Effect of Dietary Fat Saturation and Cholesterol on Low Density Lipoprotein Degradation by Mononuclear Cells of Cebus Monkeys

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The mechanism by which dietary unsaturated fatty acids lower low density lipoprotein (LDL) cholesterol is unknown. Unsaturated fatty acids incorporated into the cell membrane can increase membrane fluidity and, as a result, dramatically alter membrane-dependent cell functions. Therefore, we examined the effect of long-term dietary consumption of corn oil and coconut oil with and without cholesterol in amounts equivalent to those of a typical Western diet on the degradation of human LDL by peripheral blood mononuclear cells in Cebus albifrons monkeys. Cellular LDL degradation was dramatically enhanced in the mononuclear cells isolated from animals fed corn oil in comparison with those from animals fed coconut oil. The addition of cholesterol to the diets resulted in a slight attenuation of LDL degradation in the corn oil group while no effect was noted in the coconut oil group. Crossover LDL binding and degradation experiments with LDL isolated from animals fed corn oil diets and coconut oil diets demonstrated increased binding and degradation of LDL in mononuclear cells from animals fed corn oil diets. Enhanced mononuclear cell LDL degradation was accompanied by increased cellular cis-unsaturated fatty acyl content, increased membrane fluidity, and decreased plasma cholesterol. Increased cellular cis-unsaturated fatty acyl content with its concomitant increase in membrane fluidity mirrored the dietary lipoprotein profile of the host animal. A linear relationship was observed between cellular LDL degradation and both cellular cis-unsaturated fatty acyl content and membrane fluidity. These observations parallel results noted in whole-animal LDL catabolic studies with these same animals described elsewhere. These data suggest a novel mechanism by which dietary unsaturated fatty acids exert their LDL-lowering effect.

uptake and degradation.\textsuperscript{12} The present study was undertaken to investigate the effect of long-term dietary supplementation with unsaturated fatty acids in the form of corn oil or with saturated fatty acids in the form of coconut oil with and without added cholesterol on mononuclear cell LDL degradation in \textit{Cebus albifrons} monkeys. Animals maintained on diets rich in unsaturated fatty acids are known to have increased hepatic fractional catabolic rates for LDL.\textsuperscript{13} Thus, in the ex vivo setting we studied LDL degradation, membrane fluidity, and fatty acid content in peripheral blood mononuclear cells as functional equivalents of hepatocytes.\textsuperscript{14,15} Our results indicate that dietary unsaturated fatty acids enhance cellular LDL degradation and that this effect is accompanied by cellular enrichment in these fatty acids and decreased membrane microviscosity.

**Methods**

**Materials**

Na\textsuperscript{125I} was purchased from Amersham, Arlington Heights, IL. Separall-MN was purchased from Sepratech, Oklahoma City, OK. 1,6-Diphenyl-1,3,5-hexatriene (DPH) was obtained from Sigma Chemical, St. Louis, MO. High-performance liquid chromatography-grade hexane, isopropanol, petroleum ether, methanol, acetyl chloride, and chloroform were obtained from Aldrich Chemical, Milwaukee, WI. Heptadecanoate and fatty acyl methyl ester gas chromatography standards were purchased from NuChek Prep, Ellysian, MN. All other chemicals used were reagent grade or better.

**Animals and Diets**

Adult \textit{Cebus} monkeys (\textit{Cebus albifrons}) between the ages of 5 and 10 years were fed semi-purified diets containing 31% of calories as corn oil or coconut oil, with or without 0.1% cholesterol, for 3 to 10 years. Details of the diet compositions, as well as the fatty acid analyses, have been reported elsewhere.\textsuperscript{16} Plasma cholesterol values were measured from freshly isolated serum obtained from the same blood specimen from which mononuclear cells were isolated.

**Low Density Lipoprotein Preparation and Iodination**

Human LDL (density 1.006 to 1.063 g/ml) and monkey LDL (1.023 to 1.055 g/ml) were isolated from plasma by sequential ultracentrifugation in 50 mM tris-[hydroxymethyl]aminomethane (Tris), 5 mM disodium ethylenediaminetetraacetate (EDTA), pH 7.4.\textsuperscript{17} Potassium bromide was used to adjust the solvent densities. The LDL was then sequentially dialyzed with three changes of 50 mM Tris, pH 7.4. The total protein content was determined by the method of Lowry et al.\textsuperscript{18} LDL cholesterol was measured with a colorimetric method by using cholesterol oxidase, peroxidase, 4-hydroxybenzoate, and 4-amino-phenazone.\textsuperscript{19} Polyacrylamide gel electrophoresis (4.3%) was performed to ensure the purity of the LDL. LDL prepared in this manner typically had a cholesterol-to-total protein mass ratio of 1.3 to 1.7 for human LDL, 2.5 for LDL from monkeys fed coconut oil, and 1.2 for LDL from monkeys fed corn oil. LDL was radioiodinated by the iodine monochloride method of McFarlane,\textsuperscript{20} as modified by Langer and colleagues\textsuperscript{21} and Shepard and coworkers.\textsuperscript{22} Iodinated in this fashion, LDL had a specific activity of 300 to 800 cpm/ng protein.

**Mononuclear Cell Preparation**

Whole blood was obtained from fasting monkeys and was anticoagulated with 100 U/ml heparin. Mononuclear cells were prepared by mixing 20 ml of whole blood with 20 ml of Separall-MN solution.\textsuperscript{23,24} The suspension was then centrifuged at 1200 g for 20 minutes at 27°C. The mononuclear cells were harvested from the Separall-MN meniscus. The cells were washed twice with Hanks' balanced salt solution containing 15 mM N-2 hydroxyethylpiperazine-N'-2-ethanesulfonic acid, pH 7.4 (Hanks'-HEPES). Cellular concentrations were determined with a Coulter Counter, Model ZM, equipped with a 50 μm aperture tube. Cell counts ranged from 1 x 10^6 cells/ml to 5 x 10^6 cells/ml. Cell viability was determined by Trypan blue exclusion and was routinely greater than 95%. Mononuclear cell samples prepared in this fashion were comprised of 72% lymphocytes, 22% monocytes, and 4% neutrophils.\textsuperscript{23,24} The samples were maintained at room temperature for up to 30 minutes before use.

**Low Density Lipoprotein Degradation**

The amount of human \textsuperscript{125I}-LDL degraded by monkey mononuclear cells was determined according to published methods.\textsuperscript{14,25,26} An aliquot of freshly isolated mononuclear cells in Hanks'-HEPES (pH 7.4) was incubated with human \textsuperscript{125I}-LDL (80 μg/ml) in the presence or absence of a 20-fold excess of unlabeled human LDL at 37°C for 4 hours. Each assay was performed in the presence of 10 mM CaCl\textsubscript{2}. After incubation, an aliquot was removed from each assay to determine the total counts. The samples were treated with 20% trichloroacetic acid to precipitate the degraded, protein-bound iodotyrosine. The precipitate was sedimented by centrifugation at 14 000 g for 3 minutes. The supernatant was counted to determine the amount of acid-soluble, ether-insoluble, radiolabeled material generated by the cells and released into the aqueous phase.\textsuperscript{25,26} Degradation values are expressed as specific degradation, i.e., the difference in degradation in the presence and absence of a 20-fold excess unlabeled LDL. Degradation is expressed as micrograms of \textsuperscript{125I}-LDL protein degraded per 10^6 cells/4 hours.

**Monkey Low Density Lipoprotein Crossover Binding and Degradation**

Monkey mononuclear cells were incubated with monkey \textsuperscript{125I}-LDL in the presence or absence of a 20-fold excess of unlabeled monkey LDL at 4°C for 6 hours to determine specific binding. Each assay was carried out in the presence of 10 mM CaCl\textsubscript{2}. All reagents were chilled to 4°C before use.

A range of monkey LDL concentrations from 10 μg/ml to 80 μg/ml was used to generate binding isotherms. After incubation, an aliquot from each vial was removed to determine total counts. Surface-bound LDL was separated from free LDL by centrifuging an aliquot of cells through a 0.15 M metrizamide cushion at 14 000 g for...
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3 minutes at 4°C. The cell pellets were isolated by amputating the tip of the microfuge tube and counting the radioactivity in a gamma counter. The total and bound counts were measured, and specifically bound counts were expressed as micrograms of LDL protein bound per 10^6 cells. LDL degradation was performed as described above.

LDL binding and degradation were performed by using LDL isolated from monkeys fed corn oil and, again, with LDL isolated from monkeys fed coconut oil. Mononuclear cells from both the corn oil- and coconut oil-diet groups were used in this LDL crossover study.

Membrane Fluidity Measurements

Freshly isolated mononuclear cells or plasma membrane vesicles were incubated with DPH at a concentration of 1 μM for 1 hour at 25°C, after which the suspension was washed twice with Hanks'-HEPES buffer, pH 7.4. Fluorescence measurements were performed with a Spex Fluorolog-2 spectrofluorimeter (Spex Industries, Edison, NJ) equipped with a thermostat-controlled cell holder and a polarization accessory. The steady-state fluorescence polarization was measured at 37°C by exciting the cell suspension at 360 nm and recording the emission at 430 nm. The polarization of fluorescence emission was calculated from the equation:

\[ P = \frac{I_v - G_w}{I_v + G_w} \]

where P is polarization, I is the fluorescence intensity, the first and second subscripts refer to the plane of polarization, and \( G = l_v/h_w \).

Determination of Cellular Cholesterol and Fatty Acyl Content

Mononuclear cells were extracted with hexane-isopropanol (3:2, vol/vol). The samples were divided into two aliquots. A heptadecanoate internal standard was added to one aliquot of lipid extract. The fatty acyl groups were transesterified with methanolic-HCl and extracted into petroleum ether. The petroleum ether was then evaporated under nitrogen gas, and the lipids were resolubilized in chloroform. Separation and identification of the fatty acid methyl esters were performed by gas-liquid chromatography by using a Chrompack CP Sil 88 capillary column in a Hewlett-Packard 5890A gas chromatograph with an automated injector, flame ionization detector, and Hewlett-Packard 3393 integrator. Separation was performed in the isothermal mode at 210°C with an injection volume of 5 μl, helium as the carrier gas, and a split ratio of 60:1. Fatty acid methyl ester gas chromatography standards were used to determine retention times.

The total cellular cholesterol content of the second aliquot was then determined by an enzymatic chromogenic system by using 4-hydroxybenzoate. Cholesterol ester/total cholesterol ratio was determined by using the p-hydroxyphenylacetic acid method of Gamble and coworkers.

Determination of Plasma Membrane Fatty Acyl Content

Pooled mononuclear cell plasma membranes were prepared at 4°C by established methods. Mononuclear cell suspensions were sedimented at 200 g for 15 minutes and washed twice in 0.9% NaCl. Monocytes were resuspended in 15 ml of lysis medium (1 mM NaHCO₃, 0.5 mM CaCl₂, pH 7.4) and disrupted in a homogenizer (25 strokes). The cell lysate was diluted to 50 ml and centrifuged at 500 g for 20 minutes. The supernatant was removed and saved. The pellet was resuspended in 25 ml of lysis medium and was rehomogenized. This suspension was then centrifuged at 500 g for 20 minutes, and the supernatant was removed. The two supernatants were combined and sedimented at 12 500 g for 20 minutes. The pellet was resuspended in 10 ml lysis medium and was mixed with 30 ml of 53% sucrose prepared in lysis medium to yield a final concentration of 40% sucrose. Then 20 ml of the 40% sucrose was layered under 15 ml of a 30% sucrose solution. This sucrose step gradient was centrifuged at 55 000 g for 4 hours with a Ti70 rotor in a Beckman L8-70 ultracentrifuge. After centrifugation, the 10 ml fraction just above the interface was removed from the 30% sucrose layer and was diluted with 25 ml of lysis medium. This solution was then sedimented at 45 000 g for 1 hour. The pellet was extracted with hexane-isopropanol (3:2, vol/vol), and determination of the fatty acyl content was performed as described above. This method results in less than 5% contamination with endoplasmic reticular and mitochondrial membrane.

Statistical Analysis

All results are presented as averages±standard deviations of the means. Analysis of variance, the Newman-Keuls variant analysis, and multivariate linear regression analysis were used for the comparisons.

Results

Effect of Diet on Plasma Cholesterol

Animals maintained on a corn oil-enriched diet without cholesterol (n=5) had an average plasma cholesterol of 139±26 mg/dl; in contrast, animals fed coconut oil-enriched diets without cholesterol (n=4) had an average plasma cholesterol of 342±44 mg/dl (p<0.01, corn oil vs. coconut oil). The addition of cholesterol to the corn oil diet (n=6) resulted in an average plasma cholesterol of 158±23 mg/dl, while the addition of cholesterol to the coconut oil diet (n=5) led to an average plasma cholesterol of 291±61 mg/dl (p<0.05, corn oil vs. coconut oil). A comparison of plasma cholesterol values within the corn oil groups and within the coconut oil groups showed that the addition of cholesterol to the diets did not affect the plasma cholesterol in a statistically significant manner.

Effect of Diet on Mononuclear Cell Fatty Acyl Content

The effect of diet on the unsaturated-saturated fatty acyl ratio (U/S) for nonhuman primate mononuclear cells
is shown in Table 1. Animals fed a diet enriched with corn oil alone exhibited the highest U/S, 1.93±0.07, while those fed a diet enriched in coconut oil had a U/S of 0.95±0.04 (p<0.01). The addition of cholesterol to a corn oil-enriched diet decreased the U/S to 1.12±0.17, while the addition of cholesterol to a coconut oil-enriched diet resulted in a U/S of 0.83±0.09 (p<0.01). Cells from corn oil-fed animals without dietary cholesterol had a 72% greater U/S than those given cholesterol supplementation (1.93±0.07 vs. 1.12±0.17, p<0.01). In contrast, cells from animals fed coconut oil with or without cholesterol had U/S ratios that were not statistically different from one another (0.95±0.04 vs. 0.83±0.09).

The effect of diet on the fatty acyl profiles of monkey mononuclear cells is shown in Table 2. The corn oil diet resulted in a 152% increase in C18:2 (p<0.01) with a concomitant 39% decrease in C18:1 (p<0.01), a 32% decrease in C18:0 (p<0.01), and a 37% decrease in C16:0 (p<0.01) in comparison to the coconut oil diet. In the diet groups with cholesterol, corn oil-fed animals again exhibited increased cellular C18:2 content when compared to animals fed coconut oil. Animals maintained on corn oil diets with cholesterol had 100% more cellular C18:2 than those fed coconut oil with cholesterol (p<0.01). The contents of C18:0, C14:0, and C16:0 were identical in the two diet groups fed cholesterol, while the cellular C14:0 content was 88% greater in the diet group fed coconut oil with cholesterol (p<0.05). Comparison of the corn oil diet groups showed that dietary supplementation with cholesterol was accompanied by a 37% decrease in cellular C18:2 (p<0.01), a 40% increase in cellular C18:1 (p<0.01), and a 61% increase in cellular C18:0 (p<0.01). Cells from animals fed coconut oil with or without cholesterol showed no significant differences in specific cellular fatty acyl content.

**Table 1. Cellular Unsaturated/Saturated Fatty Acyl Ratios**

<table>
<thead>
<tr>
<th>Diet</th>
<th>C12:0</th>
<th>C14:0</th>
<th>C16:0</th>
<th>C18:0</th>
<th>C20:0</th>
<th>C18:1</th>
<th>C18:2</th>
<th>C20:4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn oil (n=5)</td>
<td>0.9±0.8</td>
<td>3.5±1.0</td>
<td>15.9±0.6</td>
<td>13.8±0.5</td>
<td>—</td>
<td>12.6±1.4</td>
<td>42.1±1.9</td>
<td>11.2±4.1</td>
</tr>
<tr>
<td>Coconut oil (n=4)</td>
<td>1.6±0.3</td>
<td>5.3±1.5</td>
<td>25.1±5.2</td>
<td>20.2±2.9</td>
<td>—</td>
<td>20.6±1.5</td>
<td>16.7±4.8</td>
<td>11.5±4.8</td>
</tr>
<tr>
<td>Corn oil+cholesterol (n=6)</td>
<td>1.5±0.3</td>
<td>4.0±2.9</td>
<td>17.7±4.5</td>
<td>22.2±3.7</td>
<td>1.9±1.2</td>
<td>17.7±3.5</td>
<td>26.7±5.4</td>
<td>8.4±3.4</td>
</tr>
<tr>
<td>Coconut oil+cholesterol (n=6)</td>
<td>2.2±1.6</td>
<td>7.5±0.8</td>
<td>19.5±6.2</td>
<td>23.0±3.0</td>
<td>2.8±1.5</td>
<td>19.2±2.2</td>
<td>13.9±1.8</td>
<td>11.2±3.3</td>
</tr>
</tbody>
</table>

The values are averages±SD and are given as mole percents. The experiments were performed as described in the Methods section. For a discussion of the significant differences between and among groups, see the Results section.

**Table 2. Mononuclear Cell Fatty Acyl Content in Monkey Diet Groups**

The values are averages±SD and are given as µg/10^6 cells. The experiments were performed as described in the Methods section. For a discussion of the significant differences between and among groups, see the Results section.

**Table 3. Mononuclear Cell Cholesterol Content**

<table>
<thead>
<tr>
<th>Diet</th>
<th>Total cholesterol</th>
<th>Cholesteryl ester</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn oil (n=4)</td>
<td>1.25±0.34</td>
<td>0.35±0.09</td>
</tr>
<tr>
<td>Corn oil+cholesterol (n=5)</td>
<td>1.94±0.36</td>
<td>0.68±0.14</td>
</tr>
<tr>
<td>Coconut oil (n=4)</td>
<td>2.43±0.53</td>
<td>0.80±0.17</td>
</tr>
<tr>
<td>Coconut oil+cholesterol (n=4)</td>
<td>2.52±0.56</td>
<td>0.98±0.21</td>
</tr>
</tbody>
</table>

The values are averages±SD and are given as µg/10^6 cells. The experiments were performed as described in the Methods section. For a discussion of the significant differences between and among groups, see the Results section.

**Effect of Diet on Cellular Cholesterol and Cholesteryl Ester Content**

The effect of diet on total cellular cholesterol and cholesteryl ester content is shown in Table 3. Mononuclear cells isolated from animals maintained on a corn oil-enriched diet had an average cellular cholesterol content of 1.25±0.03 µg/10^6 cells; in contrast, animals fed coconut oil-enriched diets without cholesterol had an average mononuclear cell cholesterol content of 2.43±0.53 µg/10^6 cells (p<0.05). Addition of cholesterol to the corn oil diet resulted in an average mononuclear cell cholesterol content of 2.52±0.56 µg/10^6 cells (p<0.05). Comparison of mononuclear cell cholesterol values with the corn oil group shows that the addition of cholesterol to the diet resulted in a 55% increase in mononuclear cell cholesterol content (p<0.05). Addition of cholesterol to the coconut oil diet did not affect the cellular cholesterol content in a statistically significant manner.

Animals fed a corn oil-enriched diet had an average cellular cholesteryl ester content of 0.35±0.09 µg/10^6 cells; in contrast, animals fed coconut oil-enriched diets had an average mononuclear cell cholesteryl ester content of 0.80±0.17 µg/10^6 cells (p<0.01). Addition of cholesterol to the corn oil diet resulted in an average cellular cholesteryl ester content of 0.88±0.14 µg/10^6 cells, while addition of cholesterol to the coconut oil diet resulted in an average cholesteryl ester content of...

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The relationship between LDL degradation and plasma membrane cholesterol content is shown in Figure 1. Animals fed a diet enriched with corn oil degraded 13.6±3.6 ng LDL protein/10^6 cells/4 hours, while animals fed a diet enriched with coconut oil degraded 2.5±0.6 ng LDL protein/10^6 cells/4 hours (p<0.01). A corn oil-enriched diet to which cholesterol was added was associated with LDL degradation of 9.6±3.6 ng/10^6 cells/4 hours, while a coconut oil-enriched diet with cholesterol resulted in LDL degradation of 2.7±1.0 ng/10^6 cells/4 hours (p<0.01). Comparison of diet groups without cholesterol showed a 5.5-fold greater degradation of LDL in the corn oil-fed animals than in those fed coconut oil (p<0.01). Similarly, in the diet groups given supplemental cholesterol, the corn oil-fed monkeys exhibited 3.6-fold greater mononuclear cell LDL degradation than those fed coconut oil (p<0.01). Degradation of LDL was identical in both coconut oil-diet groups (i.e., with and without cholesterol). Cells from the corn oil and cholesterol group degraded LDL 70% as well as those from animals fed corn oil alone (p<0.01).

Table 5. Mononuclear Cell and Plasma Membrane DPH Fluorescence Polarization

<table>
<thead>
<tr>
<th>Diet additions</th>
<th>Corn oil</th>
<th>Corn oil+cholesterol</th>
<th>Coconut oil</th>
<th>Coconut oil+cholesterol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whole cell</td>
<td>0.271±0.012</td>
<td>0.288±0.011</td>
<td>0.292±0.034</td>
<td>0.330±0.034</td>
</tr>
<tr>
<td>Plasma membrane vesicle</td>
<td>0.257</td>
<td>0.265</td>
<td>0.277</td>
<td>0.277</td>
</tr>
</tbody>
</table>

The values were averages±SD. The experiments were performed as described in the Methods section. For the whole cell measurements, n=5 in the corn oil group, n=6 in the corn oil plus cholesterol group, n=4 in the coconut oil group, n=5 in the coconut oil plus cholesterol group. For the plasma membrane vesicle measurements, pooled samples from each diet group were used.

0.98±0.21 µg/10^6 cells (p<0.05). Comparison of cholesterol ester content with the corn oil group shows that addition of cholesterol resulted in a 94% increase in mononuclear cholesterol ester content (p<0.02). Addition of cholesterol to the corn oil diet did not alter cellular cholesterol ester content in a statistically significant manner. Within all diet groups, cholesterol ester content was 30% to 40% of cellular total cholesterol content.

Effect of Diet on Plasma Membrane Fatty Acyl Content

The effect of diet on the plasma membrane fatty acyl content from pooled monkey mononuclear cells is shown in Table 4. In animals fed the corn oil diet, the mononuclear cell plasma membrane C18:2 content was 31% greater, while the C16:0 content was 19% less than that in animals fed the coconut oil diet. Addition of cholesterol to each diet resulted in a decreased C18:2 content and an increased C18:1 content in the plasma membranes. The addition of cholesterol to the corn oil diet resulted in a 5% increase in plasma membrane C18:2 content and a 25% increase in C18:1 content. Similarly, the addition of cholesterol to the coconut oil diet resulted in a 21% decrease in plasma membrane C18:2 levels and a 33% increase in the membrane content of C18:1. Interestingly, the addition of cholesterol resulted in a 37% decrease in plasma membrane C20:4 content in both the corn oil and coconut oil diet groups.

Effect of Diet on Mononuclear Cell DPH Fluorescence Polarization

The effect of diet on mononuclear cell DPH fluorescence polarization, a reflection of membrane fluidity, is shown in Table 5. A comparison of the corn oil-diet group with the coconut oil-diet group showed that corn oil-fed animals had a significantly lower mononuclear cell DPH fluorescence polarization value, indicating a more fluid membrane (p<0.05). The addition of cholesterol to each diet group was accompanied by increases in DPH fluorescence polarization, indicative of decreased membrane fluidity. The addition of dietary cholesterol to the corn oil diet resulted in an increase in the mononuclear cell DPH fluorescence polarization compared with that in cells from animals fed corn oil without cholesterol (p<0.05). The addition of dietary cholesterol to the coconut oil diet resulted in an increase in mononuclear cell DPH fluorescence polarization, which did not achieve statistical significance, compared with that in cells from animals fed coconut oil without cholesterol. DPH fluorescence polarization was significantly different for monkeys fed corn oil and cholesterol compared with those fed coconut oil and cholesterol (p<0.05).

DPH fluorescence polarization for plasma membrane vesicles prepared from pooled mononuclear cells followed the same pattern as that seen with the whole-cell preparations. The membrane vesicles from corn oil-fed animals had the lowest fluorescence polarization values followed by vesicles from the animals fed corn oil with cholesterol. The vesicles from coconut oil-fed animals had the greatest fluorescence polarization values, and the addition of cholesterol to the coconut oil diet did not alter these values.

Effect of Diet on Low Density Lipoprotein Degradation

The effect of diet on low density lipoprotein (LDL) metabolism is shown in Figure 2. Animals fed a diet enriched with corn oil degraded 13.6±3.6 ng LDL protein/10^6 cells/4 hours, while animals fed a diet enriched with coconut oil degraded 2.5±0.6 ng LDL protein/10^6 cells/4 hours (p<0.01). A corn oil-enriched diet to which cholesterol was added was associated with LDL degradation of 9.6±3.6 ng/10^6 cells/4 hours, while a coconut oil-enriched diet with cholesterol resulted in LDL degradation of 2.7±1.0 ng/10^6 cells/4 hours (p<0.01). Comparison of diet groups without cholesterol showed a 5.5-fold greater degradation of LDL in the corn oil-fed animals than in those fed coconut oil (p<0.01). Similarly, in the diet groups given supplemental cholesterol, the corn oil-fed monkeys exhibited 3.6-fold greater mononuclear cell LDL degradation than those fed coconut oil (p<0.01). Degradation of LDL was identical in both coconut oil-diet groups (i.e., with and without cholesterol). Cells from the corn oil and cholesterol group degraded LDL 70% as well as those from animals fed corn oil alone (p<0.01).

The relationship between LDL degradation and plasma cholesterol is shown in Figure 2 for all diet groups. Cellular cholesterol levels and a 33% increase in the membrane content of C18:1. Interestingly, the addition of cholesterol resulted in a 37% decrease in plasma membrane C20:4 content in both the corn oil and coconut oil diet groups.

Table 4. Mononuclear Cell Plasma Membrane Fatty Acyl Content in Monkey Diet Groups

<table>
<thead>
<tr>
<th>Diet additions</th>
<th>C12:0</th>
<th>C14:0</th>
<th>C16:0</th>
<th>C18:0</th>
<th>C18:1</th>
<th>C18:2</th>
<th>C20:4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn oil</td>
<td>2.2</td>
<td>3.6</td>
<td>2.5</td>
<td>2.2</td>
<td>2.3</td>
<td>0.4</td>
<td>0.98</td>
</tr>
<tr>
<td>Coconut oil</td>
<td>2.0</td>
<td>2.3</td>
<td>2.0</td>
<td>1.8</td>
<td>1.6</td>
<td>0.4</td>
<td>0.92</td>
</tr>
<tr>
<td>Corn oil+cholesterol</td>
<td>2.5</td>
<td>3.0</td>
<td>2.5</td>
<td>2.2</td>
<td>2.3</td>
<td>0.5</td>
<td>1.05</td>
</tr>
<tr>
<td>Coconut oil+cholesterol</td>
<td>2.8</td>
<td>3.1</td>
<td>3.0</td>
<td>2.5</td>
<td>2.5</td>
<td>0.6</td>
<td>1.15</td>
</tr>
</tbody>
</table>

The values are averages±SD. The experiments were performed as described in the Methods section. For the whole cell measurements, n=5 in the corn oil group, n=6 in the corn oil plus cholesterol group, n=4 in the coconut oil group, n=5 in the coconut oil plus cholesterol group. For the plasma membrane vesicle measurements, pooled samples from each diet group were used.
The effect of diet on the specific binding of monkey LDL by mononuclear cells is shown in Figure 5. The estimated binding constants derived from the binding isotherms are shown in Table 6. The dissociation constant was increased by 43% in mononuclear cells isolated from animals fed a coconut oil diet compared to that in cells from animals fed a diet of corn oil. This increase occurred regardless of the source of the LDL ligand, that is, plasma from corn oil-fed monkeys or coconut oil-fed monkeys. In addition, maximal binding of either type of LDL ligand was dramatically decreased in mononuclear cells from animals fed coconut oil. The source of the LDL ligand did not affect the affinity.
of the ligand for its receptor. However, LDL isolated from
animals fed coconut-oil diets had markedly decreased
maximal binding to mononuclear cells isolated from either
corn oil- or coconut oil-fed animals compared to the
binding of LDL isolated from corn oil-fed animals.

The results of LDL degradation crossover studies are
summarized in Table 7. These results parallel those found
in LDL binding experiments. LDL isolated from the plasma
of animals maintained on coconut oil diets was degraded
2.1-fold more efficiently by mononuclear cells from ani-
maled a corn oil diet than those from coconut oil-fed
animals (p<0.05). Similarly, LDL isolated from animals
fed corn oil-supplemented diets was degraded 2.4-fold
more efficiently by mononuclear cells isolated from corn
oil-fed animals than coconut oil-fed animals, although the
difference was not statistically significant. Mononuclear
cells from both coconut oil-fed animals and corn oil-fed
animals degraded LDL isolated from corn oil-fed animals
better, on average, than LDL from coconut oil-fed animals.
Although this comparison was not statistically significant,
a trend is apparent.

Discussion

In a number of whole-animal studies, the relationships
between the major dietary lipids, whole-liver LDL metabo-
list, and plasma levels of LDL cholesterol have been
investigated.7,18,30,31 From these studies, it is clear that
feeding unsaturated fatty acids enhances hepatic receptor-
dependent LDL uptake and decreases the concentration of
plasma LDL cholesterol, while dietary saturated fatty acids
suppress hepatic receptor-dependent LDL uptake and increase
levels of plasma LDL.7,31 Similarly, feeding choles-
terol alone also suppresses hepatic LDL uptake and increases
plasma LDL cholesterol.7 The detrimental effects
of feeding cholesterol or saturated fatty acids can be reversed
by returning the experimental animal to a diet low in these
lipids or to one rich in unsaturated fatty acids.7 The molec-
ular and cellular correlates of these whole-animal and whole-
organ studies are largely unknown.

Since cellular clearance of LDL is primarily mediated by
the classic LDL receptor,53,54 a deficiency or dysfunction
of this receptor leads to elevated circulating levels of LDL
and, consequently, can promote atherogenesis. A number
of steps in the processing of receptor-bound LDL can be
defective. Investigators have described receptors with
decreased LDL affinity, alterations in receptor clustering in
coated pits, changes in endosome production, and reduced
rates of LDL degradation in lysosomes.36–39 All of these
processes occur within the plasma membrane milieu and,
therefore, could be affected by the lipid composition of
the membrane and the lipid content of the host animal’s diet.

Using peripheral blood mononuclear cells isolated from
Cebus monkeys, we have demonstrated increased LDL
degradation in cells from animals fed corn oil compared to
cells from animals fed coconut oil. With the addition of
cholesterol to the diets, LDL degradation was slightly attenu-
ated in the cells from corn oil-fed animals but essentially did
not change in the cells from coconut oil-fed animals. Again,
even in the presence of dietary cholesterol, the corn oil-fed
animals demonstrated greatly enhanced cellular LDL de-
gradation. Both plasma cholesterol values and total cellular
cholesterol content paralleled the decremental changes in
cellular LDL degradation as a function of the host animal’s
maintenance diet. These observations in an ex vivo isolated
cell system parallel findings in whole-animal LDL metabo-
lism studies performed in these same monkeys described in
a companion article.40

Dietary cholesterol played a relatively minor role in the
regulation of cellular LDL degradation in this study. The
addition of cholesterol to both the corn oil and the coconut
oil diets resulted in decreased membrane levels of C18:2
and increased levels of C18:0 and C18:1. Other investi-
gators have also noted these changes in fatty acid levels
with dietary cholesterol supplementation.41,42,43 Huang and
coworkers41 have suggested the decreased activity of the
desaturase enzyme in cholesterol-fed animals as a poten-
tial explanation. No significant effect was seen in U/S,
membrane fluidity, cellular LDL degradation, total cellular
cholesterol, or individual cellular fatty acyl components in
mononuclear cells isolated from the coconut oil-fed groups.
Cholesterol supplementation of corn oil-fed animals resulted
in a small decrease in U/S, membrane fluidity, LDL degra-
dation, total cellular cholesterol, and cellular content of
linoleate. The explanation for these fluidity findings may be
that fatty acyl packing in membranes of mononuclear cells
from coconut oil-fed animals is highly ordered, reflecting
the highly saturated fatty acyl content of coconut oil. The
membrane order may already be near its maximal limit;
hence, the addition of dietary cholesterol does not further
increase the order of the membrane, possibly as a result of
homeoviscous adaptation.44 Conversely, corn oil-fed ani-

Table 6. Analysis of Low Density Lipoprotein Binding Crossover

<table>
<thead>
<tr>
<th>LDL source</th>
<th>Com LDL MNC</th>
<th>Com LDL Coconut MNC</th>
<th>Coconut LDL MNC</th>
<th>Coconut LDL Coconut MNC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimated apparent Kd (μg/ml)</td>
<td>20.0</td>
<td>28.0</td>
<td>22.0</td>
<td>32.0</td>
</tr>
<tr>
<td>Bmax (ng/10^6 cells)</td>
<td>13.9</td>
<td>4.8</td>
<td>3.8</td>
<td>0.97</td>
</tr>
</tbody>
</table>

LDL = low density lipoprotein, MNC = mononuclear cell, Kd = dissociation constant, Bmax = maximum binding.

Table 7. Low Density Lipoprotein Degradation Crossover Study

<table>
<thead>
<tr>
<th>MNC source</th>
<th>Com LDL (n=4)</th>
<th>Coconut LDL (n=4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn</td>
<td>29.6±21.5</td>
<td>10.4±3.8</td>
</tr>
<tr>
<td>Coconut</td>
<td>12.3±8.5</td>
<td>5.0±3.3</td>
</tr>
</tbody>
</table>

The units are ng LDL protein/10^6 cells/4 hours. The values are averages±SD.

LDL = low density lipoprotein, MNC = mononuclear cell.

For a discussion of the significant differences between
and among groups, see the Results section.
mals have cellular membranes that are highly disordered, reflecting the cis-unsaturated fatty acyl content of corn oil. The addition of cholesterol to this diet, in contrast, results in increased membrane order as a result of an increased cholesterol/phospholipid ratio and, hence, a relative decrease in membrane fluidity. However, these changes associated with dietary cholesterol supplementation are small compared with the differences in mononuclear cell LDL degradation, plasma cholesterol, membrane fluidity, and U/S caused by modifying the dietary fatty acid composition. These observations are particularly pertinent since these animals are fed a diet equivalent in cholesterol content to that consumed daily by the average adult in American society: 550 mg. Certainly, in human studies, it has been noted that the elevation in serum cholesterol that occurs with isocaloric dietary substitution of saturated fatty acids for unsaturated fatty acids is much greater than that seen with dietary supplementation with cholesterol.46

The effect of diet on the LDL particle itself and its binding and degradation were addressed in the crossover study with LDL from monkeys fed corn or coconut oil-supplemented diets. Again, the mononuclear cells from corn oil-fed animals degraded LDL more efficiently than did mononuclear cells from coconut oil-fed animals. Within each diet group, LDL isolated from corn oil-fed animals was bound and degraded more efficiently than was LDL from coconut oil-fed animals. This points to the possibility that dietary fats may also attenuate LDL metabolism as a result of changes in the LDL particle, although the primary and most significant effect in this study appears to be on receptor function. Interestingly, the Scatchard plots of the binding data demonstrate both increased affinity and increased maximum binding capacity of the LDL receptor when expressed on the surface of mononuclear cells from corn oil-fed animals. This occurred with LDL from both corn oil-fed animals and coconut oil-fed animals. This observation suggests that a simple increase in receptor number, or coupled receptor function. With particular relevance to this study, our group has previously shown that LDL uptake and degradation is enhanced in human peripheral blood mononuclear cells when membran cis unsaturated fatty acyl content is enhanced by brief ex vivo incubation with free fatty acids.12 A number of hypotheses have been proposed to explain these observations. It has been suggested that cryptic functional sites or cryptic receptors exist as reservoirs for the adjustment of function in response to perturbations in membrane fluidity.46 Others have suggested requirements for specific lipids within the receptor lipid annulus for optimal receptor or enzyme function.45 Based upon theoretical analyses, it has been implied that receptor turnover rate is directly proportional to membrane fluidity.48 Finally, the Optimal Fluidity Hypothesis suggests that the omerg maximal velocity of receptor or enzyme function may possess a peak value at

a specific membrane fluidity.46,48 The precise role of any of these potential mechanisms is currently unknown.

In this study, mononuclear cell LDL degradation varied in a linear manner with both cellular U/S ratio and membrane fluidity. LDL receptor binding affinity and maximal binding capacity were enhanced in mononuclear cells with increased membrane fluidity and cellular U/S. Both membrane fluidity and cellular U/S reflected the dietary lipid content of the host animals' maintenance diet. While the specific role of membrane fluidity and annular lipids in LDL receptor function are unknown, the possibilities include fluidity-induced changes in LDL receptor conformation toward a conformational state with greater ligand affinity or an absolute functional requirement for specific fatty acyl moieties in the LDL receptor lipid annulus. The effect of dietary cis-unsaturated fatty acids on cellular LDL metabolism in the context of the plasma membrane lipid microenvironment warrants further study. It remains to be seen whether enzymes involved in cellular cholesterol homeostasis, such as HMG-CoA reductase or acyl-CoA-cholesterol acyl transferase, can also be affected by alterations in the membrane milieu either directly or through alterations in second messenger signal transduction.

This study demonstrates that cellular LDL metabolism can be dramatically altered by dietary modifications of both membrane fluidity and fatty acyl content. Dietary unsaturated fatty acids are readily incorporated into the mononuclear cell membrane, and cellular LDL binding and degradation are greatly enhanced in association with membrane enrichment with these fatty acids. Our results suggest a novel mechanism by which dietary fatty acids can alter LDL catabolism.

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Index Terms: unsaturated fatty acid • low density lipoprotein • diet • cholesterol • atherogenesis
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