In Vivo Metabolism of Apolipoprotein A-I in a Patient With Homozygous Familial Hypercholesterolemia


Familial hypercholesterolemia (FH), caused by a defect in the low density lipoprotein (LDL) receptor, results in high plasma concentrations of LDL cholesterol due to both overproduction and delayed catabolism of LDL. FH is also associated with significantly lower levels of plasma high density lipoprotein cholesterol and apolipoprotein (apo) A-I in both heterozygous and homozygous patients. However, the metabolic basis of the hypoalphalipoproteinemia in FH has not been elucidated. We investigated the kinetics of apo A-I in a homozygous FH patient and two normal control subjects by using endogenous labeling with a stable isotopically labeled amino acid. Study subjects were administered a primed constant infusion of –C₂-phenylalanine for 12 hours. Apolipoproteins were isolated from plasma drawn at selected time points and analyzed for their isotopic enrichment by gas chromatography-mass spectrometry. The fractional catabolic rate of apo A-I in the FH subject was found to be substantially increased (0.38 day	extsuperscript{-1}) compared with that of the normal subjects (mean, 0.26 day	extsuperscript{-1}). In addition, the apo A-I production rate was decreased in the FH subject (6.5 mg/kg·day	extsuperscript{-1}) compared with the normal subjects (mean, 11.1 mg/kg·day	extsuperscript{-1}). In conclusion, the low levels of high density lipoprotein cholesterol and apo A-I in this homozygous FH patient are due to the combined metabolic defects of increased apo A-I catabolism and decreased apo A-I production. (Arteriosclerosis and Thrombosis 1992;12:843–848)

KEY WORDS • familial hypercholesterolemia • fractional catabolic rate • apolipoprotein A-I • low density lipoproteins

Familial hypercholesterolemia (FH) is caused by a variety of genetic defects in the gene for the low density lipoprotein (LDL) receptor. Heterozygotes for FH have approximately twofold elevations in plasma LDL cholesterol concentrations, whereas FH homozygotes have LDL cholesterol levels elevated as much as sixfold. Plasma apolipoprotein B-100 (apo B-100), apo E, and lipoprotein(a) (Lp[a]) concentrations are also significantly elevated in FH. Conversely, plasma high density lipoprotein (HDL) cholesterol and apo A-I levels are significantly decreased in both homozygous and heterozygous FH.

The in vivo metabolism of apo B–containing lipoproteins has been extensively studied in FH, establishing that there is overproduction as well as delayed catabolism of apo B–containing lipoproteins in this disease. Apo E catabolism is also delayed in FH, presumably because of decreased LDL receptor-mediated catabolism. We have demonstrated that the fractional catabolic rate (FCR) of Lp(a) in homozygous FH is decreased as well.

In contrast, there has been no investigation of the metabolic basis of the low plasma HDL cholesterol and apo A-I levels in FH. In this article we report the results of a kinetic study of apo A-I in a patient with homozygous FH that used endogenous labeling with a primed constant infusion of a stable isotopically labeled amino acid.

Methods

Study Subjects

Studies were performed in a homozygous FH patient and two normal control subjects. The FH subject is a 26-year-old man who is homozygous for a class 1 defect in the LDL receptor, with no detectable receptors on the cell surfaces as determined by functional and immunologic studies. The medical history of this patient includes a myocardial infarction (7 years of age), ileal bypass surgery (9 years of age), and bilateral carotid endarterectomies (25 years of age). The patient usually undergoes biweekly LDL apheresis, which was stopped 5 weeks before this study to achieve lipoprotein steady-state conditions. Total cholesterol, LDL cholesterol, apo B, and apo E levels in the FH subject were elevated, whereas HDL cholesterol and apo A-I levels were...
Amino Acid concentration of 0.1% (wt/vol). Plasma was separated before the priming bolus, 10 minutes after the bolus, and then at selected times during the infusion. Blood samples were drawn in small equal portions every 2 hours during the infusion. Meals were provided in small equal portions every 2 hours and at a final concentration of 0.05% (wt/vol) and 200 kIU/ml, respectively.

Isolation of Free Plasma Amino Acids
Free plasma amino acids were isolated from 0.5 ml plasma by cation-exchange column chromatography as previously described. Briefly, 1 ml 30% acetic acid was added to 0.5 ml plasma and applied to pre-filled PolyPrep columns (Bio-Rad, Richmond, Calif.). The columns were washed with 8 ml distilled water and eluted with 5 ml 4N NH$_4$OH directly into 5-ml reaction vials (Pierce, Rockford, Ill.).

Isolation and Preparation of Apolipoproteins
Lipoprotein density subfractions were isolated by sequential ultracentrifugation$^{20}$ of 5 ml plasma collected at selected time points. Very low density lipoproteins (VLDLs; d<1.006 g/ml) and HDL (d = 1.063-1.21 g/ml) were used for isolation of apolipoproteins. Apo B-100 was isolated from delipidated VLDL by preparative discontinuous gradient sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) (5%/15% acrylamide) using a modification of a previously published method.$^{21}$ Approximately 0.5 mg VLDL protein was delipidated using chloroform/methanol (2:1, vol/vol)$^{22}$ and solubilized in 2% SDS containing 0.1 M tris(hydroxymethyl)aminomethane HCl (pH 6.8) and 1% (vol/vol) diethiothreitol. The samples were heated at 100°C for 10 minutes and applied to a 3-mm-thick vertical slab gel (12X14 cm). After electrophoresis the gels were stained with Coomassie Blue R-250 (Bio-Rad) and destained in a solution of 5% (vol/vol) methanol and 7.5% (vol/vol) acetic acid. Apo A-I was isolated from HDL by preparative isoelectric focusing.$^{23}$ After dialysis, lyophilization, and delipidation of HDL as described above, approximately 1 mg HDL protein was solubilized in buffer containing 8.6 M urea and 1% (vol/vol) diethiothreitol. Isoelectric focusing was carried out in a 3-mm-thick vertical slab gel using 7.5% acrylamide, 8 M urea, and 2% (vol/vol) Pharmalyte, pH 4-6.5 (Pharmacia, Piscataway, N.J.). Gels were electrofocused at 250 V for 20 hours at 4°C with 0.02 M NaOH and 0.01 M H$_3$PO$_4$ as the upper and lower buffers, respectively. After electrophoresis the gels were stained with Coomassie Blue G-250 (Bio-Rad). Stained apolipoprotein bands were cut from the gels, and the gel slices were dried in a 90°C oven and then hydrolyzed in 6N HCl (Pierce) for 24 hours at 110°C under nitrogen vacuum. After removal of HCl by speed-vac lyophilization the samples were dissolved in 50% (vol/vol) acetic acid and applied to cation-exchange columns as described above. Amino acids were recovered by elution with 4N NH$_4$OH into reaction vials.

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**Table 1. Subject Characteristics**

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age (years)</th>
<th>Apo E phenotype</th>
<th>Chol (mg/dl)</th>
<th>Tg (mg/dl)</th>
<th>HDL (mg/dl)</th>
<th>Apo B (mg/dl)</th>
<th>Apo E (mg/dl)</th>
<th>Apo A-I (mg/dl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FH subject</td>
<td>26</td>
<td>3/3</td>
<td>478</td>
<td>101</td>
<td>13</td>
<td>268</td>
<td>6.1</td>
<td>44</td>
</tr>
<tr>
<td>Control 1</td>
<td>22</td>
<td>3/4</td>
<td>190</td>
<td>54</td>
<td>42</td>
<td>111</td>
<td>2.5</td>
<td>109</td>
</tr>
<tr>
<td>Control 2</td>
<td>25</td>
<td>3/3</td>
<td>220</td>
<td>147</td>
<td>32</td>
<td>123</td>
<td>3.6</td>
<td>111</td>
</tr>
</tbody>
</table>

Apo, apolipoprotein; chol, cholesterol; Tg, triglyceride; HDL, high density lipoprotein; FH, familial hypercholesterolemia.

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**Preparation of Stable Isotopically Labeled Amino Acid**

The stable isotopically labeled amino acid used in this study was a custom-synthesized $^{13}$C$_6$-labeled L-phenylalanine, with the six labeled carbons positioned in the aromatic ring (Cambridge Isotope Laboratories, Woburn, Mass.). Multiple labeling of the amino acid was selected because the additional mass shifts the labeled amino acid peak well out of the range of the peak due to the natural abundance of heavy isotopes on mass spectrometric analysis. The use of $^{13}$C$_6$-labeled phenylalanine therefore significantly increases the accuracy of the mass spectrometric detection of the tracer because the background level is virtually zero. Phenylalanine was chosen as the tracer amino acid in part because it undergoes irreversible conversion to tyrosine by the hepatic intracellular enzyme phenylalanine hydroxylase,$^{18}$ resulting in the generation of sixfold-labeled tyrosine in plasma. A plasma steady state of phenylalanine thus reflects a steady state within the hepatocyte of its intracellular $^{13}$C$_6$-labeled phenylalanine precursor. The $^{13}$C$_6$-phenylalanine was dissolved in physiological salt solution, sterile filtered, and tested for pyrogenicity and sterility before the study.

**Study Protocol**

Three days before the start of the study, subjects were placed on a controlled isoweight diet containing 37% fat, 47% carbohydrate, 16% protein, 200 mg cholesterol/1,000 kcal, and a polyunsaturated to saturated fat ratio of approximately 0.3. After a 12-hour fast, the $^{13}$C$_6$-phenylalanine was administered as a priming bolus of 550 mg/kg immediately followed by a constant infusion of 12 mg·kg$^{-1}$·min$^{-1}$ over a period of 12 hours. Meals were provided in small equal portions every 2 hours during the infusion. Blood samples were drawn before the priming bolus, 10 minutes after the bolus, and then at selected times during the infusion. Blood was drawn into tubes containing EDTA at a final concentration of 0.1% (wt/vol). Plasma was separated by low-speed centrifugation for 30 minutes at 4°C. Sodium azide and aprotinin were added to the plasma.
Gas Chromatographic–Mass Spectrometric Analysis

Recovered amino acids were derivatized to the N-heptfluorobutyl isobutyl esters as previously described. Briefly, 500 μl isobutyl HCl (Alltech Associates, Inc., Deerfield, Ill.) was added to the samples, and vials were heated for 1 hour at 110°C, cooled to room temperature, and lyophilized. The residue was dissolved in 200 μl high-performance liquid chromatography-grade ethyl acetate and further treated with 150 μl heptfluorobutyric acid (Alltech Associates Inc.) at 150°C for 10 minutes to complete the derivatization. After cooling to room temperature and lyophilizing to dryness, the derivatized product was dissolved in 100 μl ethyl acetate and stored at -20°C until gas chromatographic–mass spectrometric (GC/MS) analysis.

Samples were analyzed on a Finnigan MAT 4500 GC/MS (Finnigan, San Jose, Calif.) in the chemical ionization mode with isobutane as the reagent gas. The selected positively charged ions of 418 m/z for phenylalanine, 424 m/z for 13C₆-phenylalanine, 630 m/z for tyrosine, and 636 m/z for 13C₆-tyrosine were monitored. At least three measurements were made of each apolipoprotein at each time point. In addition, a blank gel slice comparable in size to the protein gel slices was analyzed as a control. The amount of unlabeled phenylalanine in the blank gel slices was always less than 3% of the total phenylalanine in the study samples. The isotopic enrichment of the sample was determined as the fraction of labeled to total (labeled plus unlabeled) phenylalanine.

Analytical Methods

Apo A-I and apo B were quantified by enzyme-linked immunosorbent assay as previously described. Apo E was quantified by radioimmunoassay. Plasma cholesterol and triglycerides were quantified by using an enzymatic assay (Wako Pure Chemical Industries, Ltd., Houston, Tex.). HDL cholesterol was determined in plasma after dextran sulfate precipitation.

Determination of the fractional synthetic rate (FSR) of apo A-I was performed as recently reported. The isotopic enrichment of VLDL apo B-100 at plateau was used as an estimate of the precursor pool enrichment for apo A-I synthesis. The isotopic enrichment of apo A-I was divided by the precursor enrichment to obtain a "corrected isotopic enrichment." A "best-fit" line was fit to the data by using linear regression analysis. The apo A-I FSR was determined as the slope of the apo A-I corrected isotopic enrichment curve. At steady state, the FSR equals the FCR. The apo A-I production rate (PR) was determined by the formula

\[ PR = \frac{[FSR \times apo A-I concentration \times plasma volume]}{body weight} \]

Plasma volume was assumed to be 4% of body weight.

Results

A plasma steady state of free 13C₆-phenylalanine was achieved within 30 minutes in all three study subjects (Figure 1). The mean isotopic enrichment of 13C₆-phenylalanine at steady state was 5.6±0.7% in the FH subject, 5.7±0.4% in control subject 1, and 4.9±0.3% in control subject 2. A steady state of endogenously de-
rived $^{13}$C$_{6}$-tyrosine was also reached within 30 minutes in all subjects (data not shown).

The VLDL apo B-100 tracer uptake curves are shown in Figure 2. The plateau isotopic enrichment of VLDL apo B-100 was 3.6±0.1% in the FH subject, 3.8±0.1% in control subject 1, and 3.4±0.1% in control subject 2.

The corrected isotopic enrichment curves for apo A-I in the FH and the two control subjects are illustrated in Figure 3. Because the data have been corrected for differences in precursor enrichment among the study subjects, the slopes of the lines can be directly compared. The turnover of HDL apo A-I in the FH subject is faster than in either of the control subjects.

The kinetic parameters are presented in Table 2. The apo A-I FCR (FSR at steady state) in the FH subject was 0.376 day$^{-1}$, substantially greater than that in the control subjects. In addition, the apo A-I PR in the FH subject was only 6.2 mg/kg·day$^{-1}$, less than that in the control subjects. This indicates that the FH subject has both accelerated apo A-I catabolism and decreased apo A-I production compared with normal.

**Table 2. Kinetic Parameters of Apo A-I Metabolism**

<table>
<thead>
<tr>
<th>Subject</th>
<th>FSR (day$^{-1}$)</th>
<th>Apo A-I (mg/dl)</th>
<th>PR (mg/kg·day$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FH subject</td>
<td>0.376</td>
<td>44</td>
<td>6.2</td>
</tr>
<tr>
<td>Control 1</td>
<td>0.230</td>
<td>109</td>
<td>9.7</td>
</tr>
<tr>
<td>Control 2</td>
<td>0.286</td>
<td>111</td>
<td>10.7</td>
</tr>
</tbody>
</table>

*Apo, apolipoprotein; FSR, fractional synthetic rate; PR, production rate; FH, familial hypercholesterolemia.*

**Discussion**

Decreased plasma concentrations of HDL cholesterol and apo A-I are risk factors for coronary heart disease (CHD), independent of LDL cholesterol level.$^{33}$ Even within the heterozygous FH population, HDL cholesterol level is inversely related to the incidence and severity of CHD.$^{3}$ Homozygous FH patients have not only higher LDL cholesterol but also lower HDL cholesterol levels than heterozygotes$^{4}$ and are at much greater risk for CHD.$^{1}$ Therefore, low HDL levels may further increase CHD risk in FH patients.

Despite its clinical relevance, the metabolic basis of the low HDL cholesterol levels in FH has not been investigated. In contrast, the decreased HDL levels found in hypertriglyceridemic subjects have been the focus of several kinetics studies.$^{34}$–$^{38}$ The cause of the low HDL and apo A-I levels in hypertriglyceridemia has been shown to be an increased FCR of apo A-I. The apo A-I PRs in hypertriglyceridemic subjects were reported to be normal or increased.

Because so little is known about the mechanism of the hypoalphalipoproteinemia in FH, we chose to investigate the apo A-I kinetics in a homozygous FH subject. We demonstrate that this patient has a dual metabolic defect: an increased apo A-I FCR as well as decreased apo A-I production. Similar results were recently reported by Saku et al.$^{39}$ in the Watanabe heritable hyperlipidemic (WHHL) rabbit, an animal model of FH. In that study, radiolabeled HDL turnover studies revealed that WHHL rabbits have an increased apo A-I FCR (0.874 day$^{-1}$) compared with control rabbits (0.502 day$^{-1}$). In addition, the WHHL rabbits have a decreased apo A-I PR (8.67 mg/kg·day$^{-1}$) compared with control rabbits (18.14 mg/kg·day$^{-1}$). Subsequent studies have demonstrated that hepatic apo A-I mRNA levels in WHHL rabbits are significantly lower than in normal rabbits.$^{40}$

FH is characterized metabolically by overproduction and delayed clearance of apo B,$^{14}$ delayed catabolism of apo E,$^{15}$ and delayed catabolism of Lp(a).$^{16}$ The lack of a functional LDL receptor presumably accounts for the delayed catabolism of apo B, apo E, and Lp(a). The increased apo B production in FH subjects is less well understood but may be related to disturbances of intracellular cholesterol metabolism.

In the FH patient described in this report, apo A-I has an accelerated catabolism and a decreased rate of production. The mechanism by which the lack of functional LDL receptors results in these metabolic alterations is uncertain. The increased apo A-I catabolic rate has several potential explanations. One may be related to the expanded pool size of apo E in FH. Two reports have documented that the HDL-associated apo E mass in FH is more than twice that in normolipidemic subjects.$^{41}$ In our study, the mass of apo E in HDL was 2.3 times higher in the FH subject (4.7 mg/dl) than in the normal subject with the apo E-3/3 phenotype (2 mg/dl). It has been established that apo E–enriched HDL is catabolized rapidly via a receptor-dependent pathway mediated by apo E.$^{42}$ Given that the remnant receptor pathway in FH appears to be normal,$^{14}$ it may be that the apo E–enriched HDL in FH is catabolized via this pathway, resulting in an increased apo A-I FCR.

A second possibility is that the expanded pool of apo B–containing lipoproteins in FH results in a greater net mass transfer of cholesteryl ester from HDL to apo B particles via the cholesteryl ester transfer protein.$^{43}$ We have recently demonstrated that deficiency of cholesteryl ester transfer protein results in delayed apo A-I catabolism,$^{44}$ and therefore increased cholesteryl ester transfer from HDL may cause more rapid apo A-I catabolism. This remains to be established.

The reduction in apo A-I production in this FH subject is consistent with the observations in WHHL rabbits and is intriguing in light of the documented increase in apo B production in FH. Monge et al.$^{45}$ reported that incubation with LDL resulted in an increase of apo A-I mRNA in HepG2 cells. Recently, Mitchell et al.$^{46}$ reported that treatment of rats with drugs that upregulate the LDL receptor resulted in a marked increase in hepatic apo A-I mRNA levels and a decrease in hepatic apo B mRNA levels. Thus, there...
may exist a feedback system involving the LDL receptor that regulates the hepatic expression of both apo A-I and apo B. It is well established that FH fibroblasts have markedly impaired ability to normally regulate the 3-hydroxy-3-methylglutaryl coenzyme A reductase gene46; FH hepatocytes also have abnormal intracellular cholesterol homeostasis that may affect the production of apo A-I and apo B.

In conclusion, we have established that low levels of HDL cholesterol and apo A-I in a homozgyous FH subject are due to a combined metabolic defect of increased apo A-I catabolism and decreased apo A-I production compared with control subjects studied under identical conditions. These results provide new insights into the regulation of apo A-I metabolism in FH.

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In vivo metabolism of apolipoprotein A-I in a patient with homozygous familial hypercholesterolemia.

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