Cholesterol Homeostasis of Skin Fibroblasts after Incubation with Postabsorptive and Postprandial Lipoproteins

The Effect of a Fatty Meal

Richard D. Kenagy, Claes-Henrik Florén, Edwin L. Bierman, Balchandra Kudchodkar, and John J. Albers

To determine if lipoproteins formed after a fatty meal deliver more cholesterol to cultured skin fibroblasts than do lipoproteins in the basal state, very low density lipoproteins and remnants (d < 1.019), low density lipoproteins (LDL), and high density lipoproteins (HDL) were isolated from plasma obtained before, and 3 and 6 hours after, consumption of a high fat-cholesterol formula by seven normal males. Binding of \(^{125}\)I-LDL to cells and cell cholesterol content were determined after incubation of normal human skin fibroblasts for 48 hours with the lipoprotein fractions at 5% or 15% of plasma concentration. Activity of 3-hydroxy-3-methylglutaryl coenzyme A reductase was also measured after preincubation of cells with HDL for 48 hours. Despite a 40% increase in unesterified cholesterol in the d < 1.019 fraction at 3 hours compared to the 0-hour fraction, the 3-hour d < 1.019 fraction did not decrease LDL binding or increase cell cholesterol more than did the 0-hour fraction. Preincubation of cells with LDL, concentrations of which were unchanged by feeding, decreased LDL binding and increased cellular cholesterol. These effects also were not altered by the meal. HDL lipids and apo A-I were decreased at 3 hours, but not at 6 hours. Effects of HDL on LDL binding and cellular cholesterol were not altered by feeding, but the 3-hour and 6-hour fractions increased 3-hydroxy-3-methylglutaryl coenzyme A reductase activity, while the 0-hour fraction had little effect. These data indicate that consumption of a high fat-cholesterol meal as a bolus does not acutely alter the cholesterol delivery capacity of serum lipoproteins of normal male subjects.

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The relationship among dietary fat, serum lipoproteins, and atherogenesis has been of great interest for the last several decades. Of all the lipoproteins, most attention has been directed toward the low density lipoprotein (LDL) in atherogenesis and the LDL receptor pathway by which LDL regulates cellular cholesterol homeostasis. Although chylomicrons are the primary carriers of dietary lipids, much less emphasis has been focused on elucidation of the role of chylomicrons and their remnants in the regulation of cellular cholesterol metabolism. Zilversmit\(^6\) has proposed that remnants formed by the action of lipoprotein lipase on chylomicrons can be as atherogenic as LDL in that both can increase cellular cholesterol. In this regard, in previous studies from this laboratory, Florén et al.\(^3\) found chylomi-
cron remnants able to deliver cholesterol to arterial smooth muscle cells and skin fibroblasts via the LDL receptor. Therefore, lipoproteins formed during the postprandial period could be very important in the atherogenic process.

The purpose of these experiments was to characterize the changes in concentration of lipoprotein lipids after fat feeding and to test whether these changes could increase the ability of the lipoprotein fractions to deliver cholesterol to cultured fibroblasts.

**Methods**

**Subjects**

Seven healthy, nonobese, male subjects, aged 24 to 37 years, gave informed consent. All subjects fasted 12 hours and had been instructed to abstain from alcohol for 24 hours. After samples of blood were collected with or without 1.4 mg/ml EDTA, a formula consisting of 35.9 g powdered egg yolk, 145.5 g whipping cream, 20 g sucrose, and a brandy-vanilla flavoring in water was consumed within 10 minutes. This formula provided 15.1 g protein, 25.4 g carbohydrate, 75.0 g fat, and 1.2 g cholesterol, with a caloric content of 826 kcal. Additional blood samples were obtained at 3 and 6 hours after the formula was consumed.

**Lipoprotein Isolation**

Plasma was brought to \( d = 1.019 \) with KBr and centrifuged for 20 hours at 36,000 rpm in a 40.3 rotor at 10\(^\circ\). The \( d < 1.019 \) lipoproteins were then collected by tube-slicing. This density was chosen to ensure that all remnant lipoproteins would be isolated in one fraction. After the infranate was adjusted to \( d = 1.063 \), it was centrifuged at 36,000 rpm for 24 hours to isolate LDL. High density lipoprotein (HDL, \( 1.063 < d < 1.21 \)) was isolated by removal of \( d < 1.063 \) lipoproteins in one run of 24-hour duration, followed by centrifugation at \( d = 1.21 \) for 38 hours at 36,000 rpm. Lipoproteins were only centrifuged twice to minimize artificial changes in composition. Less than 1% of HDL protein was apo B by radioimmunoassay. The lipoproteins were dialyzed for 4 hours to separate the lipids after fat feeding and to test whether these changes significantly altered the binding of \(^{125}\)I-LDL in experiments in which cells were preincubated with postabsorptive and postprandial LDL. Therefore, these results were not pooled.

**Analysis**

Lipoprotein lipid classes were separated and analyzed as has been described previously. 3-Hydroxy-3-methylglutaryl coenzyme A reductase (HMG-CoA reductase) was assayed in triplicate or quadruplicate using the method of Brown et al. For the determination of cellular cholesterol, dishes in triplicate were washed twice with phosphate-buffered saline and then scraped in the presence of methanol:water as described. An enzymatic assay was performed on the chloroform extract for total and free cholesterol. Cholesteryl ester was determined as the difference between total and free cholesterol. LDL receptor activity at 4\(^\circ\) was determined in triplicate as described previously using 7.5 \( \mu \text{g} \) \(^{125}\)I-LDL/ml. Iodination of LDL was performed as has been described. Cellular protein was determined on cell hydrolysates after incubation of cell layers with 0.1 N NaOH at 25\(^\circ\) for 2 hours. Apoproteins A-I and A-II were assayed using a radial immunodiffusion assay. The coefficients of variation within each assay averaged less than 10%.

**Statistical Analysis**

Two-way analysis of variance and correlation and partial correlation analyses were performed using the SPSS package. The significance of differences between groups was determined using Dunn's multiple comparison procedure, or when only one comparison was made, using a two-tailed Student's \( t \) test. Analysis was performed on values expressed as a percentage of control, since different cell strains were used with lipoproteins from different subjects.
Table 1. Concentration of Lipids in the d < 1.019 Lipoprotein Fraction and HDL Before and After Fat Feeding

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Time post-feeding (hrs)</th>
<th>Triglyceride</th>
<th>Unesterified cholesterol</th>
<th>Cholesteryl esters</th>
<th>Phosphatidylcholine</th>
</tr>
</thead>
<tbody>
<tr>
<td>d &lt; 1.019</td>
<td>0</td>
<td>0.240 ± 0.032</td>
<td>0.105 ± 0.017</td>
<td>0.121 ± 0.027</td>
<td>0.123 ± 0.022</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.805 ± 0.103††</td>
<td>0.141 ± 0.018††</td>
<td>0.140 ± 0.026</td>
<td>0.197 ± 0.020††</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.349 ± 0.071</td>
<td>0.115 ± 0.023</td>
<td>0.111 ± 0.028</td>
<td>0.142 ± 0.029</td>
</tr>
<tr>
<td>HDL</td>
<td>0</td>
<td>0.082 ± 0.025</td>
<td>0.232 ± 0.015</td>
<td>0.807 ± 0.038</td>
<td>0.720 ± 0.062</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.102 ± 0.031</td>
<td>0.211 ± 0.014††</td>
<td>0.724 ± 0.038††</td>
<td>0.692 ± 0.055††</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>0.097 ± 0.028</td>
<td>0.254 ± 0.014</td>
<td>0.786 ± 0.040</td>
<td>0.809 ± 0.071</td>
</tr>
</tbody>
</table>

Values are expressed in \( \mu \text{mol/ml plasma} \), except for apo A-I and apo A-II which have units of \( \text{mg/dl} \). Values are the means ± SEM (n = 7, except for apoprotein values where n = 6).

†† Values for d < 1.019 represent total phospholipid.

Results

Effects of Feeding on the Concentration of Lipoprotein Lipids

Consumption of the fat load resulted in an increase in the triglyceride, cholesterol, and phospholipid content of the d < 1.019 fraction at 3 hours (table 1), but had no significant effect on cholesteryl esters. Levels of triglyceride more than tripled, while unesterified cholesterol increased only 34%, consistent with the role of triglyceride-rich chylomicrons in this postprandial lipemia. The concentration of d < 1.019 lipids returned to fasting levels by 6 hours. The only alteration in the concentration of LDL lipids was an 11% rise in phospholipids at 6 hours (unpublished observations). In contrast to d < 1.019 lipids, the concentration of HDL unesterified cholesterol, cholesteryl ester, phosphatidyl choline, and sphingomyelin was lower at 3 hours but returned to fasting levels by 6 hours (table 1). The apo A-I levels of HDL also decreased transiently at 3 hours while apo A-II was not significantly affected. The A-I/A-II ratio was not significantly altered.

Effects of Lipoproteins on Cellular Cholesterol

Content of total cholesterol, unesterified cholesterol, and cholesteryl ester in the fibroblasts increased after incubation with 2% serum, 15% d < 1.019 lipoprotein fraction, and 15% LDL, while after 5% HDL, cell cholesterol tended to be lower than control (table 2). There were no significant differences between the effects of postprandial (3 and 6 hours) and postabsorptive (0 hour) lipoproteins. Incubation of cells with LDL increased the concentration of cholesteryl ester to a greater degree (\( p < 0.05 \)) than did the d < 1.019 fraction, presumably because 15% LDL contained 1.82 \( \mu \text{mol total cholesterol/ml} \) compared to 0.24 for the d < 1.019 fraction.

Table 2. Effects of the Lipoprotein Fractions of Postabsorptive and Postprandial Serum on the Concentration of Cellular Cholesterol

<table>
<thead>
<tr>
<th>Time post-feeding (hrs)</th>
<th>15% d &lt; 1.019 (4)</th>
<th>15% LDL (3)</th>
<th>5% HDL (5)</th>
<th>2% serum (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total cholesterol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>178 ± 33</td>
<td>237 ± 72</td>
<td>94.0 ± 2.3</td>
<td>148 ± 20</td>
</tr>
<tr>
<td>3</td>
<td>178 ± 46</td>
<td>253 ± 92</td>
<td>94.7 ± 3.1</td>
<td>140 ± 19</td>
</tr>
<tr>
<td>6</td>
<td>160 ± 27</td>
<td>217 ± 70</td>
<td>92.1 ± 2.1</td>
<td>149 ± 22</td>
</tr>
<tr>
<td>Unesterified cholesterol</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>172 ± 30</td>
<td>166 ± 43</td>
<td>96.3 ± 2.3</td>
<td>125 ± 17</td>
</tr>
<tr>
<td>3</td>
<td>168 ± 34</td>
<td>178 ± 54</td>
<td>98.6 ± 2.8</td>
<td>125 ± 20</td>
</tr>
<tr>
<td>6</td>
<td>161 ± 29</td>
<td>163 ± 37</td>
<td>97.6 ± 1.8</td>
<td>120 ± 16</td>
</tr>
<tr>
<td>Cholesteryl ester</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>202 ± 47</td>
<td>651 ± 220</td>
<td>83.5 ± 7.7</td>
<td>368 ± 135</td>
</tr>
<tr>
<td>3</td>
<td>236 ± 109</td>
<td>727 ± 352</td>
<td>82.2 ± 17.8</td>
<td>306 ± 114</td>
</tr>
<tr>
<td>6</td>
<td>152 ± 21</td>
<td>533 ± 245</td>
<td>76.2 ± 11.3</td>
<td>433 ± 182</td>
</tr>
</tbody>
</table>

Values are the mean ± SEM of the number of observations in parenthesis.

Control values for experiments with the d < 1.019 fraction, LDL, and serum were 47.3 ± 8.1 and 38.1 ± 6.0 \( \mu \text{g/mg protein} \) (\( \bar{x} \) ± SEM) for total and unesterified cholesterol, respectively. Control values for experiments with HDL were 44.3 ± 3.6 and 36.7 ± 4.0.
Table 1. (continued)

<table>
<thead>
<tr>
<th>Sphingomyelin</th>
<th>Apo A-I</th>
<th>Apo A-II</th>
<th>A-I/A-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.114 ± 0.006</td>
<td>132 ± 11</td>
<td>28.5 ± 2.2</td>
<td>4.78 ± 0.60</td>
</tr>
<tr>
<td>0.104 ± 0.004†</td>
<td>122 ± 10†</td>
<td>27.1 ± 1.8</td>
<td>4.63 ± 0.53</td>
</tr>
<tr>
<td>0.118 ± 0.004</td>
<td>134 ± 9</td>
<td>28.0 ± 1.1</td>
<td>4.76 ± 0.33</td>
</tr>
</tbody>
</table>

**Effects of Lipoproteins on LDL Binding**

Alterations in the concentration of the various lipoprotein fractions after feeding did not alter the effects of these fractions on the binding of LDL (table 3). Incubation of cells with serum, LDL, and the d < 1.019 fraction decreased LDL binding, with LDL having a greater effect than the d < 1.019 fraction (p < 0.05). HDL had a variable effect on LDL binding. In three of five experiments, preincubation with HDL resulted in increased binding of LDL (154% ± 6% of control, x ± SEM, n = 9). In the remaining cases, HDL decreased binding of LDL (86.4 ± 2.2%, n = 6). These different responses could not be correlated with differences in the A-I content, the A-I/A-II ratio, or the phosphatidylcholine/cholesterol ratio of the HDL.

Since unesterified cholesterol generated by lysosomal degradation of LDL cholesteryl esters has been shown to down-regulate the LDL receptor, it might be expected that changes in LDL binding activity and changes in cellular cholesterol might be inversely correlated. Figure 1 illustrates the inverse curvilinear relation between changes in LDL binding and cellular cholesteryl ester after incubation of fibroblasts with the various lipoprotein fractions and serum. A log-log transformation of the data (figure 1, insert) yields a linear relation (y = -0.82x + 3.56, r = -0.79, p < 0.001). The correlation between changes in LDL binding and cellular free cholesterol after log-log transformation was not quite significant (r = -0.28, p = 0.051). However, using partial correlation analysis to control for the effect of experimental subjects yields a first order correlation coefficient of -0.50 (p = 0.001).

**Effect of HDL on HMG-CoA Reductase Activity**

Incubation of cells with postabsorptive HDL tended to reduce HMG-CoA reductase activity (92.4 ± 3.6% of control, x ± SEM, n = 6), while postprandial HDL increased activity 36% to 42% compared to postabsorptive HDL (p < 0.05). HMG-CoA reductase is the rate-limiting enzyme for cholesterol synthesis, and has been shown to change in parallel with LDL binding. In these experiments there was no significant correlation between these variables (r = 0.37, p = 0.12). However, the change in HMG-CoA reductase was inversely correlated with the change in cellular cholesteryl ester (r = -0.62, p < 0.02). Since the phospholipid/cholesterol ratio of lipid dispersions has been shown to regulate net flux of cholesterol to hepatoma cells, and since apo A-I may mediate cholesterol efflux, it was of interest to determine if changes in HMG-CoA reductase activity or LDL binding after incubation with HDL were correlated with either HDL apo A-I levels, the A-I/A-II ratio, or the HDL phosphatidylcholine/cholesterol ratio. None of these correlations was significant.

**Discussion**

The purpose of this study was to determine whether the acute changes in the lipid content of lipoproteins that occur after a fat load would increase the ability of these lipoproteins to deliver cholesterol to cells in vitro. Although the cholesterol content of the d < 1.019 fractions used in cholesterol accumulation experiments increased 54% at 3 hours after feeding, this postprandial fraction did not increase
the level of cellular cholesterol or decrease LDL binding activity by fibroblasts any more than did the postabsorptive fraction. In fact, in three of four experiments, the 3-hour $d < 1.019$ fraction increased cellular cholesteryl ester levels to a lesser degree than did the postabsorptive fraction, although this difference did not reach significance. The 3-hour postprandial $d < 1.019$ fraction also tended to have less effect on LDL binding activity compared to the postabsorptive fraction (table 3). Finally, the ability of the $d < 1.019$ fractions, at 1%, 4%, and 15% of plasma concentration, to stimulate incorporation of $^{14}$C-oleic acid into cholesteryl esters was determined in one experiment. At these concentrations, all of which are well below saturation for chylomicrons and remnants, the effects of the 3-hour and 6-hour samples were not different from those of the 0-hour sample (unpublished observations).

Since it has been shown previously that chylomicron remnants formed in vitro are capable of binding activity by fibroblasts any more than did the postabsorptive fraction. In fact, in three of four experiments, the 3-hour $d < 1.019$ fraction increased cellular cholesteryl ester levels to a lesser degree than did the postabsorptive fraction, although this difference did not reach significance. The 3-hour postprandial $d < 1.019$ fraction also tended to have less effect on LDL binding activity compared to the postabsorptive fraction (table 3). Finally, the ability of the $d < 1.019$ fractions, at 1%, 4%, and 15% of plasma concentration, to stimulate incorporation of $^{14}$C-oleic acid into cholesteryl esters was determined in one experiment. At these concentrations, all of which are well below saturation for chylomicrons and remnants, the effects of the 3-hour and 6-hour samples were not different from those of the 0-hour sample (unpublished observations).

Since it has been shown previously that chylomicron remnants formed in vitro are capable of binding and delivering cholesterol to cultured fibroblasts and arterial smooth muscle cells about as well as LDL, the inability to observe increased delivery of cholesteryl esters to cells if the remnants, the effects of the 3-hour and 6-hour samples were not different from those of the 0-hour sample (unpublished observations).

Table 3. Effects of Lipoprotein Fractions of Postabsorptive and Postprandial Serum on LDL Binding Activity

<table>
<thead>
<tr>
<th>Time post-feeding (hrs)</th>
<th>15% d &lt; 1.019 (2)</th>
<th>15% LDL (3)</th>
<th>5% HDL (5)</th>
<th>2% serum (4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(%) control</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>59.1, 53.2*</td>
<td>27.4*, 10.1, 10.0</td>
<td>123.4 ± 14.3</td>
<td>29.9 ± 5.2</td>
</tr>
<tr>
<td>3</td>
<td>71.0, 60.8*</td>
<td>31.1*, 9.5, 10.8</td>
<td>130.1 ± 17.4</td>
<td>31.5 ± 5.4</td>
</tr>
<tr>
<td>6</td>
<td>59.3, 47.6*</td>
<td>28.3*, 11.3, 11.7</td>
<td>126.7 ± 21.2</td>
<td>28.5 ± 4.4</td>
</tr>
</tbody>
</table>

Values are the mean ± SEM of the number of observations in parenthesis.

*Cells were incubated with lipoproteins in medium containing 5% fetal calf LPDS.

Control values for experiments with the $d < 1.019$ fraction, LDL, and serum averaged 64.8 ± 11.8 ng/mg protein ($\bar{x} ± \text{SEM}$). For experiments using HDL, the control value was 80.8 ± 31.6.

1.40 at 3 hours, but the difference did not reach significance. However, chylomicrons have been observed to increase LDL receptor activity (C.-H. Floren, J.J. Albers, E.L. Bierman, unpublished observations).

Daer et al. have demonstrated that HDL$_3$ increases and HDL$_2$ decreases HMG-CoA reductase activity of fibroblasts. The HDL$_{30}$/HDL$_{3}$ ratio was critical in determining the net effect. In addition, in previous studies from our laboratory, Oram et al. reported that HDL$_3$ increases LDL binding activity of fibroblasts and HDL$_2$ blocks this effect. Presumably, these effects of HDL$_3$ on LDL binding and HMG-CoA reductase are mediated by efflux of cholesterol from the cells. In this regard the stimulation of HMG-CoA reductase by postprandial HDL was associated with decreased cell free cholesterol and cholesteryl ester. It might be expected that the stimulatory effect of postprandial HDL on HMG-CoA reductase would be associated with a decreased HDL$_{30}$/HDL$_{3}$ ratio. However, the A-I/A-II ratio, changes in which reflect changes in the HDL$_{30}$/HDL$_{3}$ ratio, was not altered. The different effects of the HDL fractions might also be related to changes in apo E content, since apo E also mediates uptake of lipoproteins by fibroblasts. In a repeat test of one subject, apo E was measured in the lipoprotein fractions. Apo E apparently transferred from HDL to the $d < 1.019$ fraction at 3 hours but returned again by 6 hours (for 0-, 3-, and 6-hour samples, respectively, apo E values for the $d < 1.019$ fraction were 7.8, 13.6, and 8.5 $\mu$g/ml, and for HDL were 20.4, 18.6, and 20.4 $\mu$g/ml). In this case only the 3-hour HDL stimulated HMG CoA reductase activity.

The importance of the time pattern of fat ingestion in relation to the response of HDL apo A-I levels has recently been reported by Kay et al. In contrast to a bolus meal such as was used in the present study, a fat load distributed over 12 hours increased concentrations of HDL A-I and increased the A-I/A-II ratio at 3 hours suggesting an increased HDL$_2$/HDL$_{30}$ ratio. A bolus of fat caused a decrease in HDL A-I at 3 hours similar to the present data, although Kay et al. found...
this change statistically insignificant. Interestingly, HDL cholesterol decreased at 3 hours regardless of the ingestion schedule. The fate of HDL apo A-I and lipids after the bolus of fat is not known. Cholesteryl esters and phospholipids could be transferred to lower density fractions by serum transfer proteins, but transfer of A-I from HDL to less dense lipoproteins has not been demonstrated. Therefore, either removal of A-I of HDL from the serum is increased and/or synthesis is decreased. That the former possibility may be correct is suggested by the work of Koga et al. Those investigators reported that levels of apo A-I in whole serum increased after the consumption of a bolus of fat, which suggests increased, not decreased, apo A-I synthesis. Thus, the changes in lipoprotein composition of the plasma after a meal are the result of the complex interaction of a number of variables. Further work is needed to determine the effects these changes in lipoprotein composition may have on cellular cholesterol metabolism and its possible relation to atherosclerosis.

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