Effect of Fish Oil on Atherogenesis in Watanabe Heritable Hyperlipidemic Rabbit

Alice H. Lichtenstein and Aram V. Chobanian

The effect of dietary supplementation with fish oil was investigated in the Watanabe heritable hyperlipidemic (WHHL) rabbit. Rabbits were fed Maxepa (1 g/kg body weight) from weaning for a 6-month period and were compared to controls. Fish oil supplements resulted in significant decreases in plasma triglyceride and cholesterol at 4 weeks after the start of the study, and these differences persisted over the 6-month period. No differences in the distribution of cholesteryl or triglyceride among lipoprotein particles were found, nor were there differences in low density lipoprotein particle size. The decreases in plasma cholesterol and triglyceride were accompanied by significant increases in the percent of eicosapentaenoic and docosahexaenoic acids in both plasma and platelets. Fish oil supplementation resulted in a decrease in platelet count and response to the aggregating agents adenosine diphosphate, arachidonic acid, and collagen. Systolic blood pressure was significantly lower in the rabbits fed fish oil. At the end of the study period, aortic free and esterified cholesterol and intimal surface area covered with plaque were determined in the arch and in the descending and abdominal aorta. Significantly less cholesterol was found in the descending and abdominal aorta. These differences were mirrored by decreased activities of acid lipase and N-acetyl-β-glucosaminidase. In contrast, no differences in the intimal surface area covered with plaque were found. In conclusion, dietary fish oil resulted in a decrease in aortic lipid deposition in the WHHL rabbit, which may have been due to decreases in plasma triglyceride and cholesterol, platelet count and aggregability, and systolic blood pressure.

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rabbits and did not predict the changes seen in the vessel wall chemically or biochemically. This decrease may have been related to decreases in plasma lipids, blood pressure, and platelet aggregability.

Methods

Watanabe Heritable Hyperlipidemic Rabbits

Twenty WHHL rabbits (2 months old) weighing 1.71 ± 0.21 kg were obtained from the breeding colony maintained at the Boston University School of Medicine. This colony was established from homozygous WHHL rabbits kindly provided by Russell Ross of the University of Washington School of Medicine and Alan Fogelman of the University of California School of Medicine in Los Angeles, whose colonies originated from Dr. Yoshio Watanabe’s animals. There were five male and five female rabbits per group. These rabbits were derived from four litters, and each litter was divided equally between the control and fish oil-fed groups with balanced sex distribution. The rabbits used were at least a third-generation product of the original rabbits. The animals were housed individually and were given free access to water. Fish oil (1 g/kg body weight/day; Maxepa, generously provided by R.P. Scherer Corp., Troy, MI) was mixed with a pelleted diet (45 g/kg body weight/day, Agway ProLab High Fiber Rabbit Chow, Syracuse, NY). Analysis of the oil indicated that the eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) contents were 26% and 21%, respectively, by weight, and there was, respectively, 2.2 mg of cholesterol and 1.4 mg of vitamin E per gram of oil. Control rabbits were treated identically except that the fish oil was omitted from the diet. Systolic blood pressure was monitored at monthly intervals by tail cuff plethysmography with a photoelectric cell detector developed in our laboratory.18 Pressures were recorded with an IITC Model 59 preamplifier and a Narcotrace 40 physiograph. Blood pressure recordings could not be made in two control animals due to the loss of tails soon after birth. The average blood pressure for each group for the final 3 months of the study was used for the statistical analyses.

Plasma Lipids

The rabbits were fasted overnight before blood sampling. Blood (approximately 2 ml) was removed from the central ear artery at monthly intervals. Total serum cholesterol, HDL cholesterol, and triglyceride concentrations were assayed with enzymatic techniques (Sigma Diagnostics, St. Louis, MO). Twice the amount of the recommended HDL precipitating reagent was used to ensure complete precipitation of the apolipoprotein (apo) B-containing lipoproteins. During the third month of the study, approximately 10 ml of blood was taken for plasma and platelet fatty acid analysis.

Fatty Acid Analysis

Fatty acid methyl esters (FAME) were prepared from plasma, platelets, and homogenates of the ascending aorta and arch according to the method of LePage and Roy.19 The FAME were analyzed on a Hewlett-Packard 5890 gas-liquid chromatograph fitted with a 105 m fused silica capillary column (Quadrex Corp., New Haven, CT) with liquid phase RTX 2330 (Restek Corp., Bellefonte, PA) and a flame ionization detector. Peak identification was validated by chromatography of mixtures of authenticated FAME.

Lipoprotein Analysis

Plasma lipoproteins were separated on 1% agarose gel by using a Corning eletrophoresis system and were stained with fat red 7B to monitor lipid distribution. During the fourth month of the study, plasma from six randomly selected rabbits (three control, three fish oil-fed) was fractionated on a discontinuous density gradient according to a modification of the method described by Fisher et al.20 Briefly, a 3.0 ml sample of plasma was adjusted to a density of 1.21 g/ml with potassium bromide and was overlayed sequentially with potassium bromide solutions of density=1.15 g/ml (1 ml), density=1.063 g/ml (3 ml), density=1.019 g/ml (3 ml), and normal saline (1 ml). The samples were centrifuged in a Beckman Sw41 rotor at 35 000 rpm for 22 hours at 4°C. The contents of the ultracentrifuge tube were fractionated into 18 aliquots and were analyzed for cholesterol and triglycerides as described. The LDL subtraction distribution was determined by nondenaturing polyacrylamide-agarose gradient gel electrophoresis21 on plasma obtained just before sacrifice. Aliquots of whole plasma that had been stored at −70°C were run on 2% to 16% gels (Pharmacia, Piscataway, NJ) and were stained with Sudan black B. The migration patterns of the LDL were compared to those of human pooled plasma.

Platelet Aggregation

Platelet aggregation was assessed among 10 randomly selected rabbits from those not used for lipoprotein analysis (five control, five fish oil-fed) during the fourth month of the study by using a Model PAP-4 Platelet Aggregation Profiler (Bio/Data Cap, Hatboro, PA) fitted with a microvolume adaptor. Platelet-rich plasma and platelet-poor plasma were prepared from blood containing 0.011 M sodium citrate by centrifuging at 160 g for 10 minutes and 1000 g for 6 minutes, respectively. A total of 300 000 platelets were used per assay. The samples were analyzed within 3 hours of preparation. The aggregating agents evaluated were adenosine diphosphate (ADP) (50 mM, Chrono-Log, Havertown, PA); arachidonic acid (1.2 mM, Bio/Data); and collagen (20 mg/ml, Chrono-Log, Hatboro, PA). Percent aggregation at 1 minute and at maximum aggregation was analyzed. Platelet count and volume were determined by the clinical laboratory at University Hospital (Boston, MA).

Tissue Preparation

Rabbits were sacrificed after 6 months of fish oil supplementation with an overdose of intravenously administered sodium pentobarbital (100 mg/kg). The entire aorta from the aortic valve to the bifurcation was removed quickly and was placed in normal saline at 4°C. The heart, adrenals, kidney, and liver were removed for weight determinations. The aorta was opened along the mid-dorsal line to expose the intimal surface, and a
photograph was made. The aorta was divided into the ascending aorta and arch, the descending aorta, and the abdominal aorta by cutting 0.5 cm proximal to the first pair of intercostal arteries and 0.3 cm proximal to the celiac artery. The intimal-medial layer was dissected free of adventitia and was weighed and homogenized with a motor-driven glass-glass homogenizer at 0 to 2°C in 10 volumes of 0.25 M sucrose, 10 mM HEPES, pH 7.4. Aliquots were taken for protein, lipid, enzyme, and fatty acid determinations.

Chemical Analysis
The protein contents of the samples were determined by the method of Lowry et al. Lipids were extracted from aliquots of tissue homogenate according to the procedure of Folch et al. Free cholesterol (FC) and esterified cholesterol (CE) were separated by thin-layer chromatography as previously described, and the cholesterol content was determined according to the method of Rudel and Morris. The recovery of the FC and CE averaged 94% and 95%, respectively.

Enzyme Assays
Supernatants obtained by centrifuging aliquots of the descending aortic intima-media homogenate at 10,000 rpm for 15 minutes at 4°C were used to determine enzyme activity. Lysosomal enzyme activity was assessed by monitoring the hydrolysis of methylumbelliferyl-N-acetyl-β-glucosaminide (NAGA) and acid lipase. NAGA and acid lipase activity were estimated by monitoring the hydrolysis of methylumbelliferyl-N-acetyl-β-glucosaminide and methylumbelliferyl palmitate, respectively.

Morphologic Determinations
Intimal surface area covered by plaque was quantitated by using the Optimas image processing and analysis system (BioScan, Edmonds, WA).

Statistical analyses were performed by using analysis of variance and Student's t tests for independent and paired samples. Data are reported as the means ± standard deviations.

Results
The fish oil supplement appeared to be well tolerated by the WHHL rabbits. The rate of weight gains of the control and fish oil-fed rabbits were comparable. Final body weights did not differ significantly (2.88 ± 0.42 kg and 2.99 ± 0.28 kg for control and fish oil-fed rabbits, respectively). Plasma fatty acid patterns reflected dietary intake when assessed during the fourth month of the study (Table 1). Although the levels of all the major fatty acids evaluated differed significantly between the two groups of rabbits, the most striking alterations were the increases in circulating plasma levels of EPA and DHA in the fish oil-fed rabbits as compared to controls. EPA and DHA as well were noted in the fish oil-fed rabbits as compared to controls.

<table>
<thead>
<tr>
<th>Fatty acid</th>
<th>Control</th>
<th>Fish oil-fed</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:0</td>
<td>0.3±0.1</td>
<td>0.5±0.1†</td>
</tr>
<tr>
<td>16:0</td>
<td>17.2±0.9</td>
<td>19.2±0.3‡</td>
</tr>
<tr>
<td>18:0</td>
<td>11.0±0.4</td>
<td>9.2±0.6†</td>
</tr>
<tr>
<td>18:1 (w9)</td>
<td>24.3±2.2</td>
<td>11.2±0.6‡</td>
</tr>
<tr>
<td>18:2 (w6)</td>
<td>36.2±2.8</td>
<td>25.3±1.7†</td>
</tr>
<tr>
<td>18:3 (w3)</td>
<td>3.2±0.4</td>
<td>2.5±0.2‡</td>
</tr>
<tr>
<td>20:4 (w6)</td>
<td>2.2±0.4</td>
<td>2.5±0.1</td>
</tr>
<tr>
<td>20:5 (w3)</td>
<td>0.2±0.1</td>
<td>13.0±1.3‡</td>
</tr>
<tr>
<td>22:6 (w3)</td>
<td>2.5±1.8</td>
<td>11.1±1.2‡</td>
</tr>
</tbody>
</table>

Values are given as percents and are the means ± standard deviations.

There were 10 rabbits in both the control and the fish oil-fed groups. A significant difference between control and fish oil-fed animals (p<0.01, †p<0.001).

Plasma lipids were also affected by fish oil feeding in the WHHL rabbit. After 4 weeks on the fish oil-supplemented diet, plasma cholesterol levels decreased by 27% (p<0.01; Figure 1A). This reduction was maintained throughout the study period so that after 6 months on the diet, the average plasma cholesterol levels were 78% of the initial level. Plasma cholesterol levels in the control WHHL rabbits did not vary significantly throughout the period and differed significantly from the fish oil-fed rabbits at all experimental time-points except 2 months. Plasma triglyceride levels in the fish oil-fed rabbits declined by 58% after 4 weeks on the diet (p<0.01). This reduction was maintained throughout the study period (Figure 1B). In contrast, plasma triglyceride levels in the control rabbits were relatively constant, with no significant changes during the 6-month period. HDL cholesterol levels averaged 7.7±2.6 mg/dl and 6.4±2.5 mg/dl, respectively, in control and fish oil-fed WHHL rabbits. There were no statistically significant changes in HDL cholesterol during the study period. When the data on plasma lipids were analyzed on the basis of sex, there were no significant differences between male and female rabbits within groups.

When plasma was electrophoresed on nondenaturing polyacrylamide-agarose gradient gels, no differences in LDL size were seen between the two groups of rabbits. It should be noted that LDL size or type in the WHHL rabbits corresponds to a position between LDL types 1 and 2. Similarly, no differences in the pattern of lipid staining on agarose gels were seen, either between groups of rabbits or over the time course of the study. Only one band was seen corresponding to LDL.

Depicted in Figure 2 are representative discontinuous density gradient distributions of plasma cholesterol and triglyceride derived from control (Figure 2A) and fish oil-fed (Figure 2B) WHHL rabbits. Virtually all of the cholesterol and triglyceride in both groups of rabbits was present in a band corresponding to the LDL.

At the beginning of the study, systolic blood pressure was about 100 mm Hg in both groups of rabbits (Table 2).
With advancing age, as we have previously reported, blood pressure rose in the WHHL rabbit. However, fish oil-feeding attenuated this trend so that during the latter half of the study, the supplemented group had a significantly lower systolic blood pressure than the control group (p < 0.05).

The effects of dietary fish oil supplements on platelet count, volume, fatty acid composition, and aggregability were also assessed. Fish oil feeding resulted in a 24% decrease in platelet count (p < 0.001) over the 6-month period (Table 3). There was also a significant decrease in platelet volume in the fish oil-fed WHHL rabbits (p < 0.01). Platelet fatty acid patterns reflected dietary intake (Table 4). There was a significant increase in platelet omega-3 fatty acid content in the fish oil-fed rabbits (12.3% EPA and 5.5% DHA) when compared to control rabbits (<0.1% EPA and 3.3% DHA). There was a concomitant decrease in the relative proportions of oleic, linoleic, and arachidonic acid within platelets in the fish oil-supplemented group.

The effects of ADP, arachidonic acid, and collagen were investigated with respect to their abilities to induce platelet aggregation. Shown in Figure 3 are data on maximum aggregation in response to these three platelet aggregating agents. In all cases, there was a decreased tendency of platelets from WHHL rabbits fed fish oil to aggregate, differences that reached statistical significance for ADP and collagen. Similar results were observed when aggregation was assessed at the 1-minute time-point. No evidence of spontaneous aggregation in either group was observed over a 5-minute period.

After 6 months of fish oil supplementation, the rabbits were sacrificed. There were no significant differences in liver, heart, adrenal, or kidney weights between the two
Table 4. Effect of Dietary Fish Oil Supplements on Platelet Fatty Acid Patterns in WHHL Rabbit

<table>
<thead>
<tr>
<th>Fatty acid</th>
<th>Control</th>
<th>Fish oil-fed</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:0</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>16:0</td>
<td>17.2±1.2</td>
<td>17.6±1.7</td>
</tr>
<tr>
<td>18:0</td>
<td>27.6±2.7</td>
<td>26.8±2.7</td>
</tr>
<tr>
<td>18:1 (w9)</td>
<td>10.4±3.2</td>
<td>7.5±1.1*</td>
</tr>
<tr>
<td>18:2 (w6)</td>
<td>29.0±1.3</td>
<td>20.0±1.8t</td>
</tr>
<tr>
<td>18:3 (w3)</td>
<td>&lt;0.1</td>
<td>&lt;0.1</td>
</tr>
<tr>
<td>20:4 (w6)</td>
<td>9.2±1.3</td>
<td>5.8±0.8t</td>
</tr>
<tr>
<td>20:5 (w3)</td>
<td>&lt;0.1</td>
<td>12.3±1.0t</td>
</tr>
<tr>
<td>22:6 (w3)</td>
<td>3.3±3.4</td>
<td>5.5±0.8*</td>
</tr>
</tbody>
</table>

Values are given in percents and are the means±standard deviations. There were 10 rabbits in both the control and fish oil-fed groups.

A significant difference between control and fish oil-fed animals (**p<0.05, ***p<0.001).

Figure 3. Effect of dietary fish oil feeding on percent maximum platelet aggregation in response to adenosine diphosphate (ADP) (50 mM), arachidonic acid (1.2 mM), and collagen (20 mg/ml) in the Watanabe heritable hyperlipidemic rabbit. Asterisks indicate a significant difference between the two groups of rabbits (**p<0.05).

Table 5. Characteristics of WHHL Rabbits Fed Fish Oil-supplemented Diet for 6 Months

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Control</th>
<th>Fish oil-fed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>1.27±0.27</td>
<td>1.39±0.31</td>
</tr>
<tr>
<td>Intima/medial weight</td>
<td>0.19±0.07</td>
<td>0.23±0.07</td>
</tr>
<tr>
<td>Arch</td>
<td>0.33±0.11</td>
<td>0.36±0.13</td>
</tr>
<tr>
<td>Descending</td>
<td>0.10±0.03</td>
<td>0.11±0.04</td>
</tr>
<tr>
<td>Abdominal</td>
<td>67.0±14.6</td>
<td>78.3±11.1</td>
</tr>
<tr>
<td>Liver</td>
<td>6.25±1.26</td>
<td>6.0±0.72</td>
</tr>
<tr>
<td>Heart</td>
<td>0.25±0.04</td>
<td>0.26±0.07</td>
</tr>
<tr>
<td>Adrenal</td>
<td>7.31±0.44</td>
<td>7.65±0.74</td>
</tr>
</tbody>
</table>

Values are given as grams and are the means±standard deviations. There were 10 rabbits in both the control and the fish oil-fed groups.

Table 6. Effect of Fish Oil Supplements on Percent of Intimal Surface Area Covered by Plaque in Aortic Segments of WHHL Rabbit

<table>
<thead>
<tr>
<th>Location</th>
<th>Control</th>
<th>Fish oil-fed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch</td>
<td>55.6±15.7</td>
<td>53.2±9.1</td>
</tr>
<tr>
<td>Descending</td>
<td>17.0±16.1</td>
<td>9.9±14.3</td>
</tr>
<tr>
<td>Abdominal</td>
<td>14.4±9.3</td>
<td>10.9±9.2</td>
</tr>
</tbody>
</table>

Values are given in percents and are the means±standard deviations. There were 10 rabbits in both the control and the fish oil-fed groups.

Table 7. Effect of Fish Oil Supplements on Free and Esterified Cholesterol Content in Aortic Segments of WHHL Rabbit

<table>
<thead>
<tr>
<th>Location</th>
<th>Lipid</th>
<th>Control</th>
<th>Fish oil-fed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arch</td>
<td>FC</td>
<td>8.5±3.1</td>
<td>7.1±2.9</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>12.2±4.1</td>
<td>13.5±6.3</td>
</tr>
<tr>
<td>Descending</td>
<td>FC</td>
<td>4.1±1.6</td>
<td>2.2±1.4†</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>5.8±3.2</td>
<td>3.1±2.8*</td>
</tr>
<tr>
<td>Abdominal</td>
<td>FC</td>
<td>7.7±4.4</td>
<td>4.3±2.5*</td>
</tr>
<tr>
<td></td>
<td>CE</td>
<td>6.4±3.9</td>
<td>4.1±4.6</td>
</tr>
</tbody>
</table>

Values are given as mg/g wet weight and are the means±standard deviations. There were 10 rabbits in both the control and the fish oil-fed groups.

A significant difference between control and fish oil-fed animals (**p<0.05, ***p<0.01). FC=free cholesterol, CE=cholesteryl ester.

The chemical composition of the aortic segments with respect to cholesterol is shown in Table 7. There were no significant differences in the FC or CE content of the ascending aorta and arch. However, in contrast to the morphologic data, dietary omega-3 fatty acid supplementation resulted in significantly less deposition of FC and CE in the descending region of the aorta. Additionally, both the FC and EC content of the abdominal aorta was decreased in the fish oil-fed animals, although only the concentration for FC reached statistical significance.

Data on the fatty acid composition of the ascending aorta and arch from control and fish oil-fed WHHL rabbits...
Table 8. Effect of Dietary Fish Oil Supplements on Aortic Wall Fatty Acid Patterns in WHHL Rabbit

<table>
<thead>
<tr>
<th>Fatty acid</th>
<th>Control</th>
<th>Fish oil-fed</th>
</tr>
</thead>
<tbody>
<tr>
<td>14:0</td>
<td>1.1±0.5</td>
<td>1.4±0.5</td>
</tr>
<tr>
<td>16:0</td>
<td>19.7±3.6</td>
<td>20.1±1.6</td>
</tr>
<tr>
<td>18:0</td>
<td>7.6±0.6</td>
<td>6.8±0.6*</td>
</tr>
<tr>
<td>18:1 (w9)</td>
<td>21.8±2.5</td>
<td>17.9±1.2</td>
</tr>
<tr>
<td>18:2 (w6)</td>
<td>21.9±3.9</td>
<td>17.0±1.6</td>
</tr>
<tr>
<td>18:3 (w3)</td>
<td>2.4±1.1</td>
<td>2.1±1.2</td>
</tr>
<tr>
<td>20:4 (w6)</td>
<td>6.5±1.4</td>
<td>5.2±1.1*</td>
</tr>
<tr>
<td>20:5 (w3)</td>
<td>0.8±0.2</td>
<td>0.7±1.4†</td>
</tr>
<tr>
<td>22:6 (w3)</td>
<td>0.4±0.1</td>
<td>0.7±1.3</td>
</tr>
</tbody>
</table>

The values are given in percent and are the means±standard deviations.

A significant difference between control and fish oil-fed groups was observed.

Table 9. Effects of Fish Oil Supplements on Descending Aortic Lysosomal Enzyme Activity in WHHL Rabbit

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Acid Lipase</th>
<th>NAGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>5.89±2.14</td>
<td>132±72</td>
</tr>
<tr>
<td>Fish oil-fed</td>
<td>4.07±1.03*</td>
<td>84±39</td>
</tr>
</tbody>
</table>

Values are given as nmol umbelliferone/min/mg and are the means±standard deviations.

A significant difference between control and fish oil-fed groups was observed.

**Discussion**

These studies suggest that daily supplements of fish oil retarded the development of aortic fatty lesions in the WHHL rabbit. This conclusion was based upon the significant decreases in concentrations of FC and CE in both the descending and abdominal regions of the aorta in animals given the fish oil supplement. Decreased activity of acid lipase and NAGA was also observed. In contrast to the chemical and enzymatic data, the percent of intimal surface area covered by plaques was not significantly different between the control and fish oil-fed rabbits. However, there tended to be less surface area involvement in those regions of the aorta which had lower concentrations of FC and CE, indicating that measures of surface area covered with plaque alone may not be as sensitive an assessment of degree of atherosclerosis as chemical or enzymatic measures.

Rich et al. has recently reported that supplementing the diet of WHHL rabbits for 1 year with fish oil had no effect on plasma lipids or percent surface area covered by atherosclerotic lesions. Clubb et al. subsequently reported that 6 months of fish oil feeding resulted in a significant decrease in plasma lipids (which was somewhat gender-specific), whereas the extent of surface area involvement of the lesions was unaffected. The additional variables assessed in the current study, lipid deposition in the aorta and activity of two aortic lysosomal enzymes, were not assessed in either of the two previous studies.

The lack of effect of fish oil supplements on altering the rate of lesion progression reported by Rich and coworkers may have been related to the absence of changes in plasma lipids also reported in their rabbits. The amounts of EPA fed to the WHHL rabbits was about half that fed in the other two studies. This was reflected in only a modest increase in plasma EPA (3.4%). The data of Clubb et al. are more comparable to that of our own. The duration of the two studies was the same (6 months) as was the amount of EPA fed to the rabbits (about 200mg/kg/day) and the route of administration (mixed with chow). Both sets of WHHL rabbits showed a significant decrease in plasma cholesterol and triglyceride (restricted to females in the study of Clubb et al.), enrichment of platelet EPA, and decreased response of platelets to aggregating agents. The results of the two studies diverged with respect to the effect of fish oil on atherogenesis. On the basis of morphological data, Clubb et al. reported no effect of fish oil feeding on atherogenesis. On the basis of morphologic data, we likewise did not observe statistically significant differences in intimal surface area involvement; however, on the basis of chemical composition and enzymatic data of the vessel wall, we observed significantly less atherosclerosis in the aortas of the fish oil-fed rabbits. It is difficult to directly compare the data generated by the two methods used to assess the degree of lesion development. Quantitating the cholesterol content of an aorta provides a measure of excess material deposited in the vessel wall that might potentially narrow the vessel and decrease blood flow or interfere with the normal elasticity of the vessel. Data on lysosomal enzyme activity of the vessel has been shown to corroborate the chemical data. Surface area measures provide data on the proportion of the vessel that is lesioned, hence the potentially thrombogenic or occlusive area of the vessel. Combining surface area data with measures of lesion thickness enhances the predictive value of the data, although interpretation is difficult due to marked heterogeneity within a lesion and the relatively few cross-sectional areas actually measured.
In the current study, lipid deposition was unaffected in the aortic arch when assessed after 6 months of fish oil supplementation. In the rabbit, atherosclerotic lesion formation usually progresses from the ascending aorta and arch and areas surrounding the bifurcations to the descending and abdominal aorta.29 Hence, the ascending aorta and arch are the first and most heavily affected areas under any circumstance and become lesioned when the animals are relatively young. Had the rate of lipid deposition in the ascending aorta and arch been decreased by fish oil feeding, as suggested by the findings in the descending and abdominal aorta, shorter term studies would have been necessary to yield comparable data.

A number of other animal models of atherosclerosis have been used to investigate the effect of omega-3 fatty acids on disease progression. Weiner et al.30 reported that cod-liver oil supplements decreased the progression of coronary artery disease after balloon catheter injury in swine fed an atherogenic diet (high cholesterol, high fat) for 8 months. Interestingly, the protective effect of cod-liver oil extended to vessels unaffected by the physical trauma and, unlike the present study, appeared unrelated to a reduction of plasma lipids. On the basis of decreased serum thromboxane and an altered pattern in platelet fatty acids, the authors concluded that the protective effect of the cod-liver oil may have been mediated through changes in prostaglandin metabolism. Davis et al.31 replaced coconut oil with Menhaden oil in a cholesterol-rich diet fed to rhesus monkeys for 12 months. They reported decreases in plasma cholesterol, percent aortic surface area covered by lesions, aortic FC and CE content, and aortic acid lipase, cholesterol esterase, and acyCoA: cholesterol acytransferase activities in fish oil-versus coconut oil-fed animals. In contrast, Thiery and Seide32 reported that Maxepa increased aortic surface involvement by atherosclerosis in New Zealand White rabbits fed a high cholesterol diet. Sanders33 has suggested that dramatic differences in the essential fatty acid or total fat content of the diets may have contributed to the findings. Additionally, only the rabbits fed fish oil were physically stressed by the route of administration (gavage).

The mechanisms by which fish oils may inhibit atherosclerosis could be related to several factors. As noted in the current study, significant decreases in blood pressure, plasma cholesterol, plasma triglyceride, and platelet aggregation were induced by fish oil supplements.

Elevated blood pressure appears to exacerbate atherosclerosis.34 We have recently reported that experimental hypertension markedly accelerates lesion development in the WHHL rabbit within a relatively short period of time (2 to 3 months).26 In the present study, supplementing normal rabbit chow with fish oil resulted in a significantly lower systolic blood pressure. Similar findings have been observed by others. Increasing dietary omega-3 fatty acids has reportedly decreased blood pressure in normal healthy volunteers,26 mild hypertensives,7,8,36 type II diabetics,37 patients with stable coronary heart disease,36 and hemodialysis patients.9,29-42 The data in normal subjects have been inconsi-
significant decrease in plasma cholesterol, the fish oil-fed group had significantly smaller LDL particles.

Supplementing the diet with fish oil resulted in a dramatic increase in the relative proportion of plasma EPA and DHA and a concomitant decrease in the C-18 series of fatty acids. The responsiveness of plasma fatty acid levels to fish oil feeding has also been documented in humans.8 The apparent selective enrichment of EPA and DHA into platelets was of particular interest. The absolute increase in the percent of EPA (<0.1% to 12.3%) was strikingly higher than that of DHA (3.3% to 5.5%). This discrepancy may reflect selective incorporation of EPA compared to DHA into platelet membranes or retroconversion of the longer chain fatty acid into the shorter chain. The later hypothesis is supported by the work of Schacky and Weber9 who demonstrated that dietary supplementation with DHA resulted in elevated platelet levels of EPA. We also observed that with the enrichment of platelets with EPA and DHA, the relative proportion of arachidonic acid was almost half that in platelets isolated from control rabbits. EPA and DHA compete with arachidonic acid for metabolism by the cyclooxygenases and lipoxygenases; thromboxane A2 and prostaglandin I2 are produced at the expense of thromboxane A1 and prostaglandin I1. In contrast to thromboxane A1, thromboxane A2 has no platelet aggregating activity, and prostaglandin I1 is an anti-aggregating substance. This scenario may have accounted for the decreased tendency of platelets isolated from the fish oil-fed WHHL rabbits to aggregate when challenged with collagen, ADP, or arachidonic acid.

Decreased platelet aggregation also has been reported by Brox and coworkers who fed cod-liver oil to both control subjects90 and patients with familial hypercholesterolemia.91 After 6 weeks of fish oil feeding, they found decreased collagen-induced platelet aggregation coupled with decreased platelet thrombin-induced thromboxane B2 generation. The altered property of platelets observed in the present study may have either directly or indirectly contributed to the decrease in severity of aortic lesion development seen in the WHHL rabbit fed fish oil.

Similar proportions of palmitic acid, linoleic acid, and EPA were observed in plasma and platelets at the third month of the study. The platelets had approximately 2.5 times the amount of stearic acid, a lower proportion of linoleic acid, and virtually no detectable linolenic acid when compared to plasma. As expected, the relative proportion of arachidonic acid was higher in the isolated platelets than in plasma. When the two groups of rabbits were compared with respect to platelet fatty acid composition, the proportion of arachidonic acid was lower in the fish oil-fed rabbits relative to the control rabbits, the later group having increased proportions of EPA and DHA. Although the percent of EPA was nearly identical in plasma and platelets from both groups of rabbits, the proportion of DHA was approximately one half that in the platelets as observed in plasma in the fish oil-fed rabbits. Again, this may be indicative of either retroconversion of DHA to EPA or to selective enrichment of platelets.

The fatty acid patterns of the ascending aorta and arch more closely reflected the pattern of fatty acids seen in plasma rather than in platelets and suggested a direct uptake of the circulating lipoproteins. The relatively high levels of EPA and DHA in the aortic wall of rabbits fed fish oil also suggested that the majority of lesion formation occurred during the course of the study. Rosenfeld et al.92 also observed similarities in the fatty acid composition of the cholesteryl ester between plasma and the aorta of WHHL rabbits. Their previous work93 demonstrated that the early fatty streak lesion in the WHHL rabbit is composed of macrophage-derived foam cells.

The relevance of this study to persons with familial hypercholesterolemia is highly speculative. Fish oil feeding had a positive effect on plasma lipids, blood pressure, and platelet function. Taken with the decreased accumulation of cholesterol in the vessel wall, the evidence suggested that fish oil feeding may have retarded the rate of atherogenesis, but it clearly did not arrest it. The effect of fish oil feeding on platelet function in the WHHL rabbit was consistent between investigators.94 In contrast, the effect of fish oil feeding on plasma lipids appeared to be variable among the three studies thus far reported.16,17 Similar variability in response has been noted in hypercholesterolemic humans fed fish oil. Nevertheless, evidence from work with other animal species indicates that the beneficial effects of fish oil feeding with respect to atherogenesis may be independent of either factor. Although by no means an adequate treatment, in certain individuals, diets increased in fish or fish oil may exert some positive effects.

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