of polyunsaturated fatty acids) may affect lipid and lipoprotein metabolism leading to reduced steady state plasma lipid levels.

**Omega-3 Fatty Acids and Plasma Lipids**

**Epidemiologic Studies**

Recent studies by Bang and Dyerberg have stimulated interest in the metabolism of ω-3 fatty acids and have suggested a link between the habitual ingestion of these fatty acids in the diet and the low death rates from atherosclerotic disease observed in Greenland Eskimos. Although little reliable data on cardiovascular morbidity and mortality is available among this particular group of Eskimos, Bang and Dyerberg noted that during the years 1953–1967 only two cases of atherosclerotic heart
disease and no cases of diabetes mellitus were registered in the population of 1,300 people. In 1970, Arthrand estimated deaths from cardiovascular disease to be only 16% of all deaths in Alaskan coastal Eskimos (aged 41–70 years) over the years 1959–1968. Bang and Dyerberg have provided evidence that the high levels of ω-3 fatty acids consumed in the Eskimo diets of seal, whale, and fish (5.8 g/day) may be responsible for the lower plasma lipid levels in this population compared to levels in Danes (0.8 g/day). In addition, ω-3 fatty acids may also be responsible for the prolonged bleeding times that are common in this group of Eskimos.

**Animal Studies**

Because of the large body of data available on the effects of dietary ω-6 polyunsaturated fatty acids in humans, we have not reviewed the ω-6 studies carried out in experimental animals. However, because dietary ω-3 polyunsaturated fatty acids have not been as extensively studied in humans, a brief review of the ω-3 fatty acid feeding studies in animals is desirable.

Cholesterol metabolism in animals fed various fish oils has been reviewed in depth by Stansby. Rats have been fed sardine oil, cuttlefish liver oil, cod liver oil, and tuna and menhaden oil. In the latter studies, the highly unsaturated ω-3 fatty acids found in the fish oils were compared to the ethyl esters of linolenic, linoleic, palmitic, and oleic acids in hypercholesterolemic rats. Despite the differences in unsaturation, both of the fish oils and linolenic acid produced equivalent cholesterol lowering. Linoleic acid was the next most effective, followed by oleate and palmitate.

In contrast to these findings in rats, studies in hypercholesterolemic chickens have shown that fish oils were more hypocholesterolemic than either linolenic or linoleic acids. Thus, in some species, fatty acids of the ω-3 family (from fish oils and linolenic acid) may be equally hypocholesterolemic. In other animals, the fatty acids with the greatest unsaturation (eicosapentaenoic and docosahexaenoic from fish oils) are more hypocholesterolemic than other ω-3 fatty acids that contain less unsaturation (linoleic acid).

The hypolipidemic effects of a diet containing mackerel oil (which is rich in ω-3 fatty acids) vs one supplemented with olive oil (rich in monounsaturates) has also been compared in piglets. Although plasma cholesterol levels were not affected by the mackerel oil feeding, the concentrations of plasma triglyceride were significantly depressed. Failure to balance the high cholesterol intake during the fish oil feeding (400 mg/day) by adding similar amounts of cholesterol to the olive oil diet may explain why plasma cholesterol levels were not reduced by the fish oil.

**Human Studies**

Between 1956 and 1963, eight studies of fish-oil feeding were carried out in humans. Although they varied in the kinds of subjects studied, in the degree of dietary control, in the sources of fish oil fatty acids, and in duration, there has been good agreement that fish oils were at least as hypocholesterolemic as polyunsaturated vegetable oils. The principal intent of these studies was to demonstrate that polyunsaturated fats from any source (fish or vegetable) were hypocholesterolemic. There was no indication from these studies that fish oils had any unique properties not shared by other polyunsaturated oils from vegetable sources.

Two interesting features of these studies were perhaps not appreciated at the time. First, since fish oils contain large amounts of cholesterol (300 to 500 mg/dl) and vegetable oils contain none, the vast majority of these investigators fed higher levels of cholesterol during the fish oil phase than during the vegetable oil phase. Thus, the finding of similar hypocholesterolemic effects of these two types of fat implied that the fish oils might have been even more hypocholesterolemic if they had not contained dietary cholesterol.

Second, the daily intake of ω-6 fatty acids was invariably greater than the intake of ω-3 fatty acids, and yet similar or greater reductions in plasma cholesterol levels occurred from ω-3 fatty acids. Thus, gram for gram, the ω-3 fatty acids were considerably more hypocholesterolemic than linoleic acid. Others have shown that tetra-, penta-, and hexaenes produced two to three times greater cholesterol lowering than did the di- or trienes.

More recently, dramatic reductions in the concentrations of plasma triglycerides and VLDL have been observed in both normolipidemic and hyperlipidemic subjects fed diets supplemented with fish oils. In one study, normal subjects were fed diets enriched with salmon oil, polyunsaturated vegetable oils, and a relatively saturated control diet for periods of 4 weeks each. Plasma cholesterol levels were reduced similarly with both the salmon and vegetable oil rich diets. In contrast, however, plasma triglyceride levels fell 33% as a result of the salmon oil diet but were unchanged after the vegetable oil diet (figure 1). This direct comparison provided the first clear demonstration that ω-3 fatty acids present in salmon oil possess unique hypotriglyceridemic properties not found in the polyunsaturated ω-6 fatty acids of vegetable oils. In these studies it was further demonstrated that dietary ω-3 fatty acids significantly decreased plasma VLDL (50%) and LDL (16%) levels but did not change the concentrations of HDL (figure 2). Possible mechanisms for this effect will be discussed subsequently. The fact that HDL levels were not depressed has been confirmed by others, and, in some studies, HDL cholesterol levels have actually increased on the ω-3 fatty acid rich diets.

The effects of fish oils in hypercholesterolemic and hypertriglyceridemic patients have been reported in
only two studies. Ahrens et al. examined two subjects (probably Type II-b) given isocaloric amounts of either corn oil or menhaden oil at 40% of calories. Plasma cholesterol and triglyceride levels were both reduced more by the fish oil than the vegetable oil. Phillipson et al. recently reported the effects of feeding diets rich in salmon oil, polyunsaturated vegetable oils, and saturated fats to hyperlipidemic subjects. In patients with Type II-b hyperlipidemia, plasma cholesterol levels (mg/dl) decreased from 294 to 239 (ω-6 diet) and 200 (ω-3 diet). Plasma triglyceride levels were 397 (control), 247 (ω-6 diet), and 135 (ω-3 diet). Thus, the fish oil diet was significantly more hypolipidemic than the polyunsaturated vegetable oil diet.

The effects of dietary fish oil upon the plasma lipids of patients with severe hypertriglyceridemia (Type V phenotype) were first reported in 1981. These patients, in whom hypertriglyceridemia is normally exacerbated by even moderate intakes of dietary fat, were able to consume up to 30% of their calories as fish oil, with a concomitant lowering of their plasma lipid levels. The ω-3 fatty acid-rich diet resulted in a 46% decline in plasma cholesterol levels and a 77% drop in triglyceride levels when compared to a control diet having only 5% fat (figure 3). Comparative diets containing 30% of calories as ω-6 fatty acids caused rapid increases in the concentrations of both plasma cholesterol and triglycerides so that it became necessary to stop these diets after 14 days because of the increasing risk of abdominal pains, hepatomegaly, and acute pancreatitis. The ω-3 fatty acids had distinctly different effects upon plasma lipid levels than ω-6 fatty acids and may be of substantial therapeutic benefit in hypertriglyceridemic patients.

A few attempts have been made to determine the minimum intake of ω-3 fatty acids necessary to pro-
produce significant changes in plasma lipid levels. Although dose responses have not been fully ascertained, it has been shown that approximately 4 g/day of ω-3 fatty acids from 20 ml of cod liver oil produced a greater cholesterol lowering than did 16 g of linoleic acid. In a second study, however, the addition of up to 8 g of ω-3 fatty acids (from cod liver oil) did not change the plasma cholesterol levels but did result in a significant reduction in plasma triglycerides. A further study showed that 4 g of ω-3 fatty acids per day were able to reduce the levels of plasma triglycerides but not of cholesterol.

A major problem with many of these studies is that the fish oils were simply given as supplements and were not incorporated into a metabolic diet as a replacement for a portion of the customary dietary fat. In addition, the cholesterol intake was usually higher during the fish oil phase. For these reasons it seems likely that more significant hypocholesterolemic effects might have occurred if the dietary periods had been more rigorously matched in terms of both fat and cholesterol content.

In summary, although relatively few studies have examined the effects of ω-3 polyunsaturated fatty acids upon plasma lipids and lipoproteins, there has been an impressive consistency in the findings, not only in metabolic studies but also with free-living human beings consuming high levels of ω-3 fatty acids. Fish oils have always been at least as effective as vegetable oils (if not more so) in lowering plasma cholesterol levels. These reductions occurred when ω-3 fatty acids constituted from 1% to 8% of total calories. In light of the fact that linoleic acid intakes of 15% to 20% of calories were needed to achieve similar depressions in plasma cholesterol levels, the dietary ω-3 fatty acids were roughly 2 to 5 times more potent than the ω-6 acids.

The most striking effects of fish oil feeding have been the rapid and drastic decreases in the levels of plasma triglyceride and VLDL. Since vegetable oils produce little or no depression in plasma triglyceride concentrations, it is evident that ω-3 fatty acids have unique effects not shared with the ω-6 fatty acids. Studies in hyperlipidemic subjects have demonstrated that small quantities of ω-3 fatty acids are much more hypolipidemic than large amounts of linoleic acid. Thus, dietary ω-3 fatty acids may prove to be very effective in the treatment of hyperlipidemia.
Hypolipidemic Mechanisms of Omega-3 Fatty Acids

Plasma Cholesterol

The mechanism of the ω-3 induced hypcholesterolemia has not been studied as extensively as that resulting from ω-6 fatty acid ingestion. Nevertheless, there is data to suggest that the following mechanisms may be involved: 1) increased fecal steroid excretion; 2) changes in the fatty acid composition (fluidity) of lipoproteins; and 3) changes in the rates of synthesis and/or catabolism of VLDL and LDL.

In studies recently reported from our laboratory, both polyunsaturated fat diets (ω-6 or ω-3) led to increased fecal steroid excretion.44 Net fecal excretion of cholesterol and its metabolites was 673 mg/day during the saturated control diet, 926 mg/day with the vegetable oil diet, and 975 mg/day after the salmon oil diet. The slightly greater excretion with ω-3 fatty acids as compared to the ω-6 fatty acids occurred primarily from an increase in the excretion of bile acids. Thus, increased steroid excretion was a common result of feeding both ω-6 and ω-3 polyunsaturated fatty acids.

In terms of lipoprotein composition, we found that the cholesterol-to-protein ratio was not different after saturated and ω-3 dietary periods despite a decrease in LDL levels (Harris, unpublished observations). Hence, changes in this ratio would not explain the hypcholesterolemic effect of ω-3 fatty acids.

Although no data on the fatty acid composition of individual lipid classes from the major lipoprotein fractions have been reported as yet, the fatty acids of each plasma lipid class have been studied during ω-3 diets.38, 90, 91, 93 The percent of total fatty acids occurring as ω-3 in each class of plasma lipids (triglyceride, phospholipid, and cholesteryl esters) was 1% to 3% on the control diet and increased to 31%, 33%, and 26%, respectively, after the ω-3 diet.93 Since these ω-3 fatty acids are highly unsaturated (5 to 6 double bonds), the fluidity of the lipoprotein particles would probably be affected54, 95 and the interaction between lipoproteins and lipolytic enzymes may be enhanced.66, 67

Omega-3 fatty acids have affected plasma triglycerides and VLDL cholesterol levels more extensively than total and LDL cholesterol levels. This suggests that ω-3 fatty acids may primarily affect the synthesis or clearance of triglycerides and/or VLDL. Because of the well-established precursor-product relationship between VLDL and LDL, reductions in the synthesis of VLDL may in turn lead to lower concentrations of HDL.90 Chait et al.45 and Grundy59 have provided evidence that ω-6 fatty acids may reduce plasma cholesterol levels in this manner in hyperlipidemic subjects. Recent studies in our laboratory have shown that feeding ω-3 fatty acids to normal subjects reduced the synthetic rate of LDL apo B by 23% as compared to a saturated-fat control diet. The fractional catabolic rate did not differ during the two diets (Hillingworth, unpublished observations). These findings indicate that a decrease in VLDL synthesis could be responsible for lower LDL levels. Comparative studies of VLDL kinetics during the feeding of diets rich in ω-3, ω-6, and saturated fatty acids will be needed to clarify this issue.

Plasma Triglyceride

Reductions in the concentrations of plasma triglycerides and VLDL may occur from lower rates of synthesis of the triglyceride or apo B moieties of VLDL or may result from an increased rate of clearance of VLDL from the plasma. In light of the first possibility, Iritani et al.96 showed in rats that eicosapentaenoic acid (20:5 ω-3) reduced the activity of the lipogenic enzyme acetyl CoA carboxylase when compared to linoleic acid. Similar findings have been reported by others.97 Thus, ω-3 fatty acids may reduce hepatic lipogenesis with a concomitant reduction in the supply of fatty acids for triglyceride synthesis.

The most important source of fatty acids for triglyceride synthesis is the adipose tissue.98 A reduction in adipose tissue lipolysis could lower fasting free fatty acid levels and reduce triglyceride synthesis. Such a mechanism has been proposed for the hypolipidemic effects of niacin.99 However, Chait et al.45 found no difference in plasma free fatty acid levels in subjects fed saturated and ω-6 polyunsaturated fat diets. This finding does not preclude the possibility that ω-3 fatty acids could affect triglyceride levels via a reduction in free fatty acid release, especially in view of the dramatic and consistent triglyceride lowering that accompanies ω-3 fatty acid feeding. One possible way in which ω-3 fatty acids could influence adipose tissue lipolysis is via their participation in prostaglandin metabolism.74 In vitro, prostaglandin E2 has been shown to inhibit lipolysis of adipose tissue triglyceride.100 However, other investigators have failed to show any effects of prostaglandins on lipolysis in vivo.101, 102 and the possible role of these compounds in the regulation of free fatty acid levels remains unsettled. Nevertheless, the possibility remains that prostaglandins derived from ω-3 fatty acids may have antilipolytic properties which may contribute to their overall hypotriglyceridemic effects.

A second mechanism by which dietary ω-3 fatty acids could reduce plasma triglyceride levels is the acceleration of VLDL clearance. Since chylomicrons and VLDL share a common clearance mechanism,103 we assessed the effects of ω-3 fatty acids upon the rate of chylomicron clearance after a standardized test meal. We consistently found that the postprandial rise in plasma triglyceride levels after a salmon oil test meal was markedly reduced as compared to the rise that followed a saturated fat test meal.95 After verifying that the salmon oil was not malabsorbed, we concluded that dietary salmon oil may increase the rate of clearance of chylomicrons. Likewise, the reduced levels of fasting triglycerides may be due to more rapid removal of VLDL from the circulation.
Should ω-3 fatty acids be shown to accelerate triglyceride clearance rates, at least two possible mechanisms should be considered: an increase in plasma lipolytic activity (lipoprotein lipase or hepatic triglyceride lipase) or the lipoprotein particle itself may be changed in such a way that it becomes a better substrate for lipolytic enzymes. Support for increased enzyme activity is sparse. In preliminary studies from our laboratory, we have found no significant difference in post-heparin lipolytic activity in normal subjects fed ω-3 and saturated fat diets (Illingworth, unpublished observations). As noted earlier, the microenvironment of membrane-bound lipolytic enzymes may be affected by dietary fatty acids, thereby altering either the affinity or activity of receptors and enzymes.67 Such phenomena have not been examined during ω-3 fatty acid feeding.

Since the activity of postheparin lipoprotein lipase does not appear to be greatly affected by dietary ω-3 fatty acids, a second possibility needs to be considered, namely, that ω-3 fatty acids may change the nature of the lipoprotein substrate and thereby enhance triglyceride clearance. Clearly, total unsaturation of plasma lipoproteins is dramatically affected by a diet rich in ω-3 fatty acids.68 Although lipoprotein lipase has no known fatty acid specificity,94,106 the size of the lipoprotein particle being cleared does influence its clearance rate in that larger particles are cleared most rapidly.106 It is not known whether chylomicrons or VLDL enriched with the long-chain highly unsaturated ω-3 fatty acids are larger than those carrying the more usual fatty acids. When relatively small amounts of fish oils were fed to subjects on otherwise uncontrolled diets, there appeared to be a relationship between decreased plasma triglyceride levels and the in vitro lipolysis of lipoprotein triglycerides by lipoprotein lipase.107 Since post-heparin lipoprotein lipase activity was derived from one individual in all experiments, the differences in the observed lipolytic rates probably resulted from the diet-induced differences in the lipoproteins themselves. Thus, the nature of the lipoprotein substrate may help determine its rate of clearance.

Polyunsaturated Fatty Acids and Thrombosis

A persistent interest in the relationships of polyunsaturated fatty acids to the role of platelets in atherosclerosis and thrombosis has spanned several decades and has now dramatically accelerated with the appreciation of the links between dietary fatty acids and prostaglandins in platelets and vascular tissue. The following sections will focus first on the early work linking free fatty acids and dietary saturated fats to vascular thrombosis and will then proceed to a detailed examination of the changes in platelet/ves...

Free Fatty Acids, Platelets, and Thrombosis

The first step taken in the study of fatty acids as potential thrombogenic substances was to add free fatty acids directly to whole blood and to administer them intravenously to experimental animals. Initially, the sodium salts of various fatty acids were added to blood and the mixtures injected into a loop of plastic tubing which was rotated semivertically on a wheel (Chandler apparatus) to induce a thrombus. In these experiments, long-chain saturated fatty acids such as stearic acid (C18:0) greatly shortened the "thrombus formation time," while polyunsaturated fatty acids were essentially inactive.9,10 Similarly, intravenous infusions of saturated fatty acids into dogs led to thromboses in the heart and great vessels whereas long-chain polyunsaturated fatty acids such as linoleic acid were much less thrombogenic.11,106,109

These experiments demonstrated the thrombogenic potential of saturated free fatty acids but it was not yet clear whether they acted via the generation of fibrin (perhaps through activation of factor 12) or whether they also possessed the ability to directly aggregate platelets. Accordingly, experiments were performed with platelets and fatty acids in the absence of plasma coagulation factors. The addition of long-chain saturated fatty acids to washed platelets led to the release reaction and irreversible platelet aggregation, whereas polyunsaturated fatty acids had little or no effect.110-112 However, the activity of arachidonic acid was not tested in this system. When the added fatty acids were bound by albumin or plasma proteins in solution, their platelet aggregating ability was generally reduced although stearic and oleic acids continued to be active.110,112 Thus, saturated free fatty acids, especially when in excess of the tight albumin binding sites, could lead to platelet aggregation in the absence of blood coagulation and the formation of fibrin.

Additional studies examined the platelet aggregating effects of endogenously generated free fatty acids in animals or humans. Acute elevations of plasma free fatty acids following subcutaneous ACTH given to rabbits led to thrombosis in isolated jugular venous segments and the appearance of "circulating platelet aggregates" in arterial blood.114,115 Similar increases in total and saturated free fatty acids induced either by fasting in normal subjects or secondary to acute coronary insuffi-
ciency in patients could also be correlated with the appearance of circulating platelet aggregates and elevated platelet factor 4 plasma concentrations in venous blood.\textsuperscript{116, 117}

In sum, under appropriate (but rather artificial) experimental conditions, saturated free fatty acids may lead to thromboses that appear to be mediated, at least in part, by increased platelet reactivity. These effects are not seen with unsaturated fatty acids. Whether acute elevations of free fatty acids from endogenous sources may lead to overt vascular occlusion in susceptible individuals such as those with severe coronary vascular disease requires further clarification.

**Dietary Fat, Platelets, and a Predisposition to Thrombosis**

Instead of using free fatty acids to initiate thrombosis, an additional series of experiments were carried out in which certain dietary fats were fed to experimental animals for weeks or months and the predisposition of the animals to thrombosis produced by biologic or mechanical stimuli determined. For example, rats fed butter or a diet augmented with specific saturated fatty acids (e.g., stearic acid) developed larger hepatic thrombi than control animals after jugular vein infusions of \textit{S. typhosa} endotoxin.\textsuperscript{118, 119} As in the experiments using injections of free fatty acids, it was not clear whether the endotoxin infusion (classically associated with disseminated intravascular coagulation) produced the larger hepatic thromboses via fibrin generation or through a diet-induced augmentation of platelet reactivity. Subsequent investigation indicated that the platelets from rats fed a high saturated fat diet showed increased sensitivity to thrombin-induced platelet aggregation and were able to release platelet factor 3 more readily than controls.\textsuperscript{120-122} Unfortunately, these studies failed to provide more direct evidence of platelet involvement in the endotoxin-induced hepatic thromboses.

Further studies have examined whether different dietary fatty acids may influence the number of platelet-derived pulmonary thrombi produced by an infusion of adenosine diphosphate into the inferior vena cava of rats.\textsuperscript{123} After the saturated fat diet, the adenosine diphosphate infusion led to the immediate formation of thrombin in 90% of the animals, whereas the incorporation of polyunsaturated fatty acids into the diet (replacing 20% of the saturated fat) significantly reduced, but failed to eliminate, pulmonary thrombi.

Lastly, following surgical insertion of a small polyethylene cannula into the abdominal aorta of male rats, the number of hours required for occlusion of the cannula by a platelet thrombus was recorded.\textsuperscript{124-126} There was a direct relationship between the dietary linoleic acid content and prolongation of the aortic occlusion time. Conversely, the ingestion of saturated fatty acids of increasing chain length was associated with a progressive shortening of the occlusion time. The platelet count was higher and the platelets more sensitive to aggregation by adenosine diphosphate in the animals fed the saturated fat diet.

These and other experiments indicate that the chronic feeding of diets rich in saturated fat to experimental animals predisposed them to thrombi initiated by endotoxin, adenosine diphosphate, or the insertion of a plastic cannula into the aorta. Although the dietary manipulations resulted in increased platelet reactivity by various in vitro measurements, it remains to be proven that the increased propensity to thrombosis was actually caused by dietary-induced alterations in platelet reactivity.

**Prostaglandins Derived from Polyunsaturated Fatty Acids in Platelets and Blood Vessels**

Our understanding of the relationships of polyunsaturated fatty acids and their role in platelet and vascular function has been greatly aided by the recent identification and characterization of platelet and endothelial cell prostaglandins (figure 4).\textsuperscript{4, 12, 127} Since these potent substances, thromboxane A\textsubscript{2} and prostaglandin I\textsubscript{2} (PGI\textsubscript{2}),\textsuperscript{4} are ultimately derived from dietary fatty acids, it is possible that manipulation of dietary fat content might alter prostaglandin synthesis and subsequent platelet/vessel interactions.

Arachidonic acid (C20:4 o-6) may be transported in the circulation either in the free fatty acid form bound to albumin or esterified in lipoprotein phospholipids and cholesterol esters.\textsuperscript{128} Direct uptake of free arachidonic acid by platelets or the vessel wall leads to its incorporation into membrane phospholipids;\textsuperscript{129} the latter also exchange with plasma phospholipids. Following activation of one or more phospholipases, arachidonic acid becomes "available" to the enzyme cyclooxygenase and is rapidly converted to the labile cyclic endoperoxides, PGG\textsubscript{2} and PGH\textsubscript{2}.\textsuperscript{130} Enzymes such as thromboxane synthetase in the platelet or prostacyclin synthetase in the endothelial cell convert the endoperoxides to biologically active thromboxane A\textsubscript{2} or PGI\textsubscript{2} (prostacyclin).\textsuperscript{131-133} The potent vasoconstricting and platelet aggregating effects of thromboxane A\textsubscript{2} and the vasodilating and platelet inhibitory effects of prostacyclin are now well known and have been extensively studied.\textsuperscript{4}

\textsuperscript{4The prostaglandins have been named in the order of their discovery beginning with A and proceeding to I; e.g., PGI\textsubscript{2}. The numerical subscript refers to the number of double bonds in the prostaglandin side chain.}
Other polyunsaturated fatty acids besides arachidonic acid may serve as substrates for prostaglandin synthesis (figure 5). For example, dihomo-gamma-linolenic acid (DHLA) (C20:3 ω-6) acts as a substrate for prostaglandins of the "1" series such as the classical prostaglandin, PGE₁ (thromboxane A₁ or PGH₁, if formed at all, appear to be inactive). Eicosapentaenoic acid (C20:5 ω-3) is the substrate for prostaglandins of the "3" series and, under certain conditions, leads to the production of thromboxane A₃ and PGJ₂. The biochemical relationships and metabolic pools of the polyunsaturated fatty acids in the human require further study. For example, the essential fatty acid, linoleic acid, is converted to C20:3 ω-6 and ultimately to arachidonic acid in the liver. Although the feeding of diets rich in linoleic acid regularly leads to its accumulation in platelet membrane phospholipids, arachidonate levels are found to be unchanged or may even be decreased in platelets. Similarly, feeding of linolenic acid (C18:3 ω-3) does not appear to lead to significant increases of eicosapentaenoic acid in adult human plasma. The feeding of marine foods rich in eicosapentaenoic acid, however, leads to rapid incorporation of this fatty acid into both platelet and endothelial cell membranes.

Recent studies have shown that arachidonic acid can also be converted by the lipoxygenase pathway to a new class of compounds called leukotrienes.
Since leukotrienes have been shown to have bronchoconstrictive properties (i.e., slow reacting substance of anaphylaxis, SRS-A), chemotactic activity, and possible influences on thromboxane and prostacyclin synthesis, they will provide a fertile area for future biochemical and clinical research. The rapidly increasing knowledge of prostaglandin and leukotriene metabolism will allow reinterpretation of older studies of the effect of dietary fatty acids on platelet function. More important, it will enable future investigators to construct more rational attempts to manipulate cellular prostaglandin synthesis by dietary or other therapeutic means.

**Effects of Omega-6 Fatty Acids upon Platelet and Vascular Composition and Function**

**Linoleic Acid**

Early studies of fatty acids and thrombosis generally supported the hypothesis that replacement of saturated by polyunsaturated fatty acids in the diet might be protective against thromboembolic events, and that this protective effect might be mediated through an inhibition of platelet function. Consequently, during the last decade, a number of investigators have examined the effects of diets containing large amounts of polyunsaturated fatty acids (especially linoleic acid) on platelet lipid composition and hemostatic function. Evaluation of these studies has been somewhat difficult because of marked variations in experimental design, dietary control, lipid analyses, and tests of platelet function. However, some important generalizations can be made in spite of these drawbacks.

**Platelet and Vessel Lipid Composition**

Although linoleic acid is rapidly converted to arachidonic acid in the liver and in cells such as fibroblasts, similar elongation and desaturation does not occur in platelet membranes. Indeed, studies in which linoleic acid was fed to rabbits in the form of corn oil led to a reproducible increase in the percent concentration of linoleic acid in platelet membrane phospholipids compared to a butter fat diet (table 4). However, platelet arachidonic acid was decreased in the corn-oil-fed animals compared to the butter fat group. Similar findings were observed in rats fed diets containing combinations of corn oil and hydrogenated coconut oil. The arachidonic acid content of aortic phospholipids was also found to be increased in butter-fed rabbits. The decrease in the total amount of arachidonate present in platelet phospholipids may be even greater than has been appreciated since it has been reported recently that total platelet fatty acid concentration may be decreased in animals fed large amounts of linoleic acid. For example, total platelet fatty acids declined by half in rats fed a 40% fat diet in which the P/S ratio was increased from 0.4 to 5.5.

A recent study conducted in human volunteers showed that feeding supplemental linoleic acid in the form of corn oil (25 ml/day) for 6 weeks led to an increase in the linoleate content of the phosphatidylcholine component of platelet phospholipids, but not the phosphatidylethanolamine or phosphatidylinositol fractions. Total platelet arachidonate levels were unchanged.

Some additional experimental data clarifying this question have recently become available using cultured endothelial cells or platelets incubated with various fatty acids for 1–72 hours. When the incubation medium was enriched with linoleic acid, the phospholipids in endothelial cells and platelets increased their linoleic acid content from 5% to 25%, but arachidonic acid levels fell by 25% to 40%. This reduction may be due in part to a Δ6 desaturase deficiency in endothelial cells that prevents conversion of C18:2 to C20:4 by interfering with the desaturation of C18:2 to C18:3. In addition, high concent-

<table>
<thead>
<tr>
<th>Platelet fatty acid</th>
<th>Linoleic acid (in vegetable oil)</th>
<th>Dihomo-gamma-linolenic acid (as purified supplement)</th>
<th>Eicosapentaenoic acid (in fish oil)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C18:2 ω-6 (linoleic acid)</td>
<td>Increased</td>
<td>Decreased</td>
<td>Decreased</td>
</tr>
<tr>
<td>C20:3 ω-6 (dihomo-gamma-linolenic acid)</td>
<td>No change</td>
<td>Increased</td>
<td>No change</td>
</tr>
<tr>
<td>C20:4 ω-6 (arachidonic acid)</td>
<td>Decreased</td>
<td>Decreased</td>
<td>Decreased</td>
</tr>
<tr>
<td>C20:5 ω-3 (eicosapentaenoic acid)</td>
<td>Nil</td>
<td>Nil</td>
<td>Increased</td>
</tr>
</tbody>
</table>
trations of linoleic acid may simply reduce arachi-
donic acid levels by competition for esterification
sites in phospholipids.

Therefore, in at least some experimental situa-
tions, feeding a diet very rich in linoleic acid may lead
to a selective decrease in arachidonic acid, whereas
diets containing saturated fatty acids may lead to the
opposite effect. Whether these changes in arachi-
donic acid content will regularly translate into equiv-
alent changes in thromboxane or prostacyclin re-
lease remains to be determined.148

Platelet and Vessel Wall Function

Changes in platelet function have been studied
after the chronic feeding of diets rich in polyunsat-
urated vegetable oils. When bleeding times were
performed in human subjects ingesting a diet rich in
ω-6 polyunsaturated fatty acids and compared to a
control dietary period, no significant differences were
found in our own studies (unpublished observations)
or in those of others (table 5).140, 149, 150 Despite this
lack of prolongation in the bleeding times, some tests
of platelet aggregation have been affected by dietary
linoleic acid.

In rabbits fed corn oil, the sensitivity for arachi-
donic acid and collagen-induced platelet aggrega-
tion was lowered when compared to aggregation in
butter-fed animals.151 In humans, Renaud et al.152
reported that platelet aggregation in response to
thrombin and adenosine diphosphate (but not cola-
gen or epinephrine) was increased in a group of
French farmers with a high saturated fat intake, com-
pared to a second group eating a diet containing less
saturated fat.152 Similarly, platelet aggregation in-
duced by low concentrations of collagen was de-
creased in a group of Norwegian subjects given a
corn oil supplement.140 In contrast to these studies, a
group of normal American men given dietary supple-
ments of margarine and vegetable oils failed to show
differences in platelet aggregation but did show a
significant reduction in platelet retention on glass
bead columns.153

Two rather large studies have used the filtra-
gometer to measure the time taken for platelets to oc-
clude a microfilter inserted in a closed "in vitro" sys-

tem containing flowing blood. In one study, patients
in a Finnish chronic-care hospital were given a diet
high in linoleic acid. The occlusion time in the filtra-
gometer was lengthened in these patients during this
dietary period.152 A similar study involving 66 elderly
patients given dietary supplements of a vegetable oil
margarine also showed a prolongation of the occlu-
sion time.154

A shortening of the heparin thrombin clotting time
is thought to represent the presence in the plasma of
platelet factor 4 which has heparin neutralizing prop-
erties. A prolonged heparin thrombin clotting time
(indicating decreased platelet factor 4 effect) was
observed in two studies in which subjects had en-
richment of their diets with margarine.149, 153 In one
of these studies, a significant increase in circulating
platelet aggregates occurred when subjects were in
a saturated fat phase of the study.153

In sum, it appears that supplementing or replacing
saturated fat with oils rich in linoleic acid leads to mild
and rather variable effects on platelet function. Al-
though the bleeding time is not significantly pro-
longed, platelet aggregation to low doses of aggre-
gating agents may be inhibited, platelet retention on
glass beads reduced, and the time to platelet aggre-
gation in the filtragometer prolonged. Platelets also
appear to be less reactive as evidenced by lengthen-
ing of the heparin thrombin clotting time and a reduc-
tion in circulating platelet aggregates.

Mechanisms

The mechanisms underlying the changes in plate-
let function and proposed antithrombotic effects of
dietary polyunsaturated fatty acids are not com-
pletely understood. However, recent studies exam-
ing prostaglandin synthesis and other biochemical
pathways of platelets and vessel walls provide some
insight and future directions for study.

Table 5. Platelet/Vessel Function and Prostaglandin Production Following Dietary Enrichment
with Polyunsaturated Fatty Acids in Humans

<table>
<thead>
<tr>
<th>Dietary fatty acid</th>
<th>Bleeding time</th>
<th>Platelet aggregation</th>
<th>Platelet thromboxane B2</th>
<th>Vessel PGI2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linoleic acid (in vegetable oil)</td>
<td>Normal</td>
<td>Inhibited</td>
<td>Decreased</td>
<td>Decreased*</td>
</tr>
<tr>
<td>Dihomo-gamma-linolenic (as purified supplement)</td>
<td>Normal</td>
<td>Inhibited</td>
<td>Decreased*</td>
<td>Decreased</td>
</tr>
<tr>
<td>Linolenic acid (in linseed oil)</td>
<td>Normal</td>
<td>Unknown</td>
<td>Decreased*</td>
<td>Decreased</td>
</tr>
<tr>
<td>Eicosapentaenoic acid (in fish oil)</td>
<td>Prolonged</td>
<td>Inhibited</td>
<td>Decreased</td>
<td>Decreased*</td>
</tr>
</tbody>
</table>

*Data are suggestive but not definitive (see text and references).
In one experiment, rabbits were fed a diet containing 8% of their calories as corn oil for 3 weeks and the conversion of exogenous radiolabelled arachidonic acid to labelled thromboxane B2 in platelet-rich plasma was examined. At low substrate concentrations of arachidonic acid, platelet thromboxane production was significantly lowered in the corn-oil-fed animals. The decrease in thromboxane B2 production was associated with less platelet aggregation following stimulation by arachidonic acid or low doses of collagen.

In a second study from the same laboratory, rabbits were fed diets enriched or depleted in linoleic acid for 3 months. The linoleate-rich diet led to an increase in linoleic acid and a decrease in arachidonic acid in platelet phospholipids. This change was paralleled by a reduced production of thromboxane B2 from exogenous radiolabelled arachidonic acid but collagen-induced thromboxane production from endogenous arachidonic acid was not changed. Recently, a preliminary report indicated that arachidonic acid content of rat platelets was directly correlated with changes in thromboxane B2 production after stimulation of the platelets by collagen.

After human volunteers were fed relatively low amounts (25 ml/day) of a corn oil supplement, collagen-induced thromboxane B2 production significantly decreased (60 to 20 ng/ml) even though the arachidonic acid content of platelet phospholipids was unchanged. Therefore, after corn oil feeding, it would seem that platelet thromboxane production is decreased. This occurs when arachidonic acid is added to the prostaglandin pathway from exogenous sources or when arachidonate is released from endogenous pools of phospholipid after stimulation with low concentrations of collagen. It is currently unclear whether the decreased prostaglandin synthesis is a result of decreased precursor fatty acids, alterations in the activity of platelet enzyme systems such as phospholipase, cyclooxygenase, or thromboxane synthetase, or related to other more remote factors such as a possible effect on thromboxane production by dietary cholesterol.

Dietary fatty acids could influence platelet reactivity in ways other than acting directly on thromboxane synthesis. One study examined the half-life of thromboxane A2 in a buffer test system containing albumin. The addition of a mixture of free fatty acids extracted from human plasma to the test system led to accelerated destruction of thromboxane A2, presumably by interfering with the thromboxane stabilizing effects of albumin. Another report suggested that the feeding of linoleic acid resulted in increased levels of platelet cyclic AMP which in turn could lead to decreased platelet reactivity. Lastly, a recent study from Japan found that polyunsaturated fatty acids (especially linoleic and arachidonic acids) markedly inhibited platelet phosphodiesterase in vitro which could prolong the effectiveness of cyclic AMP.

Platelet reactivity could also be altered by variations in vascular prostaglandin synthesis (i.e., prostacyclin). Only a few studies are currently available to examine this important question, and unfortunately variations in methodology and experimental design have made a general interpretation of the results difficult. In 1979, the investigative group from Unilever in Holland examined the PG12-like activity generated from perfused segments of rat aorta taken from animals that had been fed a diet high in sunflower seed oil. Aortas from several animals fed this vegetable oil produced somewhat less PG12-like activity than did those from animals ingesting 35% of their calories as hydrogenated coconut oil, but the differences were not statistically significant. A study from Italy using pieces of aorta taken from butter or corn oil fed rabbits also documented decreased production of PG12-like activity in the animals fed the polyunsaturated fat diet. The increased production of PG12 in the saturated fat group correlated well with the increase in the arachidonic acid found in the phosphatidylcholinol fraction of the aortic phospholipids. In contrast to the two studies cited above, a second study by the Dutch workers showed a slightly increased aortic production of PG12 in linoleic acid fed rats; this change correlated with the increased C18:2 ω-6 in the diet.

A series of experiments have been carried out using human umbilical endothelial cells cultured in vitro. Enrichment of these cells with linoleic acid led to a significant decrease in spontaneous or stimulated PG12 production. This effect may be due to a competitive inhibition of endothelial cell cyclooxygenase by linoleic acid or to a linoleic acid-induced reduction in phospholipid arachidonic acid content.

In attempting to fit most of the experimental data about mechanisms into a coherent picture, it appears that feeding diets high in linoleic acid to animals or humans leads to increased concentrations of linoleic acid in the platelet membrane and decreased concentrations of arachidonic acid. Thromboxane production is decreased from platelets after they are stimulated with low doses of collagen. PG12 production from blood vessels may also decrease because of the reduced arachidonic acid content of the vascular phospholipids or the inhibition of endothelial cell cyclooxygenase.

Dihomo-gamma-linolenic Acid (C20:3 ω-6)

The effects of DHHLA on platelets and blood vessels have been of interest because this 20-carbon fatty acid is the precursor to the "1" series of prostaglandins such as PGE1 (figure 5; tables 4 and 5). The latter has an inhibitory effect on platelet function. Since naturally occurring fats and oils contain only minute amounts of DHHLA, purified DHHLA (usually as the ethyl or methyl ester) must be given to experimental subjects in order to increase its concentration in plasma or tissues. If radiolabelled DHHLA is given to
Platelet and Vascular Composition and Function

Linolenic Acid (C18:3 ω-3)

In most tissues (except, for example, platelets and red blood cells) or in vitro systems, linolenic acid may be desaturated and elongated to eicosapentaenoic acid.127 The feeding of oils rich in linolenic acid (e.g., linseed oil, which contains 53% C18:3 ω-3) to animals or humans might theoretically lead to the accumulation of eicosapentaenoic acid in tissues such as platelets or endothelial cells. One such study showed that feeding rats up to 4% of the calories as purified methyl linolenate led to a decrease in arachidonic acid (23% to 11%) and an increase in eicosapentaenoic acid from 0.1% to 3%–4% in liver and serum lipids.166 The production of thromboxane A2 from platelets, as measured by radioimmunoassay in serum, substantially declined (130 to 27 ng/ml) as the linolenate content of the diet was increased. In contrast, Dyerberg et al.135 fed a normal volunteer 45 ml/day of linseed oil and failed to detect any increase in eicosapentaenoic acid in serum lipids. Platelet or vascular concentrations of C20:5 ω-3 were not measured.

Of the few studies that have examined the effects of feeding C18:3 ω-3 upon platelet or endothelial cell function, Borchgrevink et al.169 found no changes in platelet adhesiveness or bleeding times in humans after dietary supplements of linseed oil. Recently, ten Hoor and coworkers160 fed a diet containing 25% C18:3 ω-3 to rats and noted that collagen-induced platelet malondialdehyde production and aortic vascular production of PGI2-like material were both lower than in a comparable group of rats fed a diet high in linoleic acid (table 5).160

Eicosapentaenoic Acid (C20:5 ω-3)

As alluded to earlier, the fascinating series of scientific visits to the West Coast of Greenland by Bang and Dyerberg68 generated some provocative questions about the relationships of an “Eskimo diet” to platelet and vascular function. Previous work had established that the Eskimo diet contained large amounts of ω-3 polyunsaturated fatty acids such as eicosapentaenoic acid and that these fatty acids were present in plasma and platelets of the Eskimos.71.72.74 A bruising or bleeding tendency had been described among the Greenland Eskimos and was also noted in the 1930s by a French explorer who visited northern Canadian Eskimos eating a similar diet.68.170 Pursuing these leads, the Danish investigators studied the bleeding times of their Eskimo subjects and found them to be prolonged in comparison to a control population living in Denmark.74 These and other observations have stimulated a growing interest in the effects of ω-3 fatty acids derived from marine oils on the composition and function of platelets and on cellular prostaglandin metabolism.

Platelet Lipid Composition

Changes in platelet phospholipid composition brought about by feeding dietary supplements of fish oils to animals or humans are now quite well documented. The concentrations of both linoleic acid and
arachidonic acid were decreased in the Eskimo platelet phospholipids. Similar observations have been noted in volunteers fed mackerel oil, cod liver oil, or salmon oil, and in animals given menhaden or cod liver oils (table 4).74,92,136,137,139 This reduction in linoleic acid could be a reflection of the low linoleate intake (most fish oils contain only 1% to 2% linoleic acid) or may relate to the displacement of linoleate by other fatty acids.124 The mechanism responsible for the reduction in the arachidonic acid content of platelets is not known, but it is possible that the decreased dietary linoleic acid may lead to reduced arachidonate levels in plasma and hence, platelet membrane phospholipids. Alternatively, arachidonic acid may be simply displaced by other fatty acids.

As might be expected, the consumption of ω-3 rich fish oils led to a marked incorporation of eicosapentaenoic acid and even longer chain polyunsaturated ω-3 fatty acids in the platelet membrane phospholipids.74,92,136-140,171 The reduction in arachidonic acid and increase in eicosapentaenoic acid lead to a marked increase in the C20:5/C20:4 ratio (e.g., 0.0043 to 0.3), which may interfere with cellular prostaglandin metabolism.135,139

Platelet and Vascular Function

Both platelet function and platelet-vessel wall interactions have been altered by diets enriched in ω-3 fatty acids (table 5). With one exception,149 bleeding times have invariably been prolonged by 30% to 40% in humans ingesting fish oils for several weeks or longer although a clinical bleeding tendency has not been observed.74,92,137,139 Brox, et al.140 failed to show a lengthening of the bleeding time, but this may have been due to the lesser quantity (25 ml/day) of fish oil that was administered.

Platelet aggregation in response to ADP has been impaired in the Eskimos and in the residents of a fishing village in Japan, as well as in human subjects fed salmon and cod liver oils.74,92,139,172 In other studies, aggregation induced by low doses of collagen was also found to be diminished.136,139,140 Platelet retention on glass beads (which may reflect platelet aggregation as well as platelet adhesion) was found to be significantly decreased in subjects receiving a diet containing salmon oil supplements.138 Lastly, the occlusion time of vascular prostheses inserted into the aorta of rats was prolonged when the animals were fed cod liver oil.138

Decreased platelet counts have been observed in subjects ingesting large amounts of ω-3 fatty acids. These include the early Eskimo observations as well as a recent study of the effects of salmon oil feeding in volunteers.74,139 In general, the reduction in platelet count, while statistically significant, remained within the normal range and was not low enough to affect the duration of the bleeding times (i.e., less than 100,000/mm³). In several individuals, however, there was a more marked fall in the platelet count.139 After the salmon oil feeding was discontinued, the platelet count rose rapidly to normal levels. In one of these subjects, a repeat study feeding salmon oil led to a reduction in platelet count a second time although platelet survival using ⁵¹ Chromium performed before and during fish oil feeding was unchanged (Goodnight, unpublished observations). At present, it is not clear whether the thrombocytopenia is related to the ω-3 fatty acids in the fish oil, other natural components, or to contaminants.

In sum, feeding ω-3 fatty-acid-rich fish oils to humans leads to a reproducible prolongation of the Ivy bleeding time, inhibition of platelet aggregation by ADP and collagen, as well as a decrease in platelet retention on glass beads. In some settings, there may also be a reduction in platelet count. The mechanisms for these functional alterations may be explained in part by changes in platelet and endothelial cell prostaglandin synthesis induced by alterations in dietary fatty acid composition.

Mechanisms of Fatty Acid Effects

At least three studies in which fish oils have been fed to humans have clearly shown that thromboxane B₂ production (the stable metabolite of thromboxane A₂) was decreased following stimulation of platelets by collagen or adenosine diphosphate (Goodnight, unpublished observations).136,140 In a rat study, no appreciable production of thromboxane A₃ from platelets was observed after feeding cod liver oil.138 Thus, it seems more likely that the reduced platelet reactivity found with fish oil feeding is a result of reduced thromboxane A₂ levels rather than an increased production of the inactive thromboxane A₃.

Several investigators have also examined the platelet production of malondialdehyde which, in the past, has been assumed to be a measure of thromboxane synthesis. Two studies in humans have shown normal or increased levels of platelet malondialdehyde production associated with decreased thromboxane B₂ production.139,140 In another study, rat platelets produced less malondialdehyde after fish oil compared to sunflower seed oil feeding.138 Recent work has indicated that thiobarbituric-acid-reactive substances (similar to malondialdehyde) may also be generated via the platelet lipoxygenase pathway during the formation of leukotrienes.173 Since this pathway remains active in spite of eicosapentaenoic-acid-mediated cyclooxygenase inhibition, the increased concentrations of malondialdehyde-like material during fish oil feeding may be derived from this source.

The production of PGI₂-like activity from vessel walls after fish oil feeding has also been examined.138 Incubated segments of rat aorta produced less platelet inhibitory activity (presumed to be PGI₂) in animals ingesting cod liver oil compared to sunflower seed oil. In addition, the production of prostaglandin 6-keto-F₁₂₀ (the stable, inactive breakdown product of PGI₂) was decreased in the fish-oil-
treated animals as was Δ17-6-keto-F_{1α} (the breakdown product of PGI_{2}). It seems clear that feeding of fish oils containing ω-3 fatty acids leads to a reduction in thromboxane A_{2} production by platelets, and there may also be a reduction in prostacyclin-like activity from the walls of blood vessels.

Biochemical explanations for these findings have been sought by a number of in vitro experiments using purified fatty acids and specific assays for prostaglandin metabolites. For example, it has been shown that eicosapentaenoic acid will not induce platelet aggregation when added to platelet-rich plasma and will inhibit the second wave of platelet aggregation that follows the addition of adenosine diphosphate.\(^7\)

One explanation for the reduced formation of thromboxane B_{2} from platelets enriched in eicosapentaenoic acid may involve competitive inhibition of cyclooxygenase by eicosapentaenoic acid which leads to reduced thromboxane A_{2} synthesis from arachidonic acid (figure 6).\(^17\),\(^17\) In addition, eicosapentaenoic acid has been shown to be a relatively poor substrate for cyclooxygenase, and consequently only very small amounts of thromboxane A_{3} (a weak platelet aggregating substance) are produced.\(^17\),\(^17\) It is also possible that prostaglandins of the D series (e.g., PGD_{3}) may be formed from eicosapentaenoic acid and that these may also inhibit platelet aggregation.\(^17\)

Several other hypotheses for the decreased platelet responsiveness that follows ω-3 fatty acid ingestion are possible. These include the blockade of thromboxane receptors on platelets\(^17\) by eicosapentaenoic acid, replacement of arachidonic acid by eicosapentaenoic acid in platelet phospholipids, with a concomitant reduction in the amount of arachidonate available for prostaglandin synthesis, or an inhibitory effect of eicosapentaenoic acid on phospholipase A_{2} leading to a reduced release of arachidonic acid from platelet phospholipids.

The effects of eicosapentaenoic acid on prostaglandin production by endothelial cells has received less attention. Preliminary evidence indicates that both PGI_{2} and PGI_{3} are decreased, although some platelet inhibitory activity may still be present.\(^17\) If it should be conclusively shown that vascular PGI_{2} as well as platelet thromboxane production is diminished, then further studies on the magnitude of these decreases will be required. Since the bleeding time is prolonged in humans fed fish oil, it may be that there is a relatively greater decrease in thromboxane generation than in prostacyclin production.

In conclusion, ingestion of dietary fish oils containing the ω-3 fatty acid eicosapentaenoic acid may have rather profound effects on platelet or vessel composition and function. Cellular phospholipid concentrations of arachidonic acid are decreased, bleeding times are prolonged, and various in vitro tests of platelet function are inhibited. One explanation for the platelet inhibition may be the significant reduction in platelet thromboxane synthesis, which has been repeatedly demonstrated. More data are needed to verify these findings.

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**Figure 6.** Effects of eicosapentaenoic acid (EPA) on platelet prostaglandin synthesis. Possible sites of action upon the conversion of arachidonic acid to thromboxane A_{2}.
needed on the vascular production of prostacyclin and particularly on the balance between thromboxane and PGI₂, under various experimental or clinical conditions in vivo.

**Possible Risks from Increased Amounts of Polyunsaturated Fat in the Diet**

While the evidence is reasonably good that a reduction of risk factors for atherosclerotic disease might occur if the dietary intake of polyunsaturated fats was increased, we must consider also the potential risks that could be associated with this dietary alteration. The discussion that follows will examine the possible untoward effects of both the ω-6 and ω-3 polyunsaturated fatty acids.

**Omega-6 Fatty Acids: Safety and Side Effects**

There is no historical precedent that attests to the safety of a diet high in linoleic acid. For most of humankind, prior to the advent of 20th century technology, the total fat content of the diet has ranged from 8% to 12% of the total calories and linoleic acid constituted from 4% to 8% of the total calories, which has been the typical intake of most Americans. However, this finding was not confirmed in another study. An indication that polyunsaturated fats was increased, we must consider also the potential risks that could be associated with this dietary alteration. The possible untoward effects of both the ω-6 and ω-3 polyunsaturated fatty acids.

**Omega-3 Fatty Acids: Safety and Side Effects**

There are several aspects of dietary fish oils that may be of possible concern. Some fish oils contain high levels (about 10%) of cetoleic acid (C22:1 ω-11), which is an isomer of erucic acid (C22:1 ω-9). Erucic acid is found in rapeseed oil and other Brassica-derived oils, and, when fed in high levels, is known to cause transient myocardial lipidosis and fibrosis in several species of experimental animals (see FAO review). However, erucic acid (not to mention cetoleic acid) has never been shown to have detrimental effects in humans. Eskimo populations have consumed diets high in cetoleic acid for centuries, and no myocardial damage has been reported. In human subjects fed fish oils experimentally, this particular fatty acid has not even been detected in the plasma. This would suggest that in humans cetoleic acid is either very poorly absorbed or is rapidly metabolized. Thus, there is little evidence to suggest that the cetoleic acid found in fish oils has any detrimental effects in humans.

Another possible side effect of feeding high levels of fish oils has been reported in pigs fed mackerel oil or whale oil. These animals developed a disorder known as "yellow fat disease," which has been associated with vitamin E deficiency. No symptoms other than discoloration of the adipose tissue were noted, and growth was normal. This condition has not been reported in Eskimos nor in any other species of experimental animals. Because of the highly unsaturated nature of the ω-3 fatty acids, vitamin E requirements may indeed be increased during the consumption of fish oils as they are with polyunsaturated vegetable oils. This potential problem could be easily prevented by providing adequate amounts of vitamin E in the diet, as is commonly done in the experimental feeding of fish oils in humans.

Two effects of fish oil feeding upon platelet function may be of concern: the increased bleeding times...
and thrombocytopenia. Although in our studies the mean bleeding time increased from 6 minutes (control) to 10 minutes during the salmon oil diet, some patients with subclinical platelet defects had more dramatic prolongation. For example, one normal volunteer who had a prolonged Ivy bleeding time during the control diet (13 minutes), had a bleeding time of over 30 minutes during the salmon oil phase (Goodnight, unpublished observations). However, no clinical bleeding of any significance has been observed in any of these subjects.

A mild thrombocytopenia has been reported in most fish-oil feeding studies in humans. This has not been a cause for concern except in two subjects who transiently developed platelet counts below 100,000 (83,000 and 87,000) after 3 weeks of a diet containing 40% of the calories as salmon oil. A few days after the salmon oil diet was discontinued, the platelet counts returned to normal levels; no bleeding tendencies occurred. Such thrombocytopenia has not been observed in subjects receiving lesser amounts of salmon oil.

In summary, the expected benefits of modest increases in dietary polyunsaturated fat would far outweigh the possible risks outlined above. While linoleic acid intakes of up to 10% of the total calories would not be considered dangerous or even deleterious, only slight effects upon plasma lipid levels, platelet functions, and bleeding times without incurring significant risk. In addition, past recommendations to limit the intake of fish high in fat content may now be inappropriate. The consumption of these foods might well be encouraged. Certainly little harm would be anticipated, and the likelihood of benefit would be great. Large amounts of fish are currently consumed by some coastal populations.

Clearly, use of fish oil supplements to substantially increase the intake of ω-3 fatty acids (particularly eicosapentaenoic acid) would not be indicated at the present time except under experimental conditions. The uncontrolled consumption of large amounts (15–50 ml/day) of fish liver oils (such as cod liver oil) should certainly be discouraged because of the high levels of vitamins A and D they contain. For example, even a relatively small amount of cod liver oil (20 ml) would provide about four times the Recommended Dietary Allowance (RDA) for each vitamin. Toxic symptoms have been reported with as little as five times the RDA of vitamin D. The other hand, the daily consumption of a half a pound of salmon would provide approximately 30 g of fish oil (4 to 6 g of ω-3 fatty acids) and very small amounts of the fat soluble vitamins.

Summary

The substitution of polyunsaturated fat in the diet for saturated fat has a definite hypolipidemic effect which has been demonstrated in a variety of experiments in both animals and humans. Both the ω-6 and ω-3 families of fatty acids (as present in vegetable oil and in fish oil) are hypocholesterolemic and sharply reduce the plasma concentrations of LDL. However, only the ω-3 fatty acids from fish oils have a pronounced hypotriglyceridemic effect in both normal and hypertriglyceridemic subjects. In some subjects, ω-6 fatty acids may have a mild hypotriglyceridemic action, whereas in others no demonstrable effect upon plasma triglyceride concentrations can be shown. In patients with severe hypertriglyceridemia (Type V hyperlipidemia), dietary ω-6 fatty acids may elevate the concentrations of plasma triglyceride (both chylomicrons and VLDL) and cause a recurrence of symptoms in patients with hepatosplenomegaly. On the other hand, in all trials described to date, ω-3 fatty acids in the diet from salmon oil and other fish oils have had a profound hypotriglyceridemic effect in both normal subjects and in patients with the Types V and II-B phenotypes. Whether linoleic acid would have similar hypolipidemic effects has not been adequately tested.

The hypolipidemic effect of dietary polyunsaturated fatty acids presumably operates through a change in the fatty acid composition of cell membranes and lipoproteins, particularly in the phospholipid and cholesteryl ester moieties. This membrane change is frequently associated with an increased loss of cholesterol and bile acids from the body in the form of increased fecal steroid excretion. Coincident with, or perhaps even preceding, the increased fecal steroid excretion, the rate of removal of plasma LDL increases (increased fractional catabolic rate). This is matched by a decrease in LDL synthesis in some instances.

The profound hypotriglyceridemic action of ω-3 fatty acids from fish oils remains as yet unexplained. Perhaps the synthesis of VLDL and LDL may be decreased or their clearances enhanced. A not unreasonable hypothesis is that the flux of free fatty acids from adipose tissue to liver in fish oil-fed humans may be reduced, perhaps mediated through the prostaglandin system. Omega-3 fatty acids certainly have the capacity to modify prostaglandin synthesis. Another possibility would be reduced synthesis of triglyceride in the liver.

Polyunsaturated fat has an additional antithrombotic action in the body when it is substituted for saturated fat in the diet. The antithrombotic effects may result from either the simple reduction of more thrombogenic saturated fat by substitution with polyunsaturated fat in the diet, or, alternatively, from an independent modification of platelet or vessel wall membrane function via perturbations of prostaglandin metabolism. While experimental feeding of both ω-6 and ω-3 fatty acids leads to clear inhibition of platelet aggregation in vitro, only fish oil feeding rela-
ably leads to a significant prolongation of the Ivy bleeding time in humans. These effects may reflect the changes in the fatty acids composition that occur with polyunsaturated fat feeding (vegetable or fish oils). High levels of either linoleic acid or fish oil ω-3 fatty acids appear to reduce the levels of arachidonic acids. High levels of either linoleic acid or fish oil ω-3 fatty acids prolong bleeding times, the balance between these two compounds appears to be more favorable with fish oils than with vegetable oils. There remains a great need for studies to characterize the in vivo production of platelet thromboxane and vessel wall prostanoyl cyclic during fish oil and vegetable oil feeding.

Recommended dietary changes to fit the experimental evidence as presented in this review could be stated as follows: saturated fat in the diet, because of its thrombogenic and hyperlipidemic effects, should certainly be reduced from the current American intake of well over 20% of the total calories to less than 8% of the total calories. If dietary linoleic acid is at the level of 4% to 8% of the total calories (the present intake in the U.S. diet), there is little indication that increasing it further would result in significant health benefits. On the other hand, there are indications that benefit would be obtained and no harm produced by the ingestion of moderate amounts (4 to 8 g/day) of ω-3 fatty acids derived from fish oils. The effects of dietary polyunsaturated fatty acids of both the ω-6 and the ω-3 families will certainly continue to be the object of intensive research. The antithrombotic and hypolipidemic properties of fish oils need to be further characterized and translated into specific nutritional interventions, which may be helpful in the prevention and treatment of atherosclerotic diseases.

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